Nutrition
Nutrition

JESSICA KELLY
Comprehensive Nutrition: A Science-Based Approach

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About the Flexbook

The CK-12 foundation defines a flexbook as a “free and open source textbook platform where one can build and edit collaborative textbooks.” The FNDH 400 (formerly the HN 400 flexbook, department changed its name from Human Nutrition to Food, Nutrition, Dietetics and Health) Flexbook fits this definition, but I feel the name is particularly accurate due to the flexibility of Google Docs. Students in addition to having access through Google Docs, can download the flexbook as an .odt, .pdf, .rtf, .doc, text, or html file giving them flexibility to use the document how they would like. Students can also choose whether they would like to read the flexbook digitally or print and read it on paper.

The flexbook is divided into 13 chapters with sections and subsections. These are numbered in such a way that the first number represents the chapter. A period separates the chapter from the section number, and another period is followed by the subsection number. The figures are non-copyrighted figures or I have made them myself in PowerPoint. The flexbook also contains links to articles, videos, and animations in Web Link boxes. These can be clicked to open the link, and urls for these resources are also provided at the end of the section or subsection.

I am happy to share the flexbook and PowerPoint slides that I use for class with other instructors teaching similar courses. Please email me and we can get something arranged. I hope eventually this flexbook, or something similar, will become a collaborative project.

Brian Lindshield allows others to distribute, remix, tweak, and build upon this work, even commercially, as long as attribute this resource.
Here's a citation to use for this purpose, but if this doesn't work for your purpose, please cite the url which is also provided below.

Citation:
Lindshield, B. L. Kansas State University Human Nutrition (FNDH 400) Flexbook. goo.gl/vOAnR

Shortened URL: goo.gl/vOAnR

The flexbook was a finalist for the 2012 Education-Portal.com People’s Choice Award for the Most Open Resource (note Education-Portal.com is now Study.com).

About the Course
FNDH 400 is a 3-hour, intermediate-level, nutrition course at Kansas State University taught on campus every spring semester, and all 3 semesters (fall, spring, summer) via the Division of Continuing Education. Ideally on-campus students take the course during the spring semester of their sophomore year. Most on-campus students in the class are majoring in Nutritional Sciences, Nutrition and Health (previously Public Health Nutrition), Nutrition and Kinesiology, Athletic Training, or Dietetics. There is an increasing number of Biology, Life Sciences and other majors taking the course. Online, more students are nontraditional and a little more than half are distance dietetics students (K-State offers a distance dietetics degree).

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Brian Lindshield, Ph.D. is an Associate Professor in the Department of Food, Nutrition, Dietetics and Health. He received an A.S. from Pratt Community College in ’01, a B.S. in Human Nutrition from Kansas State University in ’03, and Ph.D. in Nutritional Sciences from the University of Illinois at Urbana-Champaign in ’08.

Peer-reviewed flexbook/OER journal articles


http://jolt.merlot.org/vol9no1/lindshield_0313.htm

Lindshield, B.L., Adhikari, K. The Kansas State University Human Nutrition (HN 400) Flexbook. Educause Quarterly. 34(4), 2011.  

Flexbook Presentations

3/5/13 Innovations in Teaching & Learning Showcase  
“Open Educational Resources, Textbook Replacements?”

3/4/13 Innovations in Teaching & Learning Workshop Panel  
“Take 5: Teaching Technologies that Work”

9/27/12 IDT Roundtable  
“E-textbooks and Beyond”

One of 3 speakers at session.  
http://id.ome.ksu.edu/roundtable/e-textbooks-and-beyond/

3/16/12 Teaching, Learning, and Technology Showcase 2012  
—“Using Flexbooks to Supplement/Replace the Traditional Textbook”

9/28/11 Axio Learning Conference 2011  
—Peer Showcase: “Using flexbooks to supplement/replace the traditional textbook”

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7/25/11 Society for Nutrition Education and Behavior Oral Presentation
    -“Kansas State University Human Nutrition (HN 400) Flexbook”
9/29/10 Axio Learning Conference 2010
    -“Flexbooks”
1/12/10 7th annual K-State Teaching Retreat
    -“Flexbooks: Better than Textbooks?”

Media Stories about the Flexbook

9/26/13 K-State Today
K-State faculty receive funding to develop open alternative textbooks

http://www.k-state.edu/today/announcement.php?id=10136&category=kudos&referredBy=email

1/29/13 Kansas State Collegian
Open-sourced ‘flexbook’ earns K-State educator national acclaim

9/19/12 College Human Ecology Press Release
Lindshield’s flexbook nominated for national people’s choice award
http://www.he.k-state.edu/news/2012/09/19/lindshields-flexbook-nominated-for-national-peoples-choice-award/

9/12/12 Partnership for Technology Innovation
Providing an Open Resource, Lowering the Financial Burden
http://partnership4techinnovation.org/providing-an-open-resource-lowering-the-financial-burden/

8/24/12 Kansas City Star
K-State professor develops textbook flexibility

Other media outlets where article was published:
    Chicago Tribune: http://www.chicagotribune.com/business/
McClatchy Wire
Sacramento Bee
Sun Herald (Biloxi-Gulfport and Mississippi Gulf Coast
Lexington Herald-Leader
The Telegraph (Georgia)
The South Carolina State
The Olympian (Olympia, Washington)
The Bradenton Herald (Florida)
Bellingham Herald (Washington)
News Observer (Raleigh, North Carolina)
The Modesto Bee (Modesto, California)
The Idaho Statesman (Boise, Idaho)
Civic Plus (Blog)
The Stockton Record (Stockton, California):

The Detroit News
8/16/12 Up to Date KCUR 89.3 (Kansas City NPR station)
The ‘Flexbook’: A Textbook Replacement
http://kcur.org/post/flexbook-textbook-replacement
8/13/12 Kansas State University Press Release
From textbook to flexbook: Professor uses new collaborative tool in the classroom
http://www.k-state.edu/media/newsreleases/aug12/flexbook81312.html

Other media outlets that published the release:
8/13/12 K-State Today

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Professor’s collaborative flexbook nominated for national people’s choice award http://www.k-state.edu/today/announcement.php?id=4284&category=kudos&referredBy=email

2/22/12 Just In Blog
Lindshield flexes his flexbook muscle and tells how you can, too
http://updatejustin.wordpress.com/2012/02/22/lindshield-flexes-his-flexbook-muscle-and-tells-how-you-can-too/

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Flexbooks: What Can They Do For You?

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Reference
1. http://creativecommons.org/weblog/entry/9378
Supplemental Videos

A TED element has been excluded from this version of the text. You can view it online here:
https://library.achievingthedream.org/herkimernutrition/?p=17

https://ed.ted.com/on/D8gzkswZ
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You can view it online here:
https://library.achievingthedream.org/herkimernutrition/?p=17
The field of nutrition is dynamic. This means that our understanding and practices are constantly changing and being updated. Some of nutrition’s dynamic nature may be due to the fact that nutrition, as a discipline, is relatively young (many vitamins weren’t isolated until the 1930s) compared to many other scientific fields. New research is always being conducted and the findings are continuously being reported to the public. With so much information, discernment must be exercised. In order to interpret these new findings, you need to understand how the research was conducted and the nutrition research hierarchy. Everyone eats, so people are going to face nutrition choices and questions on a daily basis. This section will provide you with an integrated understanding of the different forms of nutrition research and how to evaluate them relative to one another.

Sections:
1.1 The Basics
1.2 Epidemiology
1.3 In vitro/Animal Studies
1.4 Human Intervention Studies/Clinical Trials
1.5 Nutrition Research Statistics
1.6 Publishing Research
1.7 Interpreting Research
2. 1.1 The Basics

Nutrition can be defined as the science of the action of food, beverages, and their components in biological systems. A nutrient is a compound that provides a needed function in the body. Nutrients can be further classified based on the amount needed in the body.

Macronutrients: nutrients needed in larger amounts
Micronutrients: nutrients needed in smaller amounts (but still important)

The following table lists the different macronutrients and micronutrients.

Table 1.11 Macronutrients and Micronutrients

<table>
<thead>
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<td>Carbohydrates</td>
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<td>Proteins</td>
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<tr>
<td>Lipids</td>
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<tr>
<td>Water</td>
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Carbohydrates

The name carbohydrate means “hydrated carbon”, or carbon with water. Thus, it isn’t a surprise that carbohydrates are made up of carbon, hydrogen, and oxygen. Sucrose (table sugar) is an example of a commonly consumed carbohydrate. Some dietary examples of carbohydrates are whole-wheat bread, oatmeal, rice, sugary snacks/drinks, and pasta.
Proteins

Proteins are also made up of carbon, hydrogen, and oxygen, but they also contain nitrogen. Several dietary sources of proteins include nuts, beans/legumes, skim milk, egg whites, and meat.
Lipids

Lipids consist of fatty acids, triglycerides, phospholipids, and sterols (i.e. cholesterol). Lipids are also composed of carbon, hydrogen, and oxygen. Some dietary sources of lipids include oils, butter, and egg yolks.
Water

Water is made up of hydrogen and oxygen (H2O) and is the only macronutrient that doesn't provide energy.

Vitamins

Compounds that are essential for normal physiologic processes in the body.
Minerals

Elements (think periodic table) that are essential for normal physiological processes in the body.

No References
3. 1.11 Calories (Food Energy)

Food energy is measured in kilocalories (kcals), commonly referred to as calories by the general public. The general public “calorie” term is incorrect (most do not know or understand the difference between the kilocalorie and calorie terms), but it is important to understand how what the term calorie represents when it is used in this way. A kilocalorie is the amount of energy needed to raise 1 kilogram of water 1 degree Celsius. A food’s kilocalories are determined by putting the food into a bomb calorimeter and determining the energy output (energy = heat produced). The first link below is to an image of a bomb calorimeter and a link to a video showing how one is used.

Web Links

Bomb Calorimeter
Video: Bomb Calorimetry (2:19)

Among the nutrients, the amount of kilocalories per gram that each provide are shown below.

<table>
<thead>
<tr>
<th>Energy (kcal/g)</th>
<th>No Energy</th>
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<tbody>
<tr>
<td>Carbohydrates (4)</td>
<td>Vitamins</td>
</tr>
<tr>
<td>Proteins (4)</td>
<td>Minerals</td>
</tr>
<tr>
<td>Lipids (9)</td>
<td>Water</td>
</tr>
</tbody>
</table>

As can be seen, only carbohydrates, proteins, and lipids provide energy. However, there is another energy source in the diet that is not a nutrient......alcohol. Just to re-emphasize, alcohol is NOT a nutrient! But it does provide energy.
The following table lists the energy sources in the diet from lowest calories per gram to the highest calories per gram. Knowing these numbers allows a person to calculate/estimate the amount of calories the food contains if you know the grams of the different energy sources.

### Energy Sources (kcal/g)

- Carbohydrates → 4
- Protein → 4
- Alcohol → 7
- Lipids → 9

**Figure 1.12** Wine is a type of alcohol.

**Links**

- Bomb Calorimeter – https://www.learner.org/courses/chemistry/text/text.html?dis=U&num=Ym5WdEIUQS9PQ289&sec=YzJWaklUQS9OeW89
- Bomb Calorimetry – http://www.youtube.com/watch?v=ohyA9amFfsc
Beyond macronutrients and micronutrients, there is a lot of interest in non-nutritive compounds found in foods that may be either beneficial or detrimental to health.

Phytochemicals

Figure 1.121 Tomatoes and other plants contain phytochemicals.
Phytochemicals are compounds in plants (phyto) that are believed to provide healthy benefits beyond the traditional nutrients. One example is lycopene in tomatoes, which is thought to potentially decrease the risk of some cancers (in particular prostate cancer). Diets rich in fruits and vegetables have been associated with decreased risk of chronic diseases. Many fruits and vegetables are rich in phytochemicals, leading some to hypothesize that phytochemicals are responsible for the decreased risk of chronic diseases. The role that phytochemicals play in health is still in the early stages of research, relative to other areas of nutrition such as micronutrients. The following 2 links contain good information on phytonutrients if you are interested in learning more about them.

**Web Link**

[Linus Pauling Institute: Phytochemicals](#)

**Zoochemicals**

Zoochemicals are the animal equivalent of phytochemicals in plants. They are compounds in animals that are believed to provide health benefits beyond the traditional nutrients that food contains. Hopefully the name is pretty easy to remember because you can find animals at a zoo. Some compounds can be both phytochemicals and zoochemicals. An example of compounds that can be classified as both are the yellow carotenoids lutein and zeaxanthin. Kale, spinach, and corn contain phytochemicals and are good sources of lutein and zeaxanthin. Whereas egg yolks contain zoochemicals and are also a good source of these carotenoids.

**Functional Foods**

There are a number of definitions of functional foods. Functional foods are generally understood to be a food, or a food ingredient, that may provide a health benefit beyond the traditional nutrients (macro and micronutrients) it contains. Functional foods are often a rich source of a phytochemical or zoochemical, or contain more of a certain nutrient than a normal food.

**Links**

22 | 1.12 Phytochemicals, Zoochemicals & Functional Foods
5. 1.13 The Scientific Method

The basis of what we know about nutrition is derived from research and the scientific method underlies how research is conducted. The following figure shows the steps in the scientific method.

![Diagram of the scientific method]

**Figure 1.131 The scientific method**

**Steps in the Scientific Method**

1. The first step is to come up with a scientific or research question that you are interested in investigating.
2. Based on your research question, a hypothesis or an educated guess is formulated.
3. The next step is to design and conduct the experiment. A good
design should take into account what has been done previously. Thus, a thorough review of methods and results published previously should be undertaken. This will help prevent making the same mistakes and save a lot of time conducting the research.

4. Perform the experiment/research and collect results and draw conclusions.

5. If the hypothesis is not supported, then a new hypothesis/research question should be created and a new experiment be conducted.

6. Ultimately, researchers hope to publish their research in peer-reviewed journals.

No References
6. 1.2 Epidemiology

Epidemiology is defined as the study of human populations. These studies often investigate the relationship between dietary consumption and disease development. There are three main types of epidemiological studies: cross-sectional, case-control, and prospective cohort studies.

<table>
<thead>
<tr>
<th>Past</th>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-control study</td>
<td>Cross-sectional study</td>
<td>Prospective Cohort Study</td>
</tr>
</tbody>
</table>

Figure 1.21 Types of epidemiology (Adapted from Reference 1)

1. Cross-Sectional Studies

Cross-sectional studies compare different populations at the same point in time. It is as if you take a snapshot of the two different populations to compare them to one another. An example of a cross-sectional study led to a phenomenon known as the “French Paradox.” Cholesterol and saturated fat intake were associated with increased risk of coronary heart disease across a wide variety of countries. However, within the study they noticed a surprising result. European countries with very similar cholesterol-saturated fat intakes had hugely different death rates from coronary heart disease deaths, as shown below.
Figure 1.22 An example of a cross-sectional study, “The “French Paradox”. The x-axis shows four different European countries with similar cholesterol-saturated fat intakes (the numbers shown within the bars), and the y-axis represents coronary heart disease rate.

The French had a 5-fold lower risk of dying from coronary heart disease than the Finns, despite having similar cholesterol-saturated fat intakes. A paradox means something contradictory, which this finding seemed to be. The “French Paradox” has led to research on red wine, and one of its active components, resveratrol, because the French consume a lot of this alcoholic beverage. Cross-sectional studies are considered the weakest type of epidemiology because they are based only on group outcomes. This may lead people to believe that members of the group have characteristics, which as individuals they do not. This is known as ecologic (another name that is used to refer to this type of study) fallacy, and is a limitation of cross-sectional studies.

2. Case-Control Studies

Case-control studies look at a group of cases (e.g. people with a disease) vs. controls (e.g. people without the disease). Most case-control studies are retrospective (looking back in time, or looking at the past). These studies try to determine if there were differences
in the diets of the cases compared to controls in the past. Cases and controls are matched on characteristics such as age, sex, BMI, history of disease, and many others. This means researchers try to choose a control that has similar characteristics to the case. The researchers then compare the exposure levels between the cases and controls, as shown below. In this example a greater proportion of diseased (cases) individuals than disease-free individuals (controls) were exposed to something.

Using trans-fat intake as the exposure, and cardiovascular disease as the disease, the figure would be expected to look like this:
To determine people's intakes of foods and food components, food frequency questionnaires are commonly used. As the name suggests, a food frequency questionnaire is a series of questions that determines how frequently you consume a certain food. An example of a question on a food frequency questionnaire is shown below:

“Over the past 12 months, how often did you drink milk?”

Never
1 time/month less 1 time/day
2-3 times/month 2-3 times/day
1-2 times/week 4-5 times/day
3-4 times/week 6 or more times/day
5-6 times/week

An example of a food frequency questionnaire is shown in the link below.

Web Link

NHANES Food Frequency Questionnaire→
A cohort is “a group of subjects.” Most cohort studies are prospective. Initial information is collected (usually by food frequency questionnaires) on the intake of a cohort of people at baseline, or the beginning. This cohort is then followed over time (normally many years) to quantify health outcomes of the individual within it. Cohort studies are normally considered to be more robust than case-control studies, because these studies do not start with diseased people and normally do not require people to remember their dietary habits in the distant past or before they developed a disease. An example of a prospective cohort study would be if you filled out a questionnaire on your current dietary habits and are then followed into the future to see if you develop osteoporosis. As shown below, instead of separating based on disease versus disease-free, individuals are separated based on exposure. In this example, those who are exposed are more likely to be diseased than those who were not exposed.

![Diagram](image)

*Figure 1.25 An example of cohort study in which those exposed are more likely to develop the disease. (Adapted from Reference 3)*

Using trans-fat intake again as the exposure and cardiovascular disease as the disease, the figure would be expected to look like this:
Figure 1.26 An example of a cohort study where higher trans-fat intake is associated with a higher incidence of cardiovascular disease.

There are several well known examples of prospective cohorts' studies:

**Framingham Heart Study**

The Framingham Heart Study started in 1948 and has been following the residents of Framingham, Massachusetts to identify risk factors for heart disease. This cohort has been very fruitful in finding a number of important factors associated with coronary heart disease. In 2002, a third generation of participants was enrolled to be followed. The following links show more about the Framingham Heart Study.

**Web Links**

Framingham Heart Study History
Framingham Heart Study Research Milestones

**Nurses Health Study**

The Nurses’ Health Study started in 1976 and enrolled 122,000 female nurses. Every 4 years they received a food frequency questionnaire to assess their dietary habits.
Health Professionals Follow-Up Study

The Health Professionals Follow-Up Study started in 1986 and enrolled 51,529 male health professionals (dentists, pharmacists, optometrists, osteopathic physicians, podiatrists, and veterinarians). Every 4 years they received a food frequency questionnaire to assess their dietary habits.

The Health Professionals Follow-Up Study is a good example for how cohort studies can be important in nutrition research. We will consider one example in which the researchers administered food frequency questionnaires that contained 131 food and beverage items to determine whether their intake was associated with increased or decreased risk of developing prostate cancer\(^4\). Of these items, intake of four foods (tomatoes, tomato sauce, pizza, and strawberries) were associated with decreased incidence of prostate cancer, as illustrated in the figure below.
The three tomato-based foods are red due to the presence of the carotenoid lycopene. Strawberries don’t contain lycopene (their red color is due to anthocyanins). This finding has led to interest in the potential of tomatoes/lycopene to decrease the risk of prostate cancer.

**References & Links**


**Links**


Framingham Heart Study History – http://www.framinghamheartstudy.org/about-fhs/history.php


The Nurses Health Study – http://www.channing.harvard.edu/nhs/?page_id=70

Health Professionals Follow-Up Study – http://www.hsph.harvard.edu/hpfs/
7. 1.3 In Vitro & Animal Studies

The simplest form of nutrition research is an in vitro study. In vitro means “within glass”, so these methods are performed within flasks, dishes, plates, and test tubes, although most of these are no longer glass (mostly plastic now). These studies are performed outside of a living organism, so the results need to be interpreted with this fact in mind.

One common form of in vitro research is cell culture. This involves growing cells in flasks and dishes. In order for cells to grow they need a nutrient source. For cell culture the nutrient source is referred to as media. Media supplies nutrients to the cells in vitro similarly to how blood performs this function within the body. Most cells adhere to the bottom of the flask and are so small that a microscope is needed to see them.

Cells are only handled inside a biosafety cabinet (aka cell culture hood). The hood is sterile and protects the cells from the outside environment. The cells need to be protected because they do not have human skin as a barrier to keep microorganisms, etc., from contaminating them.
Figure 1.32 Flask containing media and cells (left); biosafety cabinet (cell culture hood, right)
Cells are grown inside an incubator, which is a device that provides the optimal temperature, humidity, and carbon dioxide (CO2) concentrations for cells and microorganisms. By imitating the body's temperature and CO2 levels (37 degrees Celsius, 5% CO2), the incubator allows cells to grow even though they are outside the body.

![Figure 1.33 Outside and inside of an incubator](image)

**Animal Studies**

Animal studies are one form of in vivo research, which translates to “within the living”. Rats and mice are the most common animals used in nutrition research.

**Why do animal research?**

Animals can be used in research that would be unethical to conduct in humans. Researchers can make sure that a certain regimen is safe before it is researched in humans. One advantage of animal dietary studies is that researchers can control exactly what the animals eat. In human studies, researchers can tell subjects what to eat and provide them with the food, but that does not necessarily mean that they are going to consume exactly what they are supposed to. Also people are not great at estimating, recording, or reporting how much or what they eat/ate. Animal studies are also, normally, far less expensive than human studies.

There are some important factors to keep in mind when interpreting animal research. First, an animal's metabolism and
physiology is different than humans. As a result, animals’ absorption and bioavailability of compounds can differ from humans. Furthermore, animal models of disease (cancer, cardiovascular disease, etc.), although similar, are different from the human disease. So these factors have to be considered when interpreting results from this type of research. Nevertheless, animal studies have been, and continue to be, important for nutrition research.

No References
8. 1.4 Human Intervention Studies/Clinical Trials

There are a variety of human intervention study designs in nutrition research, but the most common, especially in pharmaceutical/medical research, is the clinical trial. A clinical trial is a scientifically controlled study using consenting people to find the safety and effectiveness of different items/regimens. Clinical trials are the “gold standard” research method. Their findings carry the most weight when making decisions about a certain research area because they are the most rigorous scientific studies. Every pharmaceutical must go through a series of clinical trials before being approved for the market by the FDA (specifically the randomized, double-blind, placebo-controlled experiments). As shown in the figure below, human intervention studies/clinical trials are normally prospective. By the end of this section you should have an understanding of what randomized, double-blind, and placebo-controlled means.

<table>
<thead>
<tr>
<th>Past</th>
<th>Present</th>
<th>Future</th>
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<tbody>
<tr>
<td>Case-control study</td>
<td>Cross-sectional study</td>
<td>Prospective Cohort Study</td>
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<tr>
<td></td>
<td></td>
<td>Clinical Trial</td>
</tr>
</tbody>
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*Figure 1.41 Clinical trials are prospective (Adapted from Reference 1)*
Placebo and The Placebo Effect

A placebo is a fake pill or treatment that serves as a comparison to an active treatment. An examples of placebos are shown below.

![Figure 1.42 Placebo pills](image)

The use of a placebo is necessary in medical research because of a phenomenon known as the “placebo effect”. The placebo effect results from a subject’s belief in a treatment, even though there is actually no treatment being administered. An example would be an athlete who consumes a sports drink and runs the 100 meter dash in 11.00 seconds. The athlete then, under the exact same conditions, drinks what he is told is “Super Duper Sports Drink” and runs the 100 meter dash in 10.50 seconds. But what the athlete didn’t know was that Super Duper Sports Drink was the Sports Drink + Food Coloring. There was nothing different between the drinks, but the athlete believed that the “Super Duper Sports Drink” was going to help him run faster, so he did. This improvement is due to the placebo effect.
Ironically, a study similar to the example given above has been conducted and its results support that there is a “placebo effect.”

**Web Link**

A Placebo Can Make You Run Faster [HYPERLINK](http://www.youtube.com/watch?v=aSP2OMiFxhg)

**Randomization**

Randomization is the process of randomly assigning subjects to groups to decrease bias. Bias, according to the Merriam-Webster dictionary, is “a systematic error introduced into sampling or testing by selecting or encouraging one outcome or answer over others.” Bias can occur in assigning subjects to groups in a way that will influence the results. An example of bias in a study of an antidepressant drug is shown below. In this nonrandomized antidepressant drug example, researchers (who know what the subjects are receiving) put depressed subjects into the placebo group, while “less depressed” subjects are put into the...
antidepressant drug group. As a result, even if the drug isn’t effective, the group assignment may make the drug appear effective, thus biasing the results as shown below.

![Antidepressant Drug Group Assignment Diagram](image)

**Figure 1.44 Non-randomized antidepressant drug example**

This is a bit of an extreme example, but even if the researchers are trying to prevent bias, sometimes bias can still occur. However, if the subjects are randomized, the sick and the healthy people will ideally be equally distributed between the groups. Thus, the trial will be unbiased and a true test of whether or not the drug is effective.
Blinding

Blinding is a technique to prevent bias in human intervention studies. A study without blinding is referred to as “open label” because both the subject and the researchers know what treatment the subject is receiving (i.e. placebo or drug). This can lead to bias, so these types of trials are used less frequently.
Figure 1.46 In an open-label study, both the subject and researcher know what treatment the subject is receiving.

In a single-blind study, the researcher knows what treatment the subject is receiving, but the subject does not. If the subjects are randomized, these types of trials should produce robust results, but it is still possible that the researcher can bias the results.
Figure 1.47 In a single-blind study, the researcher knows what treatment the subject is receiving, but the subject does not.

Finally there is the double-blind study, where neither the researcher nor the subject know what treatment the subject is receiving. A separate board reviews the collected results and decides the fate of the trial. This is the “gold standard” because it prevents observer bias from occurring.
Figure 1.48 In a double-blind study, neither the subject nor the researcher know what treatment the subject is receiving.

The following video does a nice job explaining and illustrating how double-blind randomized trials are performed.

**Web Link**

**Video:** Double-blind clinical trial (1:40)

**References & Links**


**Link**
A placebo can make you run faster – http://well.blogs.nytimes.com/2015/10/14/a-placebo-can-make-you-run-faster/

**Video**

How double-blind randomized controlled trials are done – http://www.dailymotion.com/video/x12igoz_double-blind-clinical-trials_news
9. 1.5 Nutrition Research Statistics

One important aspect in being able to interpret research is to have a basic understanding of statistical significance. Statistical significance means that there is sufficient statistical evidence to suggest that the results are most likely not due to chance.

Statistical significance is represented by p-values in most research. The p-value is an estimate of whether the difference is a statistical accident or due to random chance. A p-value of less than 0.05 (commonly written p-value < 0.05 or p < 0.05) is used in most cases to indicate statistical significance. This value means that 5% of the time the statistical results are accidental or not true. Researchers accept this level of uncertainty.

Epidemiological research usually uses different statistics to analyze their results. Epidemiological results are commonly reported as odds ratios (ORs), relative risks (RRs), or hazard ratios (HRs). These values can be interpreted similarly regardless of which is used. For example, the odds ratio represents the odds of a certain event occurring (often a disease) in response to a certain exposure (in nutrition this is often a food or dietary compound). In a paper it is common to see one of these measures in this form: OR = 2.0. What does this mean? As shown below, an OR, RR, or HR of 1 means that exposure is associated with neither increased nor decreased risk (neutral). If an OR, RR or HR is less than 1, that exposure is associated with a decreased risk. If an OR, RR, or HR is greater than 1, that exposure is associated with an increased risk. An OR, RR, or HR of 2 means there is twice the risk, while an OR, RR, or HR of 0.5 means there is half the risk of the exposure versus the comparison group.
To determine whether OR, RR, and HR are significantly different for a given exposure, most epidemiological research uses 95% confidence intervals. Confidence intervals indicate the estimated range that the measure is calculated to include. They go below and above the OR, RR, and HR itself. It is a calculation of how confident the researchers are that the OR, RR, and HR value is correct. Thus:

- Large Confidence Intervals = Less Confidence in Value
- Small Confidence Intervals = More Confidence in Value

Thus, 95% confidence intervals indicate that researchers are 95% confident that the true value is within the confidence intervals. A confidence interval is normally written in parenthesis following the OR, RR, or HR or represented as bars in a figure as shown below.
Most of the time, the OR, RR, or HR will be found in the middle of the 95% confidence interval, but not necessarily all of the time. For instance, there could be much greater confidence that the value is not much lower than the OR, RR, or HR, but not much confidence that the value does not exceed the HR, RR, or HR. This could lead to confidence interval looking skewed above the OR, RR, or HR (more confidence interval above, than below, the OR, RR, or HR).

If the 95% confidence intervals of the OR, RR, or HR does not include or overlap 1, then the value is significant. If the 95% confidence intervals include or overlap 1, then the OR, RR, or HR is not significant, because it is possible the the true value is 1, which is neutral, and can not be significantly different than 1.
Figure 1.53 Confidence intervals (95%) that include 1 indicate that the value is not significantly different. Confidence intervals above or below 1 without including it indicate that the value is significantly different.

No References
After nutrition researchers have obtained their results, they want to disseminate them, or let people know what they found. The primary way they do this is by publishing their results in journals. The researchers put together a paper explaining their experiment and findings in a journal article. An article’s primary components are normally an introduction, abstract, methods, results, and discussion/conclusion. They submit the paper to a chosen journal and the journal editor then selects expert researchers who will critically review the article. These reviewers make sure that research published in journals is of good quality and of interest to readers. In more rigorous journals the article might also need to meet a certain theme of an issue that a journal wants to publish. This is a rigorous process that is humorously depicted by this cartoon.

To give you an idea of how rigorous this process is, let’s consider some major nutrition journals.

**Journal of Nutrition (JN)**

**American Journal of Clinical Nutrition (AJCN)**

**Journal of the Academy of Nutrition and Dietetics (formerly Journal of the American Dietetic Association)**

**Nutrition Reviews**

**Annual Reviews of Nutrition**

**British Journal of Nutrition**

**European Journal of Clinical Nutrition**

There are two major nutrition societies in the US: The American Society for Nutrition (ASN) and the Academy of Nutrition and Dietetics (AND, formerly the American Dietetic Association). ASN publishes the Journal of Nutrition and the American Journal of
Clinical Nutrition, while AND publishes the Journal of the Academy of Nutrition and Dietetics. If you want to see more about the major nutrition societies, use the following links.

**Web Links**

- American Society for Nutrition
- Academy of Nutrition and Dietetics

The following table contains 2 measures, impact factor and acceptance rate for these journals. The impact factor is a measure of influence of the journal. This measure indicates how many people read the articles that are published in that journal. The acceptance rate is the % of articles that are submitted that are actually accepted for publication.

Table 1.61 Selected nutrition journal impact factors and acceptance rates

<table>
<thead>
<tr>
<th>Journal</th>
<th>Impact Factor</th>
<th>Acceptance Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Reviews of Nutrition</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>American Journal of Clinical Nutrition</td>
<td>6.7</td>
<td>25%2</td>
</tr>
<tr>
<td>Journal of Nutrition</td>
<td>3.7</td>
<td>25%3</td>
</tr>
<tr>
<td>Advances in Nutrition</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Nutrition Reviews</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Journal of the Academy of Nutrition and Dietetics</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>British Journal of Nutrition</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>European Journal of Clinical Nutrition</td>
<td>3.9</td>
<td>40%4</td>
</tr>
</tbody>
</table>

The acceptance rate for three of these journals ranged from 25-40%. Thus, the majority of submitted articles are rejected and sent back to the researchers. To put nutrition journals in perspective, some of the top medical and science journals with a broad following have impact factors as high as 75 and an acceptance rate of 5-10%.
Hopefully these numbers help you understand that peer review is a rigorous process where peer reviewers “tear the article to pieces.”

They do not physically shred the article (it is all done online), but there are often extensive revisions to make (maybe even multiple times) before the paper can be published, if you’re so lucky. Generally, the more difficult it is to get a paper accepted into a journal, the more solid the research must be. Most of the information on the internet has not gone through peer review and should be explored with some caution.

The following video clearly depicts the peer review process. There is also a diagram that explains how the peer review process works.
Web Links

Video: Peer Review in 3 Minutes (3:15)

A YouTube element has been excluded from this version of the text. You can view it online here:
https://library.achievingthedream.org/herkimernutrition/?p=28

Peer Review Process Diagram

References & Links

**Links**

Peer Review Process – http://www.eophtha.com/eophtha/
Gallery/Images%20gallery/Journals/
The%20process%20of%20peerreview.jpg

American Society of Nutrition – http://www.nutrition.org/
Academy of Nutrition and Dietetics – http://www.eatright.org/

Diagram of the Peer Review Process – http://www.eophtha.com/
eophtha/Gallery/Images%20gallery/Journals/
The%20process%20of%20peerreview.jpg

**Videos**

Peer Review in 3 Minutes – https://www.youtube.com/
watch?annotation_id=annotation_2240740767&feature=iv&src_vid=twogpmM-SfY&v=rOCQZ7QnoN0
II. 1.7 Interpreting Research

Now that you are familiar with the different forms of nutrition research, the next step is understanding how to interpret and synthesize the information. To synthesize information on a certain topic, the two most popular methods are meta-analyses and systematic literature reviews. While there are differences between these two methods, they are similar overall in that they aim to draw a conclusion from the body of research evidence rather than from one study. We will focus on systematic literature reviews because of their rising popularity in biomedical literature.

A systematic literature review does what the name implies, it systematically reviews the literature related to a certain research question. For example, the research question might be, “Does chocolate decrease blood pressure?” There is a method for performing the review established ahead of time that details answers to questions such as:

- How will journal articles be identified?
- Using what databases?
- What search terms will be used?

The end product is a conclusion based on the evidence in the identified journal articles. A person in the following video compares it to reading Consumer Reviews or a consumer report about something that you are going to buy. The Cochrane Collaboration performs many systematic reviews; the first link is to a video about the Cochrane Collaboration, the second is a link to the site itself.

**Web Links**

Video: The Cochrane Collaboration – 1st 3 minutes (7:11)
The Cochrane Collaboration

Because they synthesize the findings from multiple trials, systematic literature reviews are considered the highest level of
nutrition research evidence and are therefore shown at the top of the strength of nutrition research pyramid below. In vitro studies are shown at the bottom of the triangle because they are the weakest form of evidence overall. It should be pointed out that most systematic literature reviews only consider epidemiological studies and clinical trials and do not include animal studies or in vitro evidence. While these studies are of less strength, they should still be considered.

There are a couple of other factors to consider relating to the different forms of research. First, epidemiological studies cannot show causality (i.e. smoking causes lung cancer), but instead identify relationships or associations (i.e. smoking is associated with lung cancer occurrence). Clinical trials/human studies are the best form of primary research because their findings should be directly translatable to patients. So why use other forms of research? The description below should help explain why the other forms of research are also important.
In general, a certain sequence of studies in nutrition research is often followed as shown in the figure below.

Figure 1.72 The progression of nutrition research. The shape indicates the selection of the most promising and safest hypotheses being moved to the next level. Thus, there is a decrease in the overall number of hypotheses represented by the height of the figure) being investigated by the next form of research.

Epidemiological studies find relationships between food/food components and a specific health outcome. This relationship is then investigated by in vitro studies and then, some of the most promising move to animal studies. Then the most promising and safe food/food components are moved into clinical trials/human studies. If it is an individual compound, there will be smaller trials designed to see if the compound is safe before it is moved into larger clinical trials to determine whether the food/food component results in beneficial health outcomes. The overall effect of this process is to select the most promising and safe food/food components for the clinical trials/human studies. This allows time
and money to be used more efficiently, because while clinical trials/human studies are the best form of research, they are also normally the most expensive and time-consuming.

Researchers nevertheless have been tempted to skip directly to clinical trials in the past rather than following the research progression. To illustrate what happens in these situations, the following describes a couple of examples when “normal” research progression hasn't been followed.

**Beta-Carotene and Lung Cancer**

In the early 1980s there was a lot of excitement among researchers over the epidemiological evidence showing that higher dietary consumption of the carotenoid, beta-carotene, decreased lung cancer risk. By the mid 1980’s, two large, randomized, placebo-controlled trials began to determine whether high-dose β-carotene supplementation (far higher than dietary intake) could decrease lung cancer incidence in high-risk populations before *in vitro* or animal studies had investigated this relationship. The research community was shocked when these two studies were terminated early in the mid 1990s because of significant increases in lung cancer incidence among smokers receiving β-carotene supplements. *In vitro* and animal studies completed after the clinical trial found that as β-carotene intake shifts from normal dietary levels to high, supplement-type levels, the effect on lung cancer development also shifts from beneficial to detrimental in combination with smoke or carcinogen exposure. Thus, if the normal research progression had been followed, it is likely that a lower dose of beta-carotene would have been used or trials wouldn't have been undertaken at all.

**Selenium, Vitamin E, and Prostate Cancer**

Another example of when the research progression was not followed was the relationship between selenium, vitamin E, and prostate cancer. Two clinical trials had found secondary results that suggested that selenium and vitamin E supplementation may decrease prostate cancer risk. A secondary result means it was not the primary outcome that the clinical trial was designed to
find, thus they need to be interpreted with some caution. Rather
than examining the relationship using in vitro and animal studies, a
clinical trial was undertaken to determine if selenium and vitamin
E supplementation alone, or in combination, could decrease the
development of prostate cancer incidence. This clinical trial was
also terminated early because of a nonsignificant increase in
prostate cancer in those receiving vitamin E, and a nonsignificant
increase in diabetes among those receiving selenium. In vitro
studies and animal models performed since the clinical trial was
undertaken and after its termination suggest that vitamin E is not
effective and that another form of selenium could have possibly
been more effective.

In addition to the lessons learned about the sequence of research
in nutrition, these studies add to growing evidence that suggests
that single-agent interventions, even in combination, may not be
an effective strategy for improving health. The common nutrition
research approach, after epidemiology finds an association or
relationship, is to use in vitro and animal studies to identify the
specific compound in a certain food that is responsible. This has
been termed the reductionist approach because it takes something
complex (food) and reduces it down to its simpler components.
However, there is growing evidence that this may be a flawed
approach. Some nutrition researchers feel that more focus should
be on the food itself, rather than trying to discern exactly what is
responsible for the beneficial health outcomes. Because it may not
be one or 2 compounds alone that are responsible for the effect,
it might be difficult to determine from the multitude of nutrients
in foods which are responsible for the beneficial effect. This will
mean changes in the overall research approach, especially at the
human intervention studies/clinical trials level, because in most
cases there is not a way to give a “placebo food.”

References & Links
1. Peto R, Doll R, Buckley JD, Sporn MB. Can dietary beta-carotene
2. The effect of vitamin E and beta carotene on the incidence


**Links**

Video: The Cochrane Collaboration – http://www.youtube.com/watch?v=AhtchOL1ofc

The Cochrane Colaboration – http://www.cochrane.org/
12. 2 Energy-Yielding Macronutrients

As you have learned, there are three energy-yielding macronutrients: carbohydrates, proteins, and lipids. This chapter goes more in depth about these major dietary components.

Sections:
2.1 Carbohydrates
2.2 Proteins
2.3 Lipids
Carbohydrates have become surprisingly divisive. Some people swear by them, others swear against them. But it is important to understand that carbohydrates are a diverse group of compounds that have a multitude of effects in the body. Thus, trying to make blanket statements about carbohydrates is probably not a good idea.

Carbohydrates are named because they are hydrated (as in water, H2O) carbon. Below is the formula showing how carbon dioxide (CO2) and water (H2O) are used to make carbohydrates (CH2O)n and oxygen (O2). The “n” after the carbohydrate in the formula indicates that the chemical formula is repeated an unknown number of times, but that for every carbon and oxygen, there will always be two hydrogens.

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow (\text{CH}_2\text{O})_n + \text{O}_2 \]

Carbohydrates are produced by plants through a process known as photosynthesis. In this process, plants use the energy from photons of light to synthesize carbohydrates. The formula for this reaction looks like this:

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Light} \rightarrow \text{C}_6\text{H}_12\text{O}_6 + 6\text{O}_2 \]

There are many different types of carbohydrates as shown in the figure below. The first way that carbohydrates can be divided is into simple, complex, and sugar alcohols. As the names imply, complex carbohydrates contain more sugar units, while simple carbohydrates contain either 1 or 2 sugars. In the next sections, you will learn more about the different forms of carbohydrates.
Subsections:

2.11 Simple Carbohydrates
2.12 Sugar Alcohols (Polyols, Sugar Replacers)
2.13 Alternative Sweeteners
2.14 Oligosaccharides
2.15 Polysaccharides

No References
14. 2.11 Simple Carbohydrates

As shown in the figure below, simple carbohydrates can be further divided into monosaccharides and disaccharides. Mono- means one, thus monosaccharides contain one sugar. Di- means two, thus disaccharides contain 2 sugar units.

Figure 2.111 Overview of Carbohydrates

**Monosaccharides**

The 3 monosaccharides are: glucose, fructose and galactose. Notice that all are 6-carbon sugars (hexoses). However, fructose has a five member ring, while glucose and galactose have 6 member rings. Also notice that the only structural difference between glucose and galactose is the position of the alcohol (OH) group that is shown in red.
Figure 2.112 The 3 monosaccharides

Glucose – Product of photosynthesis, major source of energy in our bodies

Fructose – Commonly found in fruits and used commercially in many beverages

Galactose – Not normally found in nature alone, normally found in the disaccharide lactose

Web Link

Not familiar with ring structures, see how glucose forms a ring–

Disaccharides

Disaccharides are produced from 2 monosaccharides. The commonly occurring disaccharides are:

Maltose (glucose + glucose, aka malt sugar) – seldom found in foods, present in alcoholic beverages and barley

Sucrose (glucose + fructose, aka table sugar) – only made by plants.

Lactose (galactose + glucose, aka milk sugar) – primary milk sugar

The different disaccharides and the monosaccharides components are illustrated below.
Each of these disaccharides contains glucose and all the reactions
are dehydration reactions. Also notice the difference in the bond structures. Maltose and sucrose have alpha-bonds, which are depicted as v-shaped above. You might hear the term glycosidic used in some places to describe bonds between sugars. A glycoside is a sugar, so glycosidic is referring to a sugar bond. Lactose, on the other hand, contains a beta-bond. We need a special enzyme, lactase, to break this bond, and the absence of lactase activity leads to lactose intolerance.

**High-Fructose Corn Syrup**

Food manufacturers are always searching for cheaper ways to produce their food. One method that has been popular is the use of high-fructose corn syrup as an alternative to sucrose. High-fructose corn syrup contains either 42 or 55% fructose, which is similar to sucrose\(^1\). Nevertheless, because an increase in high-fructose corn syrup consumption (see figure below) has coincided with the increase in obesity in the U.S., there is a lot of controversy surrounding its use.

![Figure 2.114 U.S. per capita sugar and sweetener consumption](image)

**Figure 2.114 U.S. per capita sugar and sweetener consumption\(^2\)**
Opponents claim that high-fructose corn syrup is contributing to the rise in obesity rates. As a result, some manufactures have started releasing products made with natural sugar. You can read about this trend in the following New York Times article in the link below. Also, manufacturers tried to rebrand high-fructose corn syrup as corn sugar to get around the negative perception of the name. But the FDA rejected the Corn Refiners Association request to change the name officially to corn sugar as described in the second link. The last link is a video made by the American Chemical Society that gives some background on how HFCS is produced and how it compares to sucrose.

Web Links

Sugar is back on labels, this time as a selling point
No new name for high-fructose corn syrup
(Video): Sugar vs. High Fructose Corn Syrup – What's the Difference? (2:41)

References & Links


Links

Not familiar with Ring structures, see how glucose forms a ring – http://en.wikipedia.org/wiki/File:Glucose_Fisher_to_Haworth.gif
Sugar is back on labels, this time as a selling point – http://www.nytimes.com/2009/03/21/dining/21sugar.html?_r=1&ref=nutrition
No new name for high-fructose corn syrup – http://well.blogs.nytimes.com/2012/05/31/no-new-name-for-high-fructose-corn-syrup/?_r=0

Video
Sugar vs. High Fructose Corn Syrup – What's the Difference? – https://www.youtube.com/watch?v=fXMvregmU1g
15. 2.12 Sugar Alcohols (Polyols, Sugar Replacers)

Sugar(s) can provide a lot of calories and contribute to tooth decay. Thus there are many other compounds that are used as alternatives to sugar that have been developed or discovered. We will first consider sugar alcohols and then the alternative sweeteners in subsequent sections.

Below you can see the structure of three common sugar alcohols: xylitol, sorbitol, and mannitol.

![Figure 2.121 Structure of three commonly used sugar alcohols: xylitol, sorbitol, and mannitol](image)

Remember that alcohol subgroups are (OH), and you can see many of them in these structures.

Sugar alcohols are also known as “sugar replacers”, because some in the public might get confused by the name sugar alcohol. Some might think a sugar alcohol is a sweet alcoholic beverage. Another name for them is nutritive sweeteners, which indicates that they do provide calories. Sugar alcohols are nearly as sweet as sucrose but only provide approximately half the calories as shown below. The name polyols also seems to be increasingly used to describe these compounds.

Table 2.121 Relative sweetness of monosaccharides, disaccharides, and sugar alcohols

---

2.12 Sugar Alcohols (Polyols, Sugar Replacers) | 75
<table>
<thead>
<tr>
<th>Sweetener</th>
<th>Relative Sweetness</th>
<th>Energy (kcal/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactose</td>
<td>0.2</td>
<td>4*</td>
</tr>
<tr>
<td>Maltose</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>Glucose</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>Sucrose</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>Fructose</td>
<td>1.2-1.8</td>
<td>4</td>
</tr>
<tr>
<td>Erythritol</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Isomalt</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Lactitol</td>
<td>0.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Differs based on a person’s lactase activity

Sugars are fermented by bacteria on the surfaces of teeth. This results in a decreased pH (higher acidity) that leads to tooth decay and, potentially, cavity formation. The major advantage of sugar alcohols over sugars is that sugar alcohols are not fermented by bacteria on the tooth surface. There is a nice picture of this process in the link below as well as a video explaining the process of tooth decay.

### Web Links

- [Sugar and Dental Caries](#)
- [Video: Tooth Decay (1:06)](#)

While not a sugar alcohol, tagatose is very similar to sugar alcohols. Tagatose is an isomer of fructose, that provides a small amount of energy (1.5 kcal/g). 80% of tagatose reaches the large intestine, where it is fermented by bacteria, meaning it has a prebiotic-type effect\(^3\). Notice the similarity in structure of tagatose to sugar alcohols, the only difference being a ketone (\(\equiv O\)) instead of an alcohol (OH) group.
References & Links


Link
Sugar and Dental Caries – http://www.asu.edu/courses/css335/caries.htm

Video
Tooth Decay – http://www.youtube.com/watch?v=_ollv59bTL4
Alternative sweeteners are simply alternatives to sucrose and other mono- and disaccharides that provide sweetness. Many have been developed to provide zero-calorie or low calorie sweetening for foods and drinks.

Because many of these provide little to no calories, these sweeteners are also referred to as non-nutritive sweeteners (FDA is using high-intensity sweeteners to describe these products\(^3\)). Aside from tagatose (described in sugar alcohol section), all of the sweeteners on the list below meet this criteria. Aspartame does provide calories, but because it is far sweeter than sugar, the small amount used does not contribute meaningful calories to a person's diet. Until the FDA allowed the use of stevia, this collection of sweeteners were commonly referred to as artificial sweeteners because they were synthetically or artificially produced. However, with stevia, the descriptor artificial can no longer be used to describe these sweeteners. More recently, Luo Han Guo Fruit extracts have also been allowed to be used as another high-intensity sweetener that is not synthesized or artificially produced. The table in the link below summarizes the characteristics of the FDA approved high-intensity sweeteners.

**Web Link**

FDA High-Intensity Sweeteners

**Saccharin**

Saccharin is the oldest of the artificial sweeteners. You do not want to use it in cooking or baking because it develops a bitter taste\(^4\).
Aspartame

Aspartame is made up of 2 amino acids (phenylalanine and aspartate) and a methyl (CH3) group. The compound is broken down during digestion into the individual amino acids. This is why it provides 4 kcal/g, just like protein. Because it can be broken down to phenylalanine, products that contain aspartame contain the following message: “Phenylketonurics: Contains phenylalanine.” Phenylketonuria (PKU) will be covered in greater detail in section 2.25. When heated, aspartame breaks down and loses its sweet flavor.
Neotame

Neotame is like aspartame version 2.0. Neotame is structurally identical to aspartame except that it contains an additional side group (bottom of figure below, which is flipped backwards to make it easier to compare their structures). While this looks like a minor difference, it has profound effects on the properties of neotame. Neotame is much sweeter than aspartame and is heat-stable. It can still be broken down to phenylalanine, but such small amounts are used that it is not a concern for those with PKU\textsuperscript{1,4}. 

Figure 2.132 Structure of aspartame\textsuperscript{6}
Advantame

The newest, sweetest alternative sweetener approved by the FDA in 2014 is advantame. It is heat-stable and does not have a trade name yet\(^3\). Notice it also has a similar structure to aspartame and neotame. Like Neotame it can broken down to phenylalanine, but such small amounts are used that it is not a concern for those with PKU. However, it has a much higher acceptable daily intake than Neotame\(^4\), meaning there is less concern about adverse effects from consuming too much.
Acesulfame-Potassium (K)

Acesulfame-potassium (K) is not digested or absorbed, therefore it provides no energy or potassium to the body\textsuperscript{1}. It is a heat-stable alternative sweetener.
Sucralose

Sucralose is structurally identical to sucrose except that 3 of the alcohol groups (OH) are replaced by chlorine molecules (Cl). This small change causes sucralose to not be digested and as such is excreted in feces\textsuperscript{1,4}. It is a heat-stable alternative sweetener.
Stevia

Stevia is derived from a South American shrub, with the leaves being the sweet part. The components responsible for this sweet taste are a group of compounds known as steviol glycosides. The structure of steviol is shown below.
The term glycoside means that there are sugar molecules bonded to steviol. The two predominant steviol glycosides are stevioside and rebaudioside A. The structure of these two steviol glycosides are very similar. The structure of stevioside is shown below as an example.
The common name for a sweetener containing primarily rebaudioside A is rebiana\textsuperscript{13}. Stevia sweeteners had been marketed as a natural alternative sweeteners, something that has been stopped by lawsuits as described in the following link.

\textbf{Web Link}

\textit{What is natural and who decides?}

Stevia is a heat–stable alternative sweetener.

\textbf{Luo Han Guo Fruit Extracts}
Luo Han Guo (aka *Siraitia grosvenrii* Swingle, monk) fruit extracts are a newer, natural heat-stable alternative sweetener option derived from a native Chinese fruit. These extracts are sweet because of the mogrosides that they contain. The structure of a mogroside is shown below.

![Mogroside Structure](image)

**Figure 2.139 Structure of a mogroside**

References & Links
2. [http://www.fda.gov/AboutFDA/Transparency/Basics/ucm214865.htm](http://www.fda.gov/AboutFDA/Transparency/Basics/ucm214865.htm)
3. [http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm](http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm)

**Links**
FDA High-Intensity sweeteners – [http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm](http://www.fda.gov/food/ingredientspackaginglabeling/foodadditivesingredients/ucm397725.htm)
Within complex carbohydrates, there are oligosaccharides and polysaccharides. Oligosaccharides (oligo means few) are composed of 3-10 sugar units and polysaccharides contain greater than 10 sugar units.

Raffinose and stachyose are the most common oligosaccharides. They are found in legumes, onions, broccoli, cabbage, and whole wheat\(^1\). The link below shows the raffinose and stachyose content of some plant foods.

Web Link

Raffinose and stachyose content of selected plant foods

The structures of the two oligosaccharides are shown below.
Figure 2.142 Structure of raffinose\textsuperscript{2}
Our digestive system lacks the enzymes necessary to digest these alpha 1-6 glycosidic bonds found in oligosaccharides. As a result, the oligosaccharides are not digested and reach the colon where they are fermented by the bacteria there. Gas is produced as a byproduct of this bacteria fermentation that can lead to flatulence. To combat this problem, Beano® is a popular product that contains an enzyme (alpha-galactosidase) to break down oligosaccharides, thereby preventing them from being used to produce gas. The video link below describes how Beano® works.

**Web Link**

(Video) Beano’s University of Gas: Lesson 2–

**References & Links**


**Videos**

Raffinose and stachyose content of foods – http://books.google.com/books?id=LTGFV2NOySYC&pg=PA374&lpg=PA374&dq=raffinose+and+stachyose+content+of+vegetables&source=bl&ots=X4Dr7jWmwL&sig=CIJFvhAlysSZCP2SOy_MqhfoVYQQ&hl=en&ei=TSRITdTfLNH0gAfB2MX_BQ&sa=X&oi=book_result&ct=result&resnum=6&ved=0CD0Q6AEwBQ#v=onepage&q=raffinose%20and%20stachyose%20content%20of%20vegetables&f=false

Beano’s University of Gas – http://beano.com.cn/university-of-gas
Poly means “many” and thus polysaccharides are made up of many monosaccharides (>10). There are 3 main classes of polysaccharides: starch, glycogen, and most fibers. The following sections will describe the structural similarities and differences between the 3 classes of polysaccharides that are divided in the figure below.

Subsections:
2.151 Starch
2.152 Glycogen
2.153 Fiber
2.151 Starch

Starch is the storage form of glucose in plants. There are two forms of starch: amylose and amylopectin. Structurally they differ in that amylose is a linear polysaccharide, whereas amylopectin is branched. The linear portion of both amylose and amylopectin contains alpha 1-4 glycosidic bonds, while the branches of amylopectin are made up of alpha 1-6 glycosidic bonds.

Figure 2.1511 Structure of amylose

![Structure of amylose](image)

Figure 2.1512 Structure of amylopectin

![Structure of amylopectin](image)

Amylopectin is more common than amylose (4:1 ratio on average) in starch\textsuperscript{1,2}. Some starchy foods include grains, root crops, tubers, and legumes.

**References & Links**

20. 2.152 Glycogen

Glycogen is similar to starch in that it is a storage form of glucose. Glycogen, however, is the carbohydrate storage form in animals, rather than plants. It is even more highly branched than amylopectin, as shown below.

![Structure of glycogen](image)

Like amylopectin, the branch points of glycogen are alpha 1-6 glycosidic bonds, while the linear bonds are alpha 1-4 bonds, as shown below.
The advantage of glycogen's highly branched structure is that the multiple ends (shown in red above) are where enzymes start to cleave off glucose molecules. As a result, with many ends available, it can provide glucose much more quickly to the body than it could if it was a linear molecule like amylose with only two ends. We
consume almost no glycogen, because it is rapidly broken down by enzymes in animals after slaughter\(^2\). 

**References & Links**

The simplest definition of fiber is indigestible matter. Indigestible means that it survives digestion in the small intestine and reaches the large intestine.

There are 3 major fiber classifications:

Dietary Fiber – nondigestible carbohydrates and lignin that are intrinsic and intact in plants

Functional Fiber – isolated, nondigestible carbohydrates that have beneficial physiological effects in humans

Total Fiber – dietary fiber + functional fiber

The differences between dietary and functional fiber are compared in the table below:

<table>
<thead>
<tr>
<th>Dietary Fiber</th>
<th>Functional Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact in plants</td>
<td>Isolated, extracted, or synthesized</td>
</tr>
<tr>
<td>Carbohydrates + lignins</td>
<td>Only carbohydrates</td>
</tr>
<tr>
<td>Only from plants</td>
<td>From plants or animals</td>
</tr>
<tr>
<td>No proven benefit</td>
<td>Must prove benefit</td>
</tr>
</tbody>
</table>

Dietary fiber is always intact in plants, whereas functional fiber can be isolated, extracted or synthesized. Functional fiber is only carbohydrates, while dietary fiber also includes lignins. Functional fiber can be from plants or animals, while dietary fiber is only from plants. Functional fiber must be proven to have a physiological benefit, while dietary fiber does not.

Polysaccharide fiber differs from other polysaccharides in that it contains beta-glycosidic bonds (as opposed to alpha-glycosidic bonds). To illustrate these differences, consider the structural differences between amylose and cellulose (type of fiber). Both are linear chains of glucose, the only difference is that amylose has
alpha-glycosidic bonds, while cellulose has beta-glycosidic bonds as shown below.

Figure 2.1531 Structures of amylose and cellulose

The beta-bonds in fiber cannot be broken down by the digestive enzymes in the small intestine so they continue into the large intestine.

Fiber can be classified by its physical properties. In the past, fibers were commonly referred to as soluble and insoluble. This classification distinguished whether the fiber was soluble in water. However, this classification is being phased out in the nutrition community. Instead, most fibers that would have been classified as insoluble fiber are now referred to as nonfermentable and/or nonviscous and soluble fiber as fermentable, and/or viscous because these better describe the fiber’s characteristics.  

Fermentable refers to whether the bacteria in the colon can ferment or degrade the fiber into short chain fatty acids and gas. Viscous refers to the capacity of certain fibers to form a thick gel-like consistency. The following table lists some of the common types of fiber and provides a brief description about each.
Table 2.1532 Common types of nonfermentable, nonviscous (insoluble) fiber

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>Main component of plant cell walls</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>Surround cellulose in plant cell walls</td>
</tr>
<tr>
<td>Lignin</td>
<td>Noncarbohydrate found within “woody” plant cell walls</td>
</tr>
</tbody>
</table>

Table 2.1533 Common types of fermentable, viscous (soluble) fiber

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemicellulose</td>
<td>Surround cellulose in plant cell walls</td>
</tr>
<tr>
<td>Pectin</td>
<td>Found in cell walls and intracellular tissues of fruits and berries</td>
</tr>
<tr>
<td>Beta-glucans</td>
<td>Found in cereal brans</td>
</tr>
<tr>
<td>Gums</td>
<td>Viscous, usually isolated from seeds</td>
</tr>
</tbody>
</table>

The following table gives the percentage of total dietary fiber in 5 foods.

Table 2.1534 Total dietary fiber (as percent of sample weight)

<table>
<thead>
<tr>
<th>Food</th>
<th>Total Dietary Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal, all bran</td>
<td>30.1</td>
</tr>
<tr>
<td>Blueberries, fresh</td>
<td>2.7</td>
</tr>
<tr>
<td>Broccoli, fresh, cooked</td>
<td>3.5</td>
</tr>
<tr>
<td>Pork and beans, canned</td>
<td>4.4</td>
</tr>
<tr>
<td>Almonds, with skin</td>
<td>8.8</td>
</tr>
</tbody>
</table>

The table below shows the amount of nonfermentable, nonviscous fiber in these same five foods.

Table 2.1535 Nonviscous fiber (as percent of sample weight)
The table below shows the amount of fermentable, viscous fiber in these same five foods.

Table 2.1536 Viscous Fiber (as percent of sample weight)³

<table>
<thead>
<tr>
<th>Food</th>
<th>Hemicellulose</th>
<th>Cellulose</th>
<th>Pectin</th>
<th>Lignin</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal, all bran</td>
<td>15.3</td>
<td>7.5</td>
<td>0.9</td>
<td>4.3</td>
<td>28.0</td>
</tr>
<tr>
<td>Blueberries, fresh</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td>0.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Broccoli, fresh, cooked</td>
<td>0.9</td>
<td>1.2</td>
<td>0.7</td>
<td>0.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Pork and beans, canned</td>
<td>0.9</td>
<td>1.6</td>
<td>0.3</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Almonds, with skin</td>
<td>1.8</td>
<td>3.3</td>
<td>1.6</td>
<td>1.9</td>
<td>8.6</td>
</tr>
</tbody>
</table>

tr = trace amounts

Foods that are good sources of non fermentable, non viscous fiber include whole wheat, whole grain cereals, broccoli, and other vegetables. This type of fiber is believed to decrease the risk of constipation and colon cancer, because it increases stool bulk and reduces transit time⁴. This reduced transit time theoretically means shorter exposure to consumed carcinogens in the intestine, and thus lower cancer risk.

Fermentable, viscous fiber can be found in oats, rice, psyllium seeds, soy, and some fruits. This type of fiber is believed to decrease blood cholesterol and sugar levels, thus also lowering the risk of heart disease and diabetes, respectively⁴. Its viscous nature slows the absorption of glucose preventing blood glucose from spiking after consuming carbohydrates. It lowers blood cholesterol levels.
primarily by binding bile acids, which are made from cholesterol, and causing them to be excreted. As such, more cholesterol is used to synthesize new bile acids.

References & Links


22. 2.2 Proteins

Proteins are another major macronutrient that, like carbohydrates, are made up of small repeating units. But instead of sugars, proteins are made up of amino acids. In the following sections, you will learn more about how proteins are synthesized and why they are important in the body.

Subsections:

2.21 Amino Acids
2.22 Protein Synthesis
2.23 Protein Structure
2.24 Protein Functions
2.25 Types of Amino Acids
2.26 Amino Acid Structures
2.27 Protein Quality
2.28 Protein-Energy Malnutrition
23. 2.21 Amino Acids

Similar to carbohydrates, proteins contain carbon (C), hydrogen (H), and oxygen (O). However, unlike carbohydrates (and lipids) proteins also contain nitrogen (N). Proteins are made up of smaller units called amino acids. This name, amino acid, signifies that each contains an amino (NH2) and carboxylic acid (COOH) groups. The only structural difference in the 20 amino acids is the side group represented by the R below.

![Structure of an amino acid](image)

To illustrate the differences in the side group we will consider glycine and alanine, the two simplest amino acids. For glycine the R group is hydrogen (H), while in alanine the R group is a methyl (CH3). The structures of these two amino acids are shown below.

![Structure of glycine](image)
Individual amino acids are joined together using a peptide bond (green) and is shown in the figure below.

Amino acids can also come together to form tripeptides (three
amino acids), oligopeptides (3-10 amino acids), and polypeptides (10 or more amino acids). A polypeptide is a chain of amino acids as shown below.

**Figure 2.216** A polypeptide chain

### References & Links

24. 2.22 Protein Synthesis

The process of protein synthesis is not as simple as stringing together amino acids to form a polypeptide. As shown below, this is a fairly involved process. DNA contains the genetic code that is used as a template to create mRNA in a process known as transcription. The mRNA then moves out of the nucleus into the cytoplasm where it serves as the template for translation, where tRNAs bring in individual amino acids that are bonded together to form a polypeptide.

![Diagram of protein synthesis](image)

*Figure 2.221 The process of creating a polypeptide*
Proteins, known as ribosomes, assist with translation. After translation, the polypeptide can be folded or gain structure as shown below and will be discussed in the next subsection (Protein Structure).

![Protein synthesis and processing](image)

*Figure 2.222 Protein synthesis and processing*

These videos do an excellent job of showing and explaining how protein synthesis occurs.
Web Links

Video: Transcription (1:49)
Video: Translation (2:05)

References & Links


Videos

Transcription – http://www.youtube.com/watch?v=5MfSYnltYvg
Translation – http://www.youtube.com/watch?v=8dsTvBaUMvw
There are four levels of protein structure. Primary structure is the linear polypeptide chain. Secondary structure occurs when hydrogen bonding between amino acids in the same polypeptide chain causes the formation of structures such as beta-pleated sheets and alpha-helices. Tertiary structure occurs as a result of an attraction between different amino acids of the polypeptide chain and interactions between the different secondary structures. Finally, certain proteins contain quaternary structure where multiple polypeptide chains are bonded together to form a larger molecule. Hemoglobin is an example of a protein with quaternary structure. The figure below illustrates the different levels of protein structure.

Figure 2.23.1 Different Protein Structures

110 | 2.23 Protein Structure
This video does a nice job of illustrating and explaining the different protein structures.

**Web Link**

**Video:** Protein Structure (0:52)

**References & Links**


**Video**

Protein Structure – http://www.youtube.com/watch?v=lijQ3a8yUYQ
There are various functions of proteins in the body that are described below.

**Structural**
Proteins, such as collagen, serve as the scaffolding of the body, and thus are important for the structure of tissues.

![Figure 2.241 Triple-helix structure of collagen](image)

**Enzymes**
We will discuss a number of enzymes throughout this class, and the vast majority are proteins. An enzyme catalyzes (enhances the rate) of a chemical reaction. The key part of an enzyme is its “active site”. The active site is where a compound to be acted on, known as a substrate, enters. Enzymes are specific for their substrates; they do not catalyze reactions on any random compounds floating by. You might have heard the “lock and key” analogy used for enzymes and substrates, respectively. After the substrate enters the active site and binds, the enzyme slightly changes shape (conformation). The enzyme then catalyzes a reaction that, in the example below, splits the substrate into two parts. The products of this reaction are released and the enzyme returns to its native or original shape. It is then ready to catalyze another reaction. The figure and video below nicely illustrate the function of an enzyme.
Enzymes’ names commonly end in -ase, and many are named for their substrate. For example, the enzyme amylase cleaves bonds found in amylose and amylopectin.

**Hormones**

Many hormones are proteins. A hormone is a compound that is produced in one tissue, released into circulation, then has an effect on a different organ. Most hormones are produced from several organs, collectively known as endocrine organs. Insulin is an example of a hormone that is a protein.

**Fluid Balance**

Proteins help to maintain the balance between fluids in the plasma and the interstitial fluid. Interstitial fluid is the fluid that surrounds cells. Interstitial fluid and plasma (fluid part of blood) are the two components of extracellular fluid, or the fluid outside of
cells. The following figure illustrates the exchange of fluid between interstitial fluid and plasma.

![Capillary Microcirculation](image)

*Figure 2.243 Interstitial Fluid and plasma*

**Acid-Base Balance**
Proteins serve as buffers, meaning that they help to prevent the pH of the body from getting too high or too low.

**Transport**
Transport proteins move molecules through circulation or across cell membranes. One example is hemoglobin that transports oxygen through the body. We will see a number of other examples as we move through class.

**Immune Function**
Antibodies are proteins that recognize antigens (foreign substances that generate antibody or inflammatory response) and bind to and inactivate them. Antibodies are important in our ability to ward off disease.
Other Functions
Proteins can also serve as neurotransmitters and can be used for energy by forming glucose through gluconeogenesis.

References & Links

Videos
Enzymes – http://www.youtube.com/watch?v=cbZsXjgPDLQ
Hormones – http://www.youtube.com/watch?v=kIPYVV4aThM
There are 20 amino acids our body uses to synthesize proteins. These amino acids can be classified as essential, non-essential, or conditionally essential. The table below shows how the 20 amino acids are classified.

Table 2.251 Essential, conditionally essential, and nonessential amino acids

<table>
<thead>
<tr>
<th>Essential</th>
<th>Conditionally Essential</th>
<th>Non-essential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>Arginine</td>
<td>Alanine</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>Cysteine</td>
<td>Asparagine</td>
</tr>
<tr>
<td>Leucine</td>
<td>Glutamine</td>
<td>Aspartic Acid or Aspartate</td>
</tr>
<tr>
<td>Lysine</td>
<td>Glycine</td>
<td>Glutamic Acid or Glutamate</td>
</tr>
<tr>
<td>Methionine</td>
<td>Proline</td>
<td>Serine</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>Tyrosine</td>
<td></td>
</tr>
<tr>
<td>Threonine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tryptophan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The body cannot synthesize nine amino acids. Thus, it is essential that these are consumed in the diet. As a result these amino acids are known as essential, or indispensable, amino acids. As an example of how amino acids were determined to be essential, Dr. William C. Rose at the University of Illinois discovered that threonine was essential by feeding different diets to graduate students at the university as described in the following link.

Web Link

Discovery of Threonine by William C. Rose

Non-essential, or dispensable, amino acids can be made in our body,
so we do not need to consume them. Conditionally essential amino acids become essential for individuals in certain situations. An example of a condition when an amino acid becomes essential is the disease phenylketonuria (PKU). Individuals with PKU have a mutation in the enzyme phenylalanine hydroxylase, which normally adds an alcohol group (OH) to the amino acid phenylalanine to form tyrosine as shown below.

![Figure 2.251 Phenylketonuria (PKU) results from a mutation in the enzyme phenylalanine hydroxylase](image)

Figure 2.251 Phenylketonuria (PKU) results from a mutation in the enzyme phenylalanine hydroxylase

Since tyrosine cannot be synthesized by people with PKU, it becomes essential for them. Thus, tyrosine is a conditionally essential amino acid. Individuals with PKU have to eat a very low protein diet and avoid the alternative sweetener aspartame, because it can be broken down to phenylalanine. If individuals with PKU consume too much phenylalanine, phenylalanine and its metabolites, can build up and cause brain damage and severe mental retardation. The drug Kuvan was approved for use with PKU patients in 2007 who have low phenylalanine hydroxylase activity levels. You can learn more about this drug using the link below.

**Web Link**

Kuvan

**References & Links**

2. https://en.wikipedia.org/wiki/Phenylalanine#/media/File:L-Phenylalanin_-_L-Phenylalanine.svg


**Links**

Discovery of Threonine by William C. Rose – http://www.jbc.org/content/277/37/e25.full

Kuvan – http://www.kuvan.com/
28. 2.26 Amino Acid Structures

It is a good idea to have a general idea of the structure of the different amino acids and to be able to recognize them as amino acids. You are not expected to memorize these structures. Often I say the name of amino acids and not all students understand that I am talking about an amino acid. Each amino acid differs only by its side group, which is circled in red in each figure below. Also, the more familiar you become with chemical structures, the more prepared you will be for later classes.
Histidine$^1$

Isoleucine$^2$

Lysine$^4$

Methionine$^5$
Figure 2.26 Essential amino acids

You may hear someone talk about the branch chain amino acids, which are all essential amino acids, but they are singled out in the figure below.
Figure 2.262 Branched chain amino acids; Valine, Leucine, Isoleucine
Figure 2.263 Conditionally essential amino acids

Arginine\textsuperscript{10}  
Cysteine\textsuperscript{11}  
Glutamine\textsuperscript{12}  
Glycine\textsuperscript{13}  
Proline\textsuperscript{14}  
Tyrosine\textsuperscript{15}  

Figure 2.264 Nonessential amino acids

Alanine\textsuperscript{16}  
Asparagine\textsuperscript{17}  
Aspartate (aspartic acid)\textsuperscript{18}  
Glutamate (glutamic acid)\textsuperscript{19}  
Serine\textsuperscript{20}  

References & Links

2.26 Amino Acid Structures | 123
6. https://en.wikipedia.org/wiki/Phenylalanine#/media/File:L-Phenylalanin_-_L-Phenylalanine.svg

124 | 2.26 Amino Acid Structures
Proteins can be classified as either complete or incomplete. Complete proteins provide adequate amounts of all nine essential amino acids. Animal proteins such as meat, fish, milk, and eggs are good examples of complete proteins. Incomplete proteins do not contain adequate amounts of one or more of the essential amino acids. For example, if a protein doesn't provide enough of the essential amino acid leucine it would be considered incomplete. Leucine would be referred to as the limiting amino acid, because there is not enough of it for the protein to be complete. Most plant foods are incomplete proteins, with a few exceptions such as soy. The table below shows the limiting amino acids in some plant foods.

Table 2.271 Limiting amino acids in some common plant foods

<table>
<thead>
<tr>
<th>Food</th>
<th>Limiting Amino Acid(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bean and Most Legumes</td>
<td>Methionine, Tryptophan</td>
</tr>
<tr>
<td>Tree Nuts and Seeds</td>
<td>Methionine, Lysine</td>
</tr>
<tr>
<td>Grains</td>
<td>Lysine</td>
</tr>
<tr>
<td>Vegetables</td>
<td>Methionine, Lysine</td>
</tr>
</tbody>
</table>

Complementary Proteins

Even though most plant foods do not contain complete proteins, it does not mean that they should be sworn off as protein sources. It is possible to pair foods containing incomplete proteins with different limiting amino acids to provide adequate amounts of the essential amino acids. These two proteins are called complementary proteins, because they supply the amino acid(s) missing in the other protein. A simple analogy would be that of a 4 piece puzzle. If one person has 2 pieces of a puzzle, and another person has 2 remaining pieces, neither of them have a complete puzzle. But when they are combined, the two individuals create a complete puzzle.
Two examples of complementary proteins are shown below.
Figure 2.272 Two complementary protein examples$^{2,3}$

It should be noted that complementary proteins do not need to be consumed at the same time or meal. It is currently recommended that essential amino acids be met on a daily basis, meaning that if a grain is consumed at one meal, a legume could be consumed at a later meal, and the proteins would still complement one another$^4$.

**Measures of Protein Quality**

How do you know the quality of the protein in the foods you consume? The protein quality of most foods has been determined by one of the methods below.

- Biological Value (BV) – (grams of nitrogen retained / grams of nitrogen absorbed) $\times$ 100
- Protein Efficiency Ratio (PER) – (grams of weight gained / grams of protein consumed)

This method is commonly performed in growing rats.
Chemical or Amino Acid Score (AAS) – (Test food limiting essential amino acid (mg/g protein) / needs of same essential amino acid (mg/g protein))

Protein Digestibility Corrected Amino Acid Score (PDCAAS) – (Amino Acid Score x Digestibility)

This is the most widely used method and was preferred by the Food and Agriculture Organization and World Health Organization (WHO) until recently\(^5,6\).

The following table shows the protein quality measures for some common foods.

Table 2.272 Measures of protein quality\(^5\)

<table>
<thead>
<tr>
<th>Protein</th>
<th>PER</th>
<th>Digestibility</th>
<th>AAS (%)</th>
<th>PDCAAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egg</td>
<td>3.8</td>
<td>98</td>
<td>121</td>
<td>100*</td>
</tr>
<tr>
<td>Milk</td>
<td>3.1</td>
<td>95</td>
<td>127</td>
<td>100*</td>
</tr>
<tr>
<td>Beef</td>
<td>2.9</td>
<td>98</td>
<td>94</td>
<td>92</td>
</tr>
<tr>
<td>Soy</td>
<td>2.1</td>
<td>95</td>
<td>96</td>
<td>91</td>
</tr>
<tr>
<td>Wheat</td>
<td>1.5</td>
<td>91</td>
<td>47</td>
<td>42</td>
</tr>
</tbody>
</table>

*PDCAAS scores are truncated (cut off) at 100. These egg and milk scores are actually 118 and 121 respectively.

The Food and Agricultural Organization (FAO) recently recommended that PDCAAS be replaced with a new measure of protein quality, the Digestible Indispensable Amino Acid Score (DIAAS). “DIAAS is defined as: DIAAS % = 100 x [(mg of digestible dietary indispensable amino acid in 1 g of the dietary protein) / (mg of the same dietary indispensable amino acid in 1g of the reference protein)].” Ileal digestibility should be utilized to determine the digestibility in DIAAS; ideally in humans, but if not possible in growing pigs or rats\(^6\).

The main differences between DIAAS and PDCAAS are:

- DIAAS take into account individual amino acids digestibility rather than protein digestibility.
• It focuses on ileal instead of fecal (total) digestibility.
• Has 3 different reference patterns (different age groups, 0-6 months, 6 months-3 years, 3-10 years old) instead of a single pattern
• DIAAS scores will not be truncated

How do I find out the protein quality of what I’m eating and identify complementary proteins?

Nutrition Data is a useful resource for determining protein quality and identifying complementary proteins. To use the site, go to www.nutritiondata.com, type in the name of the food you would like to know about in the search bar and hit ‘Enter’. When you have selected your food from the list of possibilities, you will be given information about this food. Included in this information is the Protein Quality section. This will give you an amino acid score and a figure that illustrates which amino acid(s) is limiting. If your food is an incomplete protein, you can click “Find foods with a complementary profile”. This will take you to a list of dietary choices that will provide complementary proteins for your food. You can read more about this option in the link below.

Web Link

Nutrition Data: Protein Quality

References & Links


**Links**

NutritionData – http://www.nutritiondata.com/

Protein deficiency rarely occurs alone. Instead it is often coupled with insufficient energy intake. As a result, the condition is called protein-energy malnutrition (PEM). This condition is not common in the U.S., but is more prevalent in less developed countries. Kwashiorkor and marasmus are the two forms of protein energy malnutrition. They differ in the severity of energy deficiency as shown in the figure below.

Kwashiorkor is a Ghanaian word that means “the disease that the first child gets when the new child comes”. The characteristic symptom of kwashiorkor is a swollen abdomen. Energy intake could be adequate, but protein consumption is too low.
Figure 2.282 A child suffering from kwashiorkor
The video below does a nice job showing the symptoms of the condition.

**Web Link**

**Video: Kwashiorkor (1:17)**

Marasmus means “to waste away” or “dying away”, and thus occurs in individuals who have severely limited energy intakes.
The video below shows individuals suffering from this condition.

**Web Link**

Video: Marasmus (2:24)
References & Links


Videos
Kwashiorkor – http://www.youtube.com/watch?v=eTU3iPWAWXg
Marasmus – https://www.youtube.com/watch?v=LDCi3eda4WM
31. 2.3 Lipids

Lipids, commonly referred to as fats, have a poor reputation among some people, in that “fat free” is often synonymous with healthy. We do need to consume certain fats and we should try to incorporate some fats into our diets for their health benefits. However, consumption of certain fats is also associated with greater risk of developing chronic disease(s). In this section we will dive deeper into fats and why they do not need to be feared altogether.

Subsections:
2.31 How does fat differ from lipids?
2.32 Fatty Acids
2.33 Fatty Acid Naming & Food Sources
2.34 Essential Fatty Acids
2.35 Triglycerides
2.36 Phospholipids
2.37 Sterols
32. 2.31 How Does Fat Differ From Lipids?

The answer you receive from this question will depend on who you ask, so it is important to have an understanding of lipids and fats from a chemical and nutritional perspective.

To a chemist, lipids consist of:

- Triglycerides
- Fatty Acids
- Phospholipids
- Sterols

These compounds are grouped together because of their structural and physical property similarities. For instance, all lipids have hydrophobic (water-fearing) properties. Chemists further separate lipids into fats and oils based on their physical properties at room temperature:

- Fats are solid at room temperature
- Oils are liquid at room temperature

From a nutritional perspective, the definition of lipids is the same. The definition of a fat differs, however, because nutrition-oriented people define fats based on their caloric contribution rather than whether they are solid at room temperature. Thus, from a nutrition perspective:

- Fats are triglycerides, fatty acids, and phospholipids that provide 9 kcal/g.

The other difference is that from a caloric perspective, an oil is a fat. For example, let’s consider olive oil. Clearly, it is an oil according to a chemist definition, but from a caloric standpoint it is a fat because it provides 9 kcal/g.

The following sections will discuss the different lipid classes introduced above in detail.

No References
33. 2.32 Fatty Acids

Fatty acids are lipids themselves, and they are also components of triglycerides and phospholipids. Like carbohydrates, fatty acids are made up of carbon (C), hydrogen (H), and oxygen (O).

On one end of a fatty acid is a methyl group (CH3) that is known as the methyl or omega end. On the opposite end of a fatty acid is a carboxylic acid (COOH). This end is known as the acid or alpha end. The figure below shows the structure of fatty acids.

![Figure 2.321 Structure of a saturated fatty acid](image)

There are a number of fatty acids in nature that we consume that differ from one another in three ways:

1. **Carbon chain length** (i.e. 6 carbons, 18 carbons)
2. **Saturation/unsaturation**
3. **Double bond configuration** (cis, trans)

### 1. Carbon Chain Length

Fatty acids differ in their carbon chain length (number of carbons in the fatty acid). Most fatty acids contain somewhere between 4-24 carbons, with even numbers (i.e. 8, 18) of carbons occurring more frequently than odd numbers (i.e. 9, 19). Fatty acids are classified as short-chain fatty acids, medium-chain fatty acids, and long-chain fatty acids based on their carbon chain length using the criteria shown in the table below.

Table 2.321 Fatty acid classification
<table>
<thead>
<tr>
<th>Classification</th>
<th># of carbons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-Chain Fatty Acid</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>Medium-Chain Fatty Acid</td>
<td>6-10</td>
</tr>
<tr>
<td>Long-Chain Fatty Acid</td>
<td>≥12</td>
</tr>
</tbody>
</table>

Carbon chain length also impacts the physical properties of the fatty acid. As the number of carbons in a fatty acid chain increases, so does the melting point as illustrated in the figure below.

![Figure 2.322 The melting point of saturated fatty acids of varied lengths](image)

Thus, shorter chain fatty acids are more likely to be liquid, while longer chain fatty acids are more likely to be solid at room temperature (20–25°C, 68–77°F).

2. **Saturation/Unsaturation**

A saturated fatty acid is one that contains the maximum number of hydrogens possible, and no carbon-carbon double bonds. Carbon normally has four bonds to it. Thus, a saturated fatty acid has hydrogens at every position except carbon-carbon single bonds and carbon-oxygen bonds on the acid end. Two examples of the same 18 carbon saturated fatty acid (stearic acid/stearate) are shown in
Figures 2.321 and 2.323. Figure 2.323 is the simplified view of the this fatty acid.

Unsaturation means the fatty acid doesn’t contain the maximum number of hydrogens on each of its carbons. Instead, unsaturated fatty acids contain a carbon–carbon double bond and only 1 hydrogen off each carbon. The simplest example of unsaturation is a monounsaturated fatty acid. Mono means one, so these are fatty acids with one degree of unsaturation, or one double bond (shown below).

Figure 2.324 Structure of the monounsaturated fatty acid (oleic acid)
Any fatty acid that has two or more double bonds is considered a polyunsaturated fatty acid. As you may remember from the polysaccharide section, poly means many. A simple example of a polyunsaturated fatty acid is linoleic acid (shown below).

![Figure 2.326 Structure of the polyunsaturated fatty acid linoleic acid, a polyunsaturated fatty acid with two carbon-carbon double bonds](image)

3. Double Bond Configuration (Shape)

Double bonds in unsaturated fatty acids are in one of two structural orientations: cis or trans. In a trans orientation, the hydrogens on the carbons involved in the double bond are opposite of one another. In the cis orientation the hydrogens are on the same side of the bond. Steric hindrance in the cis orientation causes the chain to take on a more bent shape.

![Figure 2.327 Cis and trans structural conformations of a monounsaturated fatty acid](image)
Most natural unsaturated fatty acids are in the cis conformation. As can be seen in Figure 2.327, the cis fatty acids have a more of kinked shape, which means they do not pack together as well as the saturated or trans fatty acids. As a result, the melting point is much lower for cis fatty acids compared to trans and saturated fatty acids. To illustrate this difference, the figure below shows the difference in the melting points of saturated, trans-, and cis-monounsaturated 18 carbon fatty acids.

![Figure 2.328 The melting point of saturated, trans, and cis 18 carbon monounsaturated fatty acids](image)

There are some naturally occurring trans fatty acids, such as conjugated linoleic acid (CLA), in dairy products. However, for the most part, trans fatty acids in our diets are not natural; instead, they have been produced synthetically. The primary source of trans fatty acids in our food supply is partially hydrogenated vegetable oil. The ‘hydrogenated’ means that the oil has gone through the process of hydrogenation. Hydrogenation, like the name implies, is the addition of hydrogen. If an unsaturated fatty acid is completely hydrogenated it would be converted to a saturated fatty acid as shown below.
However, this isn't/wasn't always desirable, thus partially hydrogenated vegetable oil became widely used. To visualize the difference in the amount of hydrogenation consider the difference between tub margarine and stick margarine.

Stick margarine is more fully hydrogenated leading it to have a much harder texture. This is one of the two reasons to hydrogenate, to get a more solid texture. The second reason is that it makes it more shelf-stable, because the double bond(s) of unsaturated fatty acids are susceptible to oxidation, which causes them to become rancid.

Partial hydrogenation causes the conversion of cis to trans fatty acids along with the formation of some saturated fatty acids. Originally, it was thought that trans fatty acids would be a better alternative to saturated fat (think margarine vs. butter). However, it turns out that trans fat is actually worse than saturated fat in altering biomarkers associated with cardiovascular disease. Trans fat increases LDL and decreases HDL levels, while saturated fat increased LDL without altering HDL levels. But this does not mean that butter is a better choice than margarine as described in the
first link. The FDA revoked Generally Recognized as Safe (GRAS) status of partially hydrogenated vegetable oil as described in the second link, and is requiring its use to be phased out by 2018. After that point, permission will need to be requested to use them in foods.

Web Links

Butter vs. Margarine: Which is better for my heart?
FDA to Limit Trans Fats in Foods

References & Links


Links

There are three naming systems used for fatty acids:
1. Delta nomenclature
2. Omega nomenclature
3. Common names

The omega nomenclature and common names are used more in the field of nutrition than the delta nomenclature when describing specific fatty acids.

**1. Delta Nomenclature**

For delta nomenclature you need to know 3 things:
1. Number of carbons in the fatty acid
2. Number of double bonds
3. Number of carbons from the carboxylic acid (alpha) end to the first carbon in the double bond(s)

Let's consider the example in the figure below.

---

**Figure 2.331 Delta Nomenclature**
1. Number of carbons in the fatty acid = 18  
2. Number of double bonds = 1  
3. Number of carbons from the carboxylic acid end to the first carbon in the double bond = 9  
   This is then written as shown in Figure 2.331.

2. Omega Nomenclature
   The omega nomenclature is almost exactly the same as the delta nomenclature, the only differences being:
   
   • Carbons are counted from the methyl (omega) end instead of the carboxylic acid end  
   • The omega symbol is used instead of the delta symbol

For omega nomenclature you need to know 3 things:  
1. Number of carbons in the fatty acid  
2. Number of double bonds  
3. Number of carbons from the methyl end (aka Omega end) to the first carbon in the double bond closest to the methyl end  
   We will again consider the same fatty acid.
1. Number of carbons in the fatty acid = 18
2. Number of double bonds = 1
3. Number of carbons from the methyl (aka omega) end to the first carbon in the double bond closest to the methyl end = 9

If it is a saturated fatty acid, then the omega nomenclature is not added to the end of the name. If it is an 18 carbon saturated fatty acid, then it would be named 18:0.

This is written as shown in figure 2.332. Instead of an omega prefix, the prefix n- (i.e. n-3) is also commonly used.

3. **Common Names**

The common names of fatty acids are something that, for the most part, have to be learned/memorized. The common name of the fatty acid we have been naming in this section is oleic acid.

![Figure 2.333 Oleic acid](image)

However, it can also be called oleate. The only difference is that, instead of a carboxylic acid on the end of the fatty acid, it has been ionized to form a salt (shown below). This is what the -ate ending indicates and the two names are used interchangeably.
The table below gives the common names and food sources of some common fatty acids.

Table 2.331 Common names of fatty acids\(^2\)
<table>
<thead>
<tr>
<th>Omega Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:0</td>
<td>Butyric Acid</td>
</tr>
<tr>
<td>12:0</td>
<td>Lauric Acid</td>
</tr>
<tr>
<td>14:0</td>
<td>Myristic Acid</td>
</tr>
<tr>
<td>16:0</td>
<td>Palmitic Acid</td>
</tr>
<tr>
<td>18:0</td>
<td>Stearic Acid</td>
</tr>
<tr>
<td>20:0</td>
<td>Arachidic Acid</td>
</tr>
<tr>
<td>24:0</td>
<td>Lignoceric Acid</td>
</tr>
<tr>
<td>18:1 (n-9)</td>
<td>Oleic Acid</td>
</tr>
<tr>
<td>18:2 (n-6)</td>
<td>Linoleic Acid</td>
</tr>
<tr>
<td>18:3 (n-3)</td>
<td>Alpha-linolenic Acid</td>
</tr>
<tr>
<td>20:4 (n-6)</td>
<td>Arachidonic Acid</td>
</tr>
<tr>
<td>20:5 (n-3)</td>
<td>Eicosapentanoic Acid</td>
</tr>
<tr>
<td>22:6 (n-3)</td>
<td>Docosahexanoic Acid</td>
</tr>
</tbody>
</table>

The NutritionData link below can help you identify foods that are high in a specific fatty acid.

**Web Link**

[NutritionData: Fatty Acids](#)

**Food Sources of Fatty Acids**

After going through this wide array of fatty acids, you may be wondering where they are found in nature. The figure below shows the fatty acid composition of certain oils and oil-based foods. As you can see, most foods contain a mixture of fatty acids. Stick margarine is the only product in the figure that contains an appreciable amount of trans fatty acids. Corn, walnut, and soybean are rich sources of n-6 polyunsaturated fatty acids, while flax seed is fairly unique among plants in that it is a good source of n-3 polyunsaturated fatty acids. Canola and olive oil are rich sources of monounsaturated fatty acids. Lard, palm oil, butter and coconut oil all contain a significant amount of saturated fatty acids.
References & Links

3. www.nutritiondata.com

Links
The two essential fatty acids are:
1. linoleic acid (omega-6)
2. alpha-linolenic (omega-3)

These fatty acids are essential because we cannot synthesize them. This is because we do not have an enzyme capable of adding a double bond (desaturating) beyond the omega-9 carbon counting from the alpha end (the omega-6 and 3 positions). The structures of the two essential fatty acids are shown below.

However, we do possess enzymes that can take the essential fatty acids, elongate them (add two carbons to them), and then further desaturate them (add double bonds) to other omega-6 and omega-3 fatty acids. Thus, there are 2 families of fatty acids that the majority of polyunsaturated fatty acids fit into as shown below.
The same enzymes are used for both omega-6 and omega-3 fatty acids. However, we cannot convert omega-3 fatty acids to omega-6 fatty acids or omega-6 fatty acids to omega-3 fatty acids. Among these families, the omega-3 fatty acid, eicosapentaenoic acid (EPA), and the omega-6 fatty acids, dihomo gamma-linolenic acid and arachidonic acid (AA), are used to form compounds known as eicosanoids. These 20 carbon fatty acid derivatives are biologically active in the body (like hormones, but they act locally in the tissue they are produced). There are four classes of eicosanoids:

Prostaglandins (PG)
Prostacyclins (PC)
Thromboxanes (TX)
Leukotrienes (LT)

Some examples of eicosanoid structures are shown in the figure below:
Prostaglandin E1

Thromboxane A

Leukotriene B4

Prostacyclin I2
The difference in the effects and outcomes of omega-6 and omega-3 fatty acid intake is primarily a result of the eicosanoids produced from them. Omega-6 fatty acid derived eicosanoids are more inflammatory than omega-3 fatty acid derived eicosanoids. As a result, omega-3 fatty acids are considered anti-inflammatory because replacing the more inflammatory omega-6 fatty acid derived eicosanoids with omega-3 fatty acid derived eicosanoids will decrease inflammation. As an example of the action of eicosanoids, aspirin works by inhibiting the enzymes cyclooxygenase (Cox)-1 and Cox-2. These enzymes convert arachidonic acid into inflammatory prostaglandins as shown below.
You have probably heard that you should get more omega-3s in your diet, and in general polyunsaturated fatty acids are considered healthy. However, since omega-3 fatty acids are competing for the same enzymes as omega-6 fatty acids, and because the omega-6 fatty acids are more inflammatory, consuming too many omega-6s is probably more detrimental than helpful. As a result, many people talk about the omega-3:omega-6 fatty acid ratio in people’s’ diets. For most Americans, the ratio is believed to be too high, at almost 10-20 times more omega-6 fatty acids than omega-3 fatty acids\(^\text{10}\). The table below shows good food sources of some selected omega-3 and omega-6 fatty acids.

Table 2.341 Good food sources of selected omega-3 and omega-6 fatty acids
<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Good Food Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linoleic Acid (LA, n-6)</td>
<td>Safflower Oil, Corn Oil, Sunflower Oil</td>
</tr>
<tr>
<td>Arachidonic Acid (AA, n-6)</td>
<td>Eggs, Meat</td>
</tr>
<tr>
<td>Alpha-Linolenic Acid (ALA, n-3)</td>
<td>Walnuts, Flaxseed (linseed), Canola (rapeseed), and Soybean Oils</td>
</tr>
<tr>
<td>Eicosapentaenoic Acid (EPA, n-3)</td>
<td>Fatty Fish &amp; Fish Oils</td>
</tr>
<tr>
<td>Docosahexanoic Acid (DHA, n-3)</td>
<td>Fatty Fish &amp; Fish Oils</td>
</tr>
</tbody>
</table>

Even though Figure 2.343 illustrates the conversion of alpha-linolenic acid to EPA and DHA, this conversion is actually quite limited; 0.2–8% of ALA is converted to EPA and 0–4% of ALA is converted to DHA\(^1\). Thus, dietary consumption is the most effective way to get the longer chain fatty acids (EPA and DHA) in our bodies. It is less clear whether ALA consumption is as beneficial as EPA and DHA, but a recent study found it to be equally effective in decreasing blood triglyceride concentrations. In that study, DHA had the added positive benefit of increasing HDL\(^12\). These are all positive outcomes that are expected to reduce the risk of developing cardiovascular disease. However, there is evidence accumulating that there is not much cardiovascular benefit from taking fish oil supplements as described in the article below.

**Web Link**

[Fish Oils Claims Not Supported By Research](#)

**Essential Fatty Acid Deficiency**

Essential fatty acid deficiency is rare and unlikely to occur, but the symptoms are:

- Growth retardation
- Reproductive problems
- Skin lesions
- Neurological and visual problems
References & Links


Links
Triglycerides are the most common lipid in our bodies and in the foods we consume. Fatty acids are not typically found free in nature, instead they are found in triglycerides. Breaking down the name triglyceride tells a lot about their structure. “Tri” refers to the three fatty acids, “glyceride” refers to the glycerol backbone that the three fatty acids are bonded to. Thus, a monoglyceride contains one fatty acid, a diglyceride contains two fatty acids. Triglycerides perform the following functions in our bodies:

- Provide energy
- Primary form of energy storage in the body
- Insulate and protect
- Aid in the absorption and transport of fat-soluble vitamins.

A triglyceride is formed by three fatty acids being bonded to glycerol as shown below.

When a fatty acid is added to the glycerol backbone, this process is called esterification. This process is so named, because it forms an ester bond between each fatty acid and the glycerol. Three
molecules of water are also formed during this process as shown below.

![Ester Bond](image)

*Figure 2.352 Esterification of three fatty acids to glycerol*

A stereospecific numbering (sn) system is used to number the three fatty acids in a triglyceride sn-1, sn-2, and sn-3 respectively. A triglyceride can also be simply represented as a polar (hydrophilic) head, with 3 nonpolar (hydrophobic) tails, as shown below.
The three fatty acids in a triglyceride can be the same or can each be a different fatty acid. A triglyceride containing different fatty acids is known as a mixed triglyceride. An example of a mixed triglyceride is shown below.
Figure 2.354 Structure of a mixed triglyceride

No References
Phospholipids are similar in structure to triglycerides, with the only difference being a phosphate group and nitrogen-containing compound in the place of a fatty acid.

The best known phospholipid is phosphatidylcholine (aka lecithin). As you can see in the structure below, it contains a choline off of the phosphate group.
Figure 2.362 Structure of phosphatidylcholine (lecithin)

However, you will not normally find phospholipids arranged like a triglyceride, with the 3 tails opposite of the glycerol head. This is because the phosphate/nitrogen tail of the phospholipid is polar. Thus, the structure will look like the 2 figures below.

Figure 2.363 Structure of phosphatidylcholine (lecithin)
Similar to triglycerides, phospholipids are also represented as a hydrophilic head with two hydrophobic tails as shown below.

**Phospholipid Functions**

Because its structure allows it to be at the interface of water-lipid environments, there are two main functions of phospholipids:

1. Key Component of the Cell's Lipid Bilayer
2. Emulsification

Number 1 in the figure below is a cell's lipid bilayer, while 2 is a micelle that is formed by phospholipids to assist in emulsification.
1. Key Component of Cells’ Lipid Bilayers

Phospholipids are an important component of the lipid bilayers of cells. A cross section of a lipid bilayer is shown below. The hydrophilic heads are on the outside and inside of the cell; the hydrophobic tails are in the interior of the cell membrane.
2. Emulsification

As emulsifiers, phospholipids help hydrophobic substances mix in a watery environment. It does this by forming a micelle as shown below. The hydrophobic substance is trapped on the interior of the micelle away from the aqueous environment.
As a result, it can take a hydrophobic liquid (oil) and allow it to mix with hydrophilic liquid (water).
Foods rich in phosphatidylcholine include: egg yolks, liver, soybeans,
wheat germ, and peanuts\textsuperscript{8}. Egg yolks serve as an emulsifier in a variety of recipes. Your body makes all the phospholipids that it needs, so they do not need to be consumed (not essential).

**References & Links**

The last category of lipids are the sterols. Their structure is quite different from the other lipids because sterols are made up of a number of carbon rings. The generic structure of a sterol is shown below.

![Figure 2.371 Generic structure of a sterol](image)

The primary sterol that we consume is cholesterol. The structure of cholesterol is shown below.
Cholesterol is frequently found in foods as a cholesterol ester, meaning that there is a fatty acid attached to it. The structure of a cholesterol ester is shown below.
All sterols have a similar structure to cholesterol. Cholesterol is only found in foods of animal origin. If consumers were more knowledgeable, intentionally misleading practices, such as labeling a banana “cholesterol free”, would not be as widespread as they currently are today.

**Function**

Although cholesterol has acquired the status of a nutrition “villain”, it is a vital component of cell membranes and is used to produce vitamin D, hormones, and bile acids. You can see the similarity between the structures of vitamin D and estradiol, one of the forms of estrogen shown below.
We do not need to consume any cholesterol from our diets (not essential) because our bodies have the ability to synthesize the required amounts. The figure below gives you an idea of the cholesterol content of a variety of foods.

There is neither bad nor good cholesterol, despite these descriptions being commonly used for LDL and HDL, respectively. Cholesterol is cholesterol. HDL and LDL contain cholesterol but are actually lipoproteins that will be described later in chapter 4.

References & Links
The term absorption can have a number of different meanings. Not everything that is taken up into the enterocyte from the lumen will be absorbed, so the term uptake refers to compounds being transported into the enterocyte. Absorption means that a compound is transported from the enterocyte into circulation. Under most circumstances, compounds that are taken up will then be absorbed. After this chapter, hopefully this distinction between these terms will be clear. After later micronutrient chapters, hopefully you will understand the reason for emphasizing this distinction.

Sections:
4.1 Crypts of Lieberkuhn & Enterocyte Maturation
4.2 Absorptive Lineup & Cell Membranes
4.3 Types of Cell Uptake/Transport
4.4 Carbohydrate Uptake, Absorption, Transport & Liver Uptake
4.5 Glycemic Response, Insulin & Glucagon
4.6 Protein Uptake, Absorption, Transport & Liver Uptake
4.7 Lipid Uptake, Absorption & Transport
40. 4.1 Crypts of Lieberkuhn & Enterocyte Maturation

There are some additional anatomical and physiological features of the small intestine that are important to understand before defining uptake and absorption. Crypts of Lieberkuhn are pits between villi as pointed out by the green arrow in the figure below.

![Small intestine and villi diagram](image)

**Figure 4.11** A crypt of Lieberkuhn is the pit between the villi in the small intestine as pointed out by the green arrow.

The crypts of Lieberkuhn (often referred to simply as crypts) are similar to the gastric pits in the stomach. The crypts contain stem cells that can produce a number of different cell types, including enterocytes. From these stem cells in the crypt, immature enterocyte cells are formed that mature as they rise, or migrate up, the villi. Thus, the tips at the top of villi are where the mature, fully functioning enterocytes are located, as represented by the purple cells in the figure below.
This maturation and migration is a continuous process. The life cycle of an enterocyte is 72 hours once it enters the villus from the crypt\(^2\). At the top, enterocytes are sloughed off, and, unless they are digested (contain proteins and lipid) and components are taken up by enterocytes still on villi, they will be excreted in feces as depicted in the figure below.
Thus, we define absorption as reaching body circulation, because compounds taken up into enterocytes might not make it into body circulation, and thus are not necessarily absorbed.

**References & Links**

4.2 Uptake Lineup & Cell Membranes

Having completed digestion in the small intestine, a number of compounds are ready for uptake into the enterocyte. The figure below shows the macronutrient uptake lineup, or what is ready to be taken up into the enterocyte.

From lipids, we have the lysolecithin (from phospholipid), 2-monoglyceride (from triglycerides), fatty acids, and cholesterol. From protein, there are small peptides (di- and tripeptides) and amino acids. From carbohydrates, only the monosaccharides glucose, galactose, and fructose will be taken up. The other macronutrient, water, has not been discussed so far because it does not undergo digestion.

However, these compounds must now cross the plasma (cell) membrane, which is a phospholipid bilayer. In the cell membrane, the hydrophilic heads of the phospholipids point into the lumen as...
well as towards the interior of the cell, while the tails are on the interior of the plasma membrane as shown below.

![Figure 4.22 Plasma membrane of a cell](image)

The plasma membrane contains proteins, cholesterol, and carbohydrates in addition to the phospholipids. Membrane proteins, such as channels and pumps, are important for the transport of some compounds across the cell membrane. The figure and two videos below do a nice job of illustrating the components of the cell membrane.
Figure 4.23 Cell membrane

Web Links

Video: Cell Membrane (1:27)
Video: Voyage inside the cell: Membrane (1:23)

References & Links

   File:Cell_membrane_detailed_diagram_4.svg
Videos

Cell Membrane – http://www.youtube.com/watch?v=owEgqrq51zY
Voyage Inside the Cell: Membrane – http://www.youtube.com/watch?v=GW0lqf4Fqpg
42. 4.3 Types of Cell Uptake/Transport

There are a number of different forms of uptake/transport utilized by your body. These can be classified as passive or active. The difference between the two is whether energy is required and whether they move with or against a concentration gradient. Passive transport does not require energy and moves with a concentration gradient. Active transport requires energy to move against the concentration gradient.

The energy for active uptake/transport is provided by adenosine triphosphate (ATP), which is the energy currency in the body. The structures of adenosine and phosphate are shown below.

Figure 4.31 Structures of adenosine (left) and phosphate (right)

Tri- means three, thus ATP is adenosine with three phosphate groups bonded to it, as shown below.
Phosphorylation is the formation of a phosphate bond. Dephosphorylation is removal of a phosphate bond. Overall phosphorylation is a process that require energy. The net effect of dephosphorylation is the release of energy. Thus, energy is required to add phosphates to ATP, energy is released through removing phosphates from ATP.

The concentration gradient is a way to describe the difference between the concentration of the solute outside of a cell versus the concentration inside of a cell. A solute is what is dissolved in a solvent in a solution; the more solute the higher the concentration. Moving with the gradient is moving from a region of higher concentration to an area of lower concentration. Moving against the gradient is moving from an area of lower concentration to an area of higher concentration.

Subsections:
4.31 Passive Uptake/Transport
4.32 Active Uptake/Transport
There are three forms of passive uptake/transport:

1. Simple Diffusion
2. Osmosis
3. Facilitated Diffusion

Below is more information of each type of uptake/transport.

**1. Simple Diffusion**

Simple diffusion is the movement of solutes from an area of higher concentration (with the concentration gradient) to an area of lower concentration without the help of a protein, as shown below.

![Figure 4.311 Simple diffusion](image)

**2. Osmosis**

---

4.31 Passive Uptake/Transport | 187
Osmosis is similar to simple diffusion, but water moves instead of solutes. In osmosis water molecules move from an area of lower concentration to an area of higher concentration of solute as shown below. The effect of this movement is to dilute the area of higher concentration.

The following videos do a nice job of illustrating osmosis.

**Web Links**

- Video: Osmosis (0:47)
- Video: Osmosis in the Kitchen (0:58)

Another example illustrating osmosis is the red blood cells in different solutions shown below.
We will consider the simple example of salt as the solute. If the solution is hypertonic, that means that there is a greater concentration of salt outside (extracellular) the red blood cells than within them (intracellular). Water will then move out of the red blood cells to the area of higher salt concentration, resulting in the shriveled red blood cells depicted. Isotonic means that there is no difference between concentrations. There is an equal exchange of water between intracellular and extracellular fluids. Thus, the cells are normal, functioning red blood cells. A hypotonic solution contains a lower extracellular concentration of salt than the red blood cell intracellular fluid. As a result, water enters the red blood cells, possibly causing them to burst.

### 3. Facilitated Diffusion

The last form of passive absorption is similar to diffusion in that it follows the concentration gradient (higher concentration to lower concentration). However, it requires a carrier protein to transport the solute across the membrane. The following figure and video do a nice job of illustrating facilitated diffusion.
Figure 4.314 Facilitated diffusion examples

---

**Web Link**

**Video:** Facilitated Diffusion (0:27)

**References & Links**


**Videos**

- Osmosis - [http://www.youtube.com/watch?v=sdiJtDRJQEc](http://www.youtube.com/watch?v=sdiJtDRJQEc)
- Osmosis in the Kitchen - [http://www.youtube.com/watch?v=H6N1iiJTMnc&NR=1&feature=fvwp](http://www.youtube.com/watch?v=H6N1iiJTMnc&NR=1&feature=fvwp)
- Facilitated Diffusion - [http://www.youtube.com/watch?v=s0p1ztrbXPY](http://www.youtube.com/watch?v=s0p1ztrbXPY)
44. 4.32 Active Uptake/Transport

There are two forms of active uptake/transport:

1. Active Carrier Transport
2. Endocytosis

1. **Active Carrier Transport**

   Active carrier transport is similar to facilitated diffusion in that it utilizes a protein (carrier). However, energy is also used to move compounds against their concentration gradient. The following figure and video do a nice job of illustrating active carrier transport.

![Figure 4.321 Sodium-potassium ATPase (aka sodium-potassium pump) an example of active carrier transport](image)

**Web Link**

**Video: Active Transport (0:21)**

2. **Endocytosis**

   Endocytosis is the engulfing of particles, or fluids, to be taken up into the cell. If a particle is endocytosed, this process is referred to
as phagocytosis. If a fluid is endocytosed, this process is referred to as pinocytosis as shown below.

![Endocytosis diagram](image)

Figure 4.322 Different types of endocytosis

The following video does a really nice job of showing how endocytosis occurs.

**Web Link**

Video: Endocytosis (0:35)

**References & Links**


**Videos**

- Active Transport – [http://www.youtube.com/watch?v=STzOiRqzzL4](http://www.youtube.com/watch?v=STzOiRqzzL4)
- Endocytosis – [http://www.youtube.com/watch?v=4gLtk8Yc1Zc](http://www.youtube.com/watch?v=4gLtk8Yc1Zc)
45. 4.4 Carbohydrate Uptake, Absorption, Transport & Liver Uptake

Monosaccharides are taken up into the enterocyte. Glucose and galactose are taken up by the sodium-glucose cotransporter 1 (SGLT1, active carrier transport). The cotransporter part of the name of this transporter means that it also transports sodium along with glucose or galactose. Fructose is taken up by facilitated diffusion through glucose transporter (GLUT) 5. There are 12 glucose transporters that are named GLUT 1-12, and all use facilitated diffusion to transport monosaccharides. The different GLUTs have different functions and are expressed at high levels in different tissues. Thus, the intestine might be high in GLUT5, but not in GLUT12. Moving back to monosaccharides, inside the enterocyte, all three are then transported out of the enterocyte into the capillary (absorbed) through GLUT2 as shown below.

Figure 4.41 Carbohydrate uptake and absorption
Inside of each villus there are capillaries and lacteals as shown below. Capillaries are the smallest blood vessels in the body, lacteals are also small vessels but are part of the lymphatic system, as will be described further in a later subsection.

![Anatomy of a villus](image)

Figure 4.42 Anatomy of a villus

The following video does a nice job of illustrating capillaries and lacteal and provides some basic detail on uptake and absorption.
The capillaries in the small intestine join to the portal vein, which transports monosaccharides directly to the liver. The figure below shows the portal vein and all the smaller vessels from the stomach, small intestine, and large intestine that feed into it.

Figure 4.43 The portal vein transports monosaccharides and amino acids to the liver.\(^3\)

At the liver, galactose and fructose are completely taken up through GLUT5, while only 30-40% of glucose is taken up through GLUT2. After the monosaccharides are taken up, they are phosphorylated by their respective kinase enzymes forming galactose-1-phosphate, fructose-1-phosphate, and glucose-6-phosphate as shown below.
Kinase enzymes normally phosphorylate substrates. Phosphorylation of the monosaccharides is important for maintaining the gradient (by keeping unphosphorylated monosaccharide levels within hepatocytes low) needed for facilitated diffusion through the GLUT transporters.\(^3\)

**References & Links**

3. [https://commons.wikimedia.org/wiki/File:Gray591.png](https://commons.wikimedia.org/wiki/File:Gray591.png)

**Video**

Absorption in the Small Intestine – [http://www.youtube.com/watch?v=P1sDOJM65Bc](http://www.youtube.com/watch?v=P1sDOJM65Bc)
If only 30-40% of glucose is being taken up by the liver, then what happens to the rest? How the body handles the rise in blood glucose after a meal is referred to as the glycemic response. The pancreas senses the blood glucose levels and responds appropriately. After a meal, the pancreatic beta-cells sense that glucose levels are high and secrete the hormone insulin, as shown below\(^1\).

Thus, as can be seen in the following figure, blood insulin levels peak and drop with blood glucose levels over the course of a day.
Blood glucose and insulin levels rise following carbohydrate consumption, and they drop after tissues have taken up the glucose from the blood (described below). Higher than normal blood sugar levels are referred to as hyperglycemia, while lower than normal blood sugar levels are known as hypoglycemia.

Insulin travels through the bloodstream to the muscle and adipose cells. There, insulin binds to the insulin receptor. This causes GLUT4 transporters that are in vesicles inside the cell to move to the cell surface as shown below.

Figure 4.52 Representative figure of blood glucose and insulin levels during a 24-hour period
The movement of the GLUT4 to the cell surface allows glucose to enter the muscle and adipose cells. The glucose is phosphorylated to glucose-6-phosphate by hexokinase (different enzyme but same function as glucokinase in liver) to maintain gradient.

Figure 4.53 Response of muscle and adipose cells to insulin; 1) binding of insulin to its receptor, 2) movement of GLUT4 vesicles to the cell surface.

Figure 4.54 Response of muscle and adipose cells to insulin part 2; hexokinase phosphorylates glucose to glucose-6-phosphate
Glucagon is a hormone that has the opposite action of insulin. Glucagon is secreted from the alpha-cells of the pancreas when they sense that blood glucose levels are low, as shown below.

![Figure 4.55](image.png)

Glucagon binds to the glucagon receptor in the liver, which causes the breakdown of glycogen to glucose as illustrated below.
Figure 4.56 Glucagon binding to its receptor leads to the breakdown of glycogen to glucose.

This glucose is then released into circulation to raise blood glucose levels as shown below.

Figure 4.57 Glucagon leads to the release of glucose from the liver.
4.52 Glycemic Index
4.53 Glycemic Load

References & Links

47. 4.51 Diabetes

Diabetes is a condition of chronically high blood sugar levels. The prevalence of diabetes in the US has been rapidly increasing; the link below provides some statistics about prevalence.

**Web Link**

Diabetes Statistics

There are 2 forms of diabetes, type 1 and type 2.

In type 1 diabetes, not enough insulin is produced, as shown in the figure below.

![Figure 4.512 Type 1 diabetes](image)

As a result, GLUT4 does not make it to the surface of muscle and adipose cells, meaning glucose is not taken up into these cells.

Type 1 diabetes was previously known as juvenile-onset, or...
insulin-dependent diabetes and is estimated to account for 5-10% of diabetes cases\(^1\). Type 1 diabetics receive insulin through injections or pumps to manage their blood sugar.

In type 2 diabetes, the body produces enough insulin, but the person's body is resistant to it. In type 2 diabetics the binding of insulin to its receptor does not cause GLUT4 to move to the surface of the muscle and adipose cells, thus no glucose is taken up.

Type 2 diabetes accounts for 90-95% of diabetes cases and was once known as non-insulin-dependent diabetes or adult-onset diabetes\(^1\). However, with the increasing rates of obesity, many younger people are being diagnosed with type 2, making the latter definition no longer appropriate. Some people with type 2 diabetes can control their condition with a diet and exercise regimen. This regimen improves their insulin sensitivity, or their response to the body's own insulin. Others with type 2 diabetes must receive insulin. These individuals are producing enough insulin, but are so resistant
to it that more is needed for glucose to be taken up by their muscle and adipose cells.

The video below illustrates type 2 diabetes. However, I do not agree, nor do I teach, that type 2 diabetics have decreased insulin levels as described in the video.

---

**Web Link**

**Video:** Diabetes Mellitus (1:36)

**References & Links**


**Link**


**Video**

Diabetes Mellitus – [http://www.youtube.com/watch?v=VLiTbb6MaEU](http://www.youtube.com/watch?v=VLiTbb6MaEU)
48. 4.52 Glycemic Index

Research has indicated that hyperglycemia is associated with chronic diseases and obesity. As a result, measures of the glycemic response to food consumption have been developed so that people can choose foods with a smaller glycemic response. The first measure developed for this purpose was the glycemic index. The glycemic index is the relative change in blood glucose after consumption of 50 g of carbohydrate in a test food compared to 50 g of carbohydrates of a reference food (white bread or glucose). Thus, a high glycemic index food will produce a greater rise in blood glucose concentrations compared to a low glycemic index food, as shown below.

Figure 4.521 Blood glucose response to a high glycemic index (GI) food compared to a low glycemic index food

As a general guideline, a glycemic index that is 70 or greater is high, 56-69 is medium, and 55 and below is low. A stop light graphical presentation has been designed to emphasize the consumption of
the low glycemic index foods while cautioning against the consumption of too many high glycemic index foods.

Figure 4.522 Food glycemic index classifications

The main problem with the glycemic index is that it does not take into account serving sizes. Let’s take popcorn (glycemic index 89-127) as an example. A serving size of popcorn is 20 g, 11 g of which is carbohydrate. This is equal to approximately 2.5 cups of popcorn. Thus, a person would have to consume over 11 cups of popcorn to consume 50 g of carbohydrate needed for the glycemic
index measurement. Another example is watermelon, which has a glycemic index of 103, with a 120 g serving containing only 6 g of carbohydrates\(^3\). To consume the 50 g needed for glycemic index measurement, a person would need to consume over 1000 g (1 kg) of watermelon. Assuming this is all watermelon flesh (no rind), this would be over 6.5 cups of watermelon\(^4\).

The website glycemicindex.com (link provided below) contains a database where you can search to see the food's glycemic index and glycemic load (covered in the next section). The database contains detail on how the measurement was done and more information on the product itself. The top link below will take you to this website. The second link is to another database that contains the same information that might be easier for some people to use. However, please note that in the second link the glycemic loads are calculated using 100 g serving sizes for all foods. This might not be the actual serving size for all foods, which is what is typically used, so it is important to keep this in mind.

### Web Links

- glycemicindex.com
  - Glycemic Index & Glycemic Load of Foods

### References & Links

1. http://upload.wikimedia.org/wikipedia/commons/e/ec/Glycemic.png
2. www.glycemicindex.com

### Links

- Glycemicindex.com – http://www.glycemicindex.com/
- Glycemic Index & Glycemic Load of Foods – http://dietgrail.com/gid/
49. 4.53 Glycemic Load

To incorporate serving size into the calculation, another measure known as the glycemic load has been developed. It is calculated as shown below:

\[
\text{Glycemic Load} = \frac{\text{Glycemic Index} \times (\text{g Carbs/serving})}{100}
\]

Thus, for most people, the glycemic load is a more meaningful measure of the glycemic impact of different foods. Considering the two examples from the glycemic index section, their glycemic loads would be:

- Popcorn
  \[
  \frac{89-127 \times 11 \text{ g Carbs/Serving}}{100} = 10-14
  \]

- Watermelon
  \[
  \frac{103 \times 6 \text{ g Carbs/Serving}}{100} = 6.18
  \]

As a general guideline for glycemic loads of foods: 20 or above is high, 11-19 is medium, and 10 or below is low\(^1\).
Putting it all together, popcorn and watermelon have high glycemic indexes, but medium and low glycemic loads, respectively.

You can also use the top two links below to find the glycemic loads of foods. However, please note that in the second link the glycemic loads are calculated using 100g serving sizes for all foods. This might not be the actual serving size for all foods, which is what is typically used, so it is important to keep this in mind. The third link is to the NutritionData estimated glycemic load tool that is pretty good at estimating the glycemic loads of foods, even if actual glycemic indexes have not been measured.
Web Links

glycemicindex.com
Glycemic Index & Glycemic Load of Foods
Estimated Glycemic Load

References & Links


Links

Glycemicindex.com – http://www.glycemicindex.com/
Glycemic Index & Glycemic Load of Foods – http://dietgrail.com/gid/
There are a number of similarities between carbohydrate and protein uptake, absorption, transport, and uptake by the liver. Hopefully after this section you will understand these similarities.

Over 60% of all amino acids are taken up into the enterocyte as di- and tripeptides through the PepT1 transporter. Individual amino acids are taken up through a variety of amino acid transporters. Once inside the enterocyte, peptidases cleave the peptides to individual amino acids. These cleaved amino acids, along with those that were taken up as individual amino acids, are moved into the capillary by another variety of amino acid transporters (some are the same as on the brush border, some are different).

Figure 4.61 Protein uptake and absorption

The capillary inside a villus is shown below.
Like monosaccharides, amino acids are transported directly to the liver through the portal vein.
Amino acids are taken up into the hepatocyte through a variety of amino acid transporters. The amino acids can then be used to either make proteins or are broken down to produce glucose, as will be described in chapter 6.
References & Links


Videos
Absorption in the Small Intestine – http://www.youtube.com/watch?v=P1sDOJM65Bc
Once mixed micelles reach the brush border of the enterocyte, two different lipid uptake mechanisms are believed to occur, but lipid uptake is not completely understood. One mechanism is that individual components of micelles may diffuse across the enterocyte. Otherwise, it is believed that some components may be taken up through unresolved transporters. For example, cholesterol transporters have been identified, but their overall mechanism of absorption is not well understood. The individual compounds are taken up as shown below.

Figure 4.71 Uptake of mixed micelle components into the enterocyte

Once inside the enterocyte, there are different fates for fatty acids, depending on their length. Short- and medium-chain fatty acids move through the enterocyte and enter circulation through the capillaries; they are transported by the protein albumin. They will
be carried to the liver by the portal vein, like monosaccharides and amino acids. Long-chain fatty acids, 2-monoglyceride, lyssolecithin, and cholesterol will be re-esterified forming triglycerides, phosphatidylcholine, and cholesterol esters, respectively. These re-esterified lipids are then packaged into chylomicrons, which are lipoproteins, that are described in further detail in the next section. These chylomicrons are too large to fit through the pores in the capillaries, but they can fit through the larger fenestrations (openings) in the lacteal.

Figure 4.72 Fates of lipids in the enterocyte

Lacteals (shown below) are small vessels that feed into the lymphatic system. Thus, the chylomicrons enter the lacteals and enter into lymphatic circulation.
The lymphatic system is a system similar to the circulatory system in that it contains vessels that transport fluid. However, instead of blood, the lymphatic system contains a clear fluid known as lymph. There are a number of lymph nodes (small glands) within the lymphatic system that play a key role in the body’s immune system. The figure below shows the lymphatic system.

Figure 4.73 Anatomy of a villus, with the lacteal shown in blue

The lymphatic system is a system similar to the circulatory system in that it contains vessels that transport fluid. However, instead of blood, the lymphatic system contains a clear fluid known as lymph. There are a number of lymph nodes (small glands) within the lymphatic system that play a key role in the body’s immune system. The figure below shows the lymphatic system.
Figure 4.74 The lymphatic system

- Tonsil
- Thymus Gland
- Spleen
- Lymph Nodes
- Lymphatic Vessels
The following videos describe and illustrate how the lymphatic system and lymph functions.

**Web Links**

*Video: Lymphatic System (0:49)*
*Video: Lymph Movement (0:44)*

The lymphatic system enters general circulation through the thoracic duct that enters the left subclavian vein as shown below. General in this case means that it is not directed to the liver like other components that have been absorbed.

![Thoracic Duct](image)

*Figure 4.75 The thoracic duct is where the lymphatic system enters circulation.*
The animation below is an overview of lipid digestion, uptake, and initial transport.

Web Links

Animation: Lipid Digestion, Uptake, and Transport

Subsection:
4.71 Lipoproteins

References & Links

Link
http://www.wiley.com/college/grosvenor/0470197587/animations/Animation_Lipid_Digestion_and_Absorption/Energy/media/content/dig/anima/dig5a/frameset.htm

Videos
Lymphatic system – http://www.youtube.com/watch?v=qTXTDqvPnRk
Lymph Movement – https://www.youtube.com/watch?v=ZdYxx4CHb-A
52. 4.71 Lipoproteins

Lipoproteins, as the name suggests, are complexes of lipids and protein. The proteins within a lipoprotein are called apolipoproteins (aka apoproteins). There are a number of different apolipoproteins that are abbreviated apo-, then an identifying letter (i.e. Apo A) as shown in the chylomicron below.

The following video does a nice job of illustrating the different lipoprotein components.

**Web Link**

Video: Lipoproteins (0:28)
There are a number of lipoproteins in the body. They differ by the apolipoproteins they contain, size (diameter), density, and composition. The table below shows the difference in density and diameter of different lipoproteins. Notice that as diameter decreases, density increases.

Table 4.711 The density and diameter of different lipoproteins

<table>
<thead>
<tr>
<th>Lipoprotein</th>
<th>Density (g/dL)</th>
<th>Diameter (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chylomicrons</td>
<td>0.95</td>
<td>75-1200</td>
</tr>
<tr>
<td>VLDL (very low-density lipoproteins)</td>
<td>0.95-1.006</td>
<td>30-80</td>
</tr>
<tr>
<td>IDL (intermediate-density lipoproteins)</td>
<td>1.006-1.019</td>
<td>25-35</td>
</tr>
<tr>
<td>LDL (low-density lipoproteins)</td>
<td>1.019-1.063</td>
<td>18-25</td>
</tr>
<tr>
<td>HDL (high-density lipoproteins)</td>
<td>1.063-1.21</td>
<td>5-12</td>
</tr>
</tbody>
</table>

This inverse relationship is a result of the larger lipoproteins being composed of a higher percentage of triglyceride and a lower percentage of protein as shown below.

![Figure 4.712 Composition of lipoproteins](image)

Protein is more dense than triglyceride (why muscle weighs more...
than fat), thus the higher protein/lower triglyceride composition, the higher the density of the lipoprotein. Many of the lipoproteins are named based on their densities (i.e. very low-density lipoproteins).

As described in the last subsection, the lipoproteins released from the small intestine are chylomicrons. The video below does a nice job of showing, describing, and illustrating how chylomicrons are constructed and function.

**Web Link**

**Video: Chylomicrons (0:55)**

The endothelial cells that line blood vessels, especially in the muscle and adipose tissue, contain the enzyme lipoprotein lipase (LPL). LPL cleaves the fatty acids from lipoprotein triglycerides so that the fatty acids can be taken up into tissues. The figure below illustrates how endothelial cells are in contact with the blood that flows through the lumen of blood vessels.

*Figure 4.713 Lining of a blood vessel. The lumen is where the blood would be flowing, thus endothelial cells are those that are in contact with blood*  

224 | 4.71 Lipoproteins
LPL cleaves fatty acids from the triglycerides in the chylomicron, decreasing the amount of triglyceride in the lipoprotein. This lipoprotein with less triglycerides becomes what is known as a chylomicron remnant, as shown below.

Figure 4.714 The cleavage of triglycerides by LPL from a chylomicron leads to the formation of a chylomicron remnant.

Now in the form of a chylomicron remnant, the digested lipid components originally packaged into the chylomicron are directed to the liver where the chylomicron remnant is endocytosed. This process of clearing chylomicrons from the blood takes 2-10 hours after a meal. This is why people must fast 12 hours before having their blood lipids (triglycerides, HDL, LDL etc.) measured. This fast allows all the chylomicrons and chylomicron remnants to be cleared before blood is taken. However, whether patients should be asked to fast has been questioned as described in the link below.

Web Link
Should you fast before a cholesterol test?

After the chylomicron remnant is endocytosed, it is broken down to its individual components (triglycerides, cholesterol, protein etc.). In the liver, VLDL are produced, similar to how chylomicrons
are produced in the small intestine. The individual components are packaged into VLDL and secreted into circulation as shown below.

Like it does to chylomicrons, LPL cleaves fatty acids from triglycerides in VLDL, forming the smaller IDL (aka VLDL remnant). Further action of LPL on IDL results in the formation of LDL. The C in Figures 4.715 and 4.716 represents cholesterol, which is not increasing; rather, since triglyceride is being removed, it constitutes a greater percentage of particle mass of lipoproteins. As a result, LDL is composed mostly of cholesterol, as depicted in the figure below.
LDL contains a specific apolipoprotein (Apo B100) that binds to LDL receptors on the surface of target tissues. The LDL are then endocytosed into the target tissue and broken down to cholesterol and amino acids.

HDL are made up of mostly protein and are derived from the liver and intestine. HDL participates in reverse cholesterol transport, which is the transport of cholesterol back to the liver. HDL picks up cholesterol from tissues/blood vessels and returns it to the liver itself or transfers it to other lipoproteins returning to the liver.
Figure 4.71 HDL is involved in reverse cholesterol transport

The animation under the transport button in the following link does a really nice job of going through the process of lipoprotein transport.

**Web Link**

[Lipoprotein Animation](#)

You are probably familiar with HDL and LDL being referred to as “good cholesterol” and “bad cholesterol,” respectively. This is an oversimplification to help the public interpret their blood lipid values, because cholesterol is cholesterol; it’s not good or bad. LDL and HDL are lipoproteins, and as a result you can’t consume good or bad cholesterol, you consume cholesterol. A more appropriate descriptor for these lipoproteins would be HDL “good cholesterol transporter” and LDL “bad cholesterol transporter.”

What’s so bad about LDL? LDL enters the endothelium where it is oxidized. This oxidized LDL is engulfed by white blood cells
(macrophages), leading to the formation of what are known as foam cells. The foam cells eventually accumulate so much LDL that they die and accumulate, forming a fatty streak. From there the fatty streak, which is the beginning stages of a lesion, can continue to grow until it blocks the artery. This can result in a myocardial infarction (heart attack) or a stroke. HDL is good in that it scavenges cholesterol from other lipoproteins or cells and returns it to the liver. The figure below shows the formation of the fatty streak and how this can progress to a point where it greatly alters blood flow.

Figure 4.718 The formation of a lesion in an artery

4.71 Lipoproteins | 229
The video below does an excellent job of illustrating this process. However there are two caveats to point out. First, it incorrectly refers to cholesterol (LDL-C etc.), and second, it is clearly made by a drug company, so keep these factors in mind. The link below is the American Heart Association’s simple animation of how atherosclerosis develops.

**Web Link**

**Video: Atherosclerosis (5:36)**

**Cholesterol and CAD**

The following video gives a general overview of macronutrient digestion, uptake, and absorption.

**Web Link**

**Video: Small Intestine (1:29)**

**References & Links**


**Links**

Ask Well: Should you fast before a cholesterol test –
http://well.blogs.nytimes.com/2016/05/24/ask-well-should-you-fast-before-a-cholesterol-test/

Lipoprotein Animation – http://www.wiley.com/legacy/college/boyer/0470003790/animations/cholesterol/cholesterol.swf
Cholesterol and CAD – http://watchlearnlive.heart.org/CVML_Player.php?moduleSelect=chlcad
Study Questions Fat and Heart Disease Link – http://well.blogs.nytimes.com/2014/03/17/study-questions-fat-and-heart-disease-link/

Videos
Lipoproteins – https://www.youtube.com/watch?v=x-4ZQaiZry8
Chylomicrons – http://www.youtube.com/watch?v=hRx_i9npTDU
LDL Receptor – http://www.youtube.com/watch?v=XPguYN7dcbE
Atherosclerosis – http://www.youtube.com/watch?v=fLonh7ZesKs&feature=rec-HM-r2
Small Intestine – http://www.youtube.com/watch?v=P1sDOJMO65Bc
PART IV
CHAPTER 3
53. 3 Macronutrient Digestion

You probably do not think too much about what actually happens to the food you eat. This section will describe in depth how what you eat is digested. The desired end result for the learner will be an integrated understanding of the process. This will require higher levels of thinking, but will prove to be well worth it in the end.

Sections:
3.1 Digestion at a Glance
3.2 Mouth to the Stomach
3.3 Stomach
3.4 Small Intestine
3.5 Macronutrient Digestion Review
3.6 Large Intestine

No References
Digestion is the process of breaking down food to be absorbed or excreted. The gastrointestinal (GI, digestive) tract, the passage through which our food travels, is a “tube within a tube.” The trunk of our body is the outer tube and the GI tract is the interior tube, as shown below. Thus, even though the GI tract is within the body, the actual interior of the tract is technically outside of the body. This is because the contents have to be absorbed into the body. If it’s not absorbed, it will be excreted and never enter the body.

A number of organs are involved in digestion, which collectively are referred to as the digestive system.
The organs that form the gastrointestinal tract (mouth, esophagus, stomach, small intestine, large intestine (aka colon), rectum, and anus) come into direct contact with the food or digestive content.
The journey through the gastrointestinal tract starts in the mouth and ends in the anus as shown below:

Mouth -> Esophagus -> Stomach -> Small Intestine -> Large Intestine -> Rectum -> Anus

In addition to the GI tract, there are digestion accessory organs (salivary glands, pancreas, gallbladder, and liver) that play an integral role in digestion. The accessory organs do not come directly in contact with food or digestive content.
There are a number of enzymes that are involved in digestion. We will go through each one in detail, but this table should help give an overview of which enzymes are active at each location of the GI tract.

Table 3.11 Digestive enzymes
<table>
<thead>
<tr>
<th>Location</th>
<th>Enzyme/Coenzyme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouth</td>
<td>Salivary amylase</td>
</tr>
<tr>
<td></td>
<td>Lingual lipase</td>
</tr>
<tr>
<td></td>
<td>Pepsin</td>
</tr>
<tr>
<td>Stomach</td>
<td>Gastric lipase</td>
</tr>
<tr>
<td></td>
<td>Pancreatic alpha-amylase</td>
</tr>
<tr>
<td></td>
<td>Brush border disaccharidases</td>
</tr>
<tr>
<td></td>
<td>Pancreatic lipase</td>
</tr>
<tr>
<td>Small Intestine</td>
<td>Colipase</td>
</tr>
<tr>
<td></td>
<td>Phospholipase-A2</td>
</tr>
<tr>
<td></td>
<td>Cholesterol esterase</td>
</tr>
<tr>
<td></td>
<td>Proteases</td>
</tr>
<tr>
<td></td>
<td>Brush border peptidases</td>
</tr>
</tbody>
</table>

**References & Links**


**Video**

Enzymes and Digestion – [http://www.youtube.com/watch?v=bNMsNHqxszc](http://www.youtube.com/watch?v=bNMsNHqxszc)
55. 3.2 Mouth to the Stomach

Digestion begins in the mouth, both mechanically and chemically. Mechanical digestion is called mastication, or the chewing and grinding of food into smaller pieces. The salivary glands release saliva, mucus, and the enzymes, salivary amylase and lysozyme.

![The mouth](image)

**Figure 3.21 The mouth**

Salivary amylase cleaves the alpha 1-4 glycosidic bonds in the starch molecules, amylose and amylopectin. However, salivary amylase cannot cleave the branch points in amylopectin where there are alpha 1-6 glycosidic bonds, as shown in the figure below. Overall this enzyme accounts for a minor amount of carbohydrate digestion.
Lysozyme helps break down bacteria cell walls to prevent a possible infection. Another enzyme, lingual lipase, is also released in the mouth. Although it is released in the mouth, it is most active in the stomach where it preferentially cleaves short-chain fatty acids in the sn-3 position. Lingual lipase has a small role in digestion in adults, but may be important for infants to help break down triglycerides in breast milk.

**Swallowing**

Now that the food has been thoroughly chewed and formed into a bolus, it can proceed down the throat to the next stop in digestion. It will move down the pharynx where it reaches a “fork in the road”, with the larynx as one road and the esophagus as the other. The esophagus road leads to the stomach; this is the direction that food should go. The other road, through the larynx, leads to the trachea and ultimately the lungs. This is definitely not where you want your food or drink going, as this is the pathway for the air you breathe.
Fortunately, our body was designed in such a way that a small tissue, called the epiglottis, covers the opening to the trachea. It directs the food down the correct road as shown below.
Esophagus

Before being correctly guided into the esophagus, the bolus of food will travel through the upper esophageal sphincter. Sphincters are circular muscles that are found throughout the gastrointestinal tract that essentially serve as gates between the different sections. Once in the esophagus, wavelike muscular movements, known as peristalsis, occur, as shown in the animation and video in the links below.

Web Links

Peristalsis Animation
  Video: Peristalsis (0:57)

At the end of the esophagus the bolus will encounter the lower esophageal sphincter. This sphincter keeps the harmful acids of the stomach out of the esophagus. However, in many people this sphincter is leaky, which allows stomach acid to reflux, or creep up, the esophagus. Stomach acid is very acidic (has a low pH). The ruler below will give you an idea of just how acidic the stomach is. Notice that the pH of gastric (term used to describe the stomach) fluid is lower (more acidic) than any of the listed items besides battery acid.
The leaking of the very acidic gastric contents results in a burning sensation, commonly referred to as “heartburn.” If this occurs more than twice per week and is severe, the person may have gastroesophageal reflux disease (GERD). The following videos explain more about these conditions.

**Web Links**

Video: Acid Reflux (1:28)
Video: GERD 101 (0.55)

Table 3.21 Review of Chemical Digestion in the Mouth
<table>
<thead>
<tr>
<th>Macronutrient</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates</td>
<td>Salivary amylase cleaves 1,4-glycosidic bonds</td>
</tr>
<tr>
<td>Lipids</td>
<td>Release of lingual lipase</td>
</tr>
<tr>
<td>Protein</td>
<td>None</td>
</tr>
</tbody>
</table>

**References & Links**


**Link**


**Videos**

Peristalsis Animation – [http://www.youtube.com/watch?v=o18UycWRsaA](http://www.youtube.com/watch?v=o18UycWRsaA)

Acid Reflux – [https://www.youtube.com/watch?v=SW-QfyDSY5I](https://www.youtube.com/watch?v=SW-QfyDSY5I)

After going through the lower esophageal sphincter, food enters the stomach. Our stomach is involved in both chemical and mechanical digestion. Mechanical digestion occurs as the stomach churns and grinds food into a semisolid substance called chyme (partially digested food).

The lining of the stomach is made up of different layers of tissue. The mucosa is the outermost layer (closest to stomach cavity) as shown in the figure below.

The mucosa is not a flat surface. Instead, its surface is lined by gastric pits, as shown in the figure below.
Gastric pits are indentations in the stomach's surface that are lined by four different types of cells.
The following video is a nice introduction to gastric pits and talks about chief and parietal cells that are covered in more detail below.

**Web Link**

*Video: Gastric Pits (0:56)*

At the bottom of the gastric pit are the G cells that secrete the hormone gastrin. Gastrin stimulates the parietal and chief cells that are found above the G cells. The chief cells secrete the zymogen pepsinogen and the enzyme gastric lipase. A zymogen is an inactive precursor of an enzyme that must be cleaved or altered to form the active enzyme. The parietal cells secrete hydrochloric acid (HCl), which lowers the pH of the gastric juice (water + enzymes + acid). The HCl inactivates salivary amylase and catalyzes the conversion of pepsinogen to pepsin. Finally, the top of the pits are the neck cells that secrete mucus to prevent the gastric juice from digesting or damaging the stomach mucosa. The table below summarizes the actions of the different cells in the gastric pits.
Table 3.41 Cells involved in the digestive processes in the stomach

<table>
<thead>
<tr>
<th>Type of Cell</th>
<th>Secrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
<td>Mucus</td>
</tr>
<tr>
<td>Chief</td>
<td>Pepsinogen and gastric lipase</td>
</tr>
<tr>
<td>Parietal</td>
<td>HCl</td>
</tr>
<tr>
<td>G</td>
<td>Gastrin</td>
</tr>
</tbody>
</table>

The figure below shows the action of all these different secretions in the stomach.

![Figure 3.34 The action of gastric secretions in the stomach](image)

To reiterate, the figure above illustrates that the neck cells of the gastric pits secrete mucus to protect the mucosa of the stomach from essentially digesting itself. Gastrin from the G cells stimulates the parietal and chief cells to secrete HCl and enzymes, respectively.

The HCl in the stomach denatures salivary amylase and other proteins by breaking down the structure and, thus, the function of it. HCl also converts pepsinogen to the active enzyme pepsin. Pepsin is a protease, meaning that it cleaves bonds in proteins. It breaks down the proteins in food into individual peptides (shorter...
segments of amino acids). The other enzyme that is active in the stomach is gastric lipase. This enzyme preferentially cleaves the sn-3 position of triglycerides to produce 1,2-diglyceride and a free fatty acid, as shown below. It is responsible for up to 20% of triglyceride digestion.

Figure 3.35 Gastric Lipase action results in production of 1,2-diglyceride and a free fatty acid

The chyme will then leave the stomach and enter the small intestine via the pyloric sphincter (shown below).

Figure 3.36 Cross section of the stomach showing the pyloric sphincter
Table 3.32 Summary of chemical digestion in the stomach

<table>
<thead>
<tr>
<th>Chemical or Enzyme</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrin</td>
<td>Stimulates chief cells to release pepsinogen</td>
</tr>
<tr>
<td></td>
<td>Stimulates parietal cells to release HCl</td>
</tr>
<tr>
<td></td>
<td>Denatures salivary amylase</td>
</tr>
<tr>
<td>HCl</td>
<td>Denatures proteins</td>
</tr>
<tr>
<td></td>
<td>Activates pepsinogen to pepsin</td>
</tr>
<tr>
<td>Pepsin</td>
<td>Cleaves proteins to peptides</td>
</tr>
<tr>
<td>Gastric lipase</td>
<td>Cleaves sn-3 FA of triglycerides</td>
</tr>
</tbody>
</table>

References & Links

Video
Gastric Pits – http://www.youtube.com/watch?v=6hquzCXYINg
The small intestine is the primary site of digestion. It is divided into three sections: the duodenum, jejunum, and ileum (shown below). After leaving the stomach, the first part of the small intestine that chyme will encounter is the duodenum.

![Figure 3.41 Three sections of the small intestine](image)

The small intestine consists of many layers, which can be seen in the cross section below.
Examining these layers closer, we are going to focus on the epithelium, which comes into contact with the chyme and is responsible for absorption. The lumen is the name of the cavity that is considered “outside the body” that chyme moves through.
The organization of the small intestine is in such a way that it contains circular folds and finger-like projections known as villi. The folds and villi are shown in the next few figures.
If we were to zoom in even closer, we would be able to see that enterocytes (small intestine absorptive cells) line villi as shown below.
The side, or membrane, of the enterocyte that faces the lumen is not smooth either. It is lined with microvilli, and is known as the brush border (aka apical) membrane, as shown below.
Figure 3.48 Enterocyte, or small intestinal absorptive cell is lined with microvilli. This lined surface is referred to as the brush border membrane.

Together these features (folds + villi + microvilli) increase the surface area ~600 times versus if it was a smooth tube. More surface area leads to more contact with the enterocytes and thus, increased absorption.

Going even closer, we discover that the surface of the microvilli is covered by the hair-like glycocalyx, which is glycoproteins and carbohydrates as shown below.
Now that you have learned about the anatomy of the small intestine, the following subsections go through the different digestive processes that occur there.

Subsections:
3.41 Digestive Hormones, Accessory Organs, & Secretions
3.42 Carbohydrate Digestion in the Small Intestine
3.43 Protein Digestion in the Small Intestine
3.44 Lipid Digestion in the Small Intestine

References & Links
1. http://commons.wikimedia.org/wiki/Image:Illu_small_intestine_catal%C3%A0.png
Before we go into the digestive details of the small intestine, it is important that you have a basic understanding of the anatomy and physiology of the following digestion accessory organs: pancreas, liver, and gallbladder. Digestion accessory organs assist in digestion, but are not part of the gastrointestinal tract. How are these organs involved?

Upon entering the duodenum, the chyme causes the release of two hormones from the small intestine: secretin and cholecystokinin (CCK, previously known as pancreozymin) in response to acid and fat, respectively. These hormones have multiple effects on different tissues. In the pancreas, secretin stimulates the secretion of bicarbonate (HCO\textsubscript{3}), while CCK stimulates the secretion of digestive enzymes. The bicarbonate and digestive enzymes released together are collectively known as pancreatic juice, which travels to the small intestine, as shown below.
In addition, CCK also stimulates the contraction of the gallbladder causing the secretion of bile into the duodenum.

**Pancreas**

The pancreas is found behind the stomach and has two different portions. It has an endocrine (hormone-producing) portion that contains alpha and beta cells that secrete the hormones glucagon and insulin, respectively. However, the vast majority of the pancreas is made up of acini, or acinar cells, that are responsible for producing pancreatic juice. The following video does a nice job of showing and explaining the function of the different pancreatic cells.

**Web Link**

Video: The Pancreas (First 53 seconds)

Bicarbonate is a base (high pH) meaning that it can help neutralize
acids. You can find sodium bicarbonate (NaHCO₃, baking soda) on the ruler below to get an idea of its pH.

![Figure 3.4.12 pH of some common items](image)

The main digestive enzymes in pancreatic juice are listed in the table below. Their function will be discussed further in later subsections.

Table 3.4.11 Enzymes in pancreatic juice
Enzyme
Pancreatic alpha-amylase
Proteases
Pancreatic Lipase & Procolipase*
Phospholipase A2
Cholesterol Esterase

*Not an enzyme

Liver
The liver is the largest internal and most metabolically active organ in the body. The figure below shows the liver and the accessory organs position relative to the stomach.

![Liver and accessory organs](image)

*Figure 3.413 Location of digestion accessory organs relative to the stomach*

The liver is made up two major types of cells. The primary liver cells are hepatocytes, which carry out most of the liver’s functions. Hepatic is another term for liver. For example, if you are going to refer to liver concentrations of a certain nutrient, these are often reported as hepatic concentrations. The other major cell type is the hepatic stellate (also known as Ito) cells. These are fat storing cells in the liver. These two cell types are depicted below.
The liver’s major role in digestion is to produce bile. This is a greenish-yellow fluid that is composed primarily of bile acids, but also contains cholesterol, phospholipids, and the pigments bilirubin and biliverdin. Bile acids are synthesized from cholesterol. The two primary bile acids are chenodeoxycholic acid and cholic acid. In the same way that fatty acids are found in the form of salts, these bile acids can also be found as salts. These salts have an (–ate) ending, as shown below.
Bile acids, much like phospholipids, have a hydrophobic and hydrophilic end. This makes them excellent emulsifiers that are instrumental in fat digestion. Bile is then transported to the gallbladder.

**Gallbladder**

The gallbladder is a small, sac-like organ found just off the liver (see figures above). Its primary function is to store and concentrate bile made by the liver. The bile is then transported to the duodenum through the common bile duct.

**Why do we need bile?**

Bile is important because fat is hydrophobic and the environment in the lumen of the small intestine is watery. In addition, there is an unstirred water layer that fat must cross to reach the enterocytes in order to be absorbed.
Fat is hydrophobic, and it is in a watery environment

Figure 3.416 Fat is not happy alone in the watery environment of the small intestine.

Here triglycerides form large triglyceride droplets to keep the interaction with the watery environment to a minimum. This is inefficient for digestion, because enzymes cannot access the interior of the droplet. Bile acts as an emulsifier, or detergent. It, along with phospholipids, forms smaller triglyceride droplets that increase the surface area that is accessible for triglyceride digestion enzymes, as shown below.
Bile acids and phospholipids facilitate the production of smaller triglyceride droplets.

Secretin and CCK also control the production and secretion of bile. Secretin stimulates the flow of bile from the liver to the gallbladder. CCK stimulates the gallbladder to contract, causing bile to be secreted into the duodenum, as shown below.
Figure 3.418 Secretion stimulates bile flow from liver; CCK stimulates the gallbladder to contract.

References & Links
4. http://www.comparative-hepatology.com/content/6/1/7

Video
The Pancreas - http://www.youtube.com/watch?v=j5WF8wUFNkI
59. 3.42 Carbohydrate Digestion in the Small Intestine

The small intestine is the primary site of carbohydrate digestion. Pancreatic alpha-amylase is the primary carbohydrate digesting enzyme. Pancreatic alpha-amylase, like salivary amylase, cleaves the alpha 1-4 glycosidic bonds of carbohydrates, reducing them to simpler carbohydrates, such as glucose, maltose, maltotriose, and dextrins (oligosaccharides containing 1 or more alpha 1-6 glycosidic bonds). Pancreatic amylase is also unable to cleave the branch point alpha 1-6 bonds.

1-4 α glycosidic bonds

Glycoside = sugar

Amylose – All α 1-4 glycosidic bonds

1-4 α glycosidic bonds

Branch points are α 1-6 glycosidic bonds, amylase can’t cleave

Figure 3.421 The function of pancreatic amylase
The pancreatic amylase products, along with the disaccharides sucrose and lactose, then move to the surface of the enterocyte. Here, there are disaccharidase enzymes (lactase, sucrase, maltase) on the outside of the enterocyte. Enzymes, like these, that are on the outside of cell walls are referred to as ectoenzymes. Individual monosaccharides are formed when lactase cleaves lactose, sucrase cleaves sucrose, and maltase cleaves maltose. There is also another brush border enzyme, alpha-dextrinase. This enzyme cleaves alpha 1-6 glycosidic bonds in dextrins, primarily the branch point bonds in amylopectin. The products from these brush border enzymes are the single monosaccharides glucose, fructose, and galactose that are ready for absorption into the enterocyte.
References & Links

3.43 Protein Digestion in the Small Intestine

The small intestine is the major site of protein digestion by proteases (enzymes that cleave proteins). The pancreas secretes a number of proteases as zymogens into the duodenum where they must be activated before they can cleave peptide bonds. This activation occurs through an activation cascade. A cascade is a series of reactions in which one step activates the next in a sequence that results in an amplification of the response. An example of a cascade is shown below.

![Figure 3.431 An example of a cascade, with one event leading to many more events](image)

---

272 | 3.43 Protein Digestion in the Small Intestine
In this example, A activates B, B activates C, D, and E, C activates F and G, D activates H and I, and E activates K and L. Cascades also help to serve as control points for certain processes. In the protease cascade, the activation of B is really important because it starts the cascade.

The protease/colipase activation scheme starts with the enzyme enteropeptidase (secreted from the intestinal brush border) that converts trypsinogen to trypsin. Trypsin can activate all the proteases (including itself) and colipase (involved in fat digestion) as shown in the 2 figures below.

Figure 3.432 Protease/colipase activation cascade
The protease/colipase activation cascade

The products of the action of the proteases on proteins are dipeptides, tripeptides, and individual amino acids, as shown below.

At the brush border, much like disaccharidases, there are peptidases that cleave some peptides down to amino acids. Not all peptides are cleaved to individual amino acid, because small peptides can be taken up into the enterocyte, thus, the peptides do not need
to be completely broken down to individual amino acids. Thus the end products of protein digestion are primarily dipeptides and tripeptides, along with individual amino acids\(^1\).

Figure 3.435 Peptidases are produced by the brush border to cleave some peptides into amino acids

References & Links

The small intestine is the major site for lipid digestion. There are specific enzymes for the digestion of triglycerides, phospholipids, and cleavage of esters from cholesterol. We will look at each in this section.

**Triglycerides**

The pancreas secretes pancreatic lipase into the duodenum as part of pancreatic juice. This major triglyceride digestion enzyme preferentially cleaves the sn-1 and sn-3 fatty acids from triglycerides. This cleavage results in the formation of a 2-monoglyceride and two free fatty acids as shown below.

![Figure 3.441 Pancreatic lipase cleaves the sn-1 and sn-3 fatty acids of triglycerides](image-url)
Figure 3.442 The products of pancreatic lipase are a 2-monoglyceride and two free fatty acids

To assist lipase, colipase serves as an anchor point to help lipase attach to the triglyceride droplet.
Figure 3.443 Colipase helps anchor lipase to the triglyceride droplet

**Phospholipids**

The enzyme phospholipase A2 cleaves the C-2 fatty acid of lecithin, producing lysolecithin and a free fatty acid.

Figure 3.444 Phospholipase A2 cleaves the C-2 fatty acid of lecithin
Cholesterol Esters

The fatty acid in cholesterol esters is cleaved by the enzyme, cholesterol esterase, producing cholesterol and a free fatty acid.
Figure 3.446 Cholesterol esterase cleaves fatty acids off of cholesterol

Figure 3.447 Products of cholesterol esterase

280 | 3.44 Lipid Digestion in the Small Intestine
**Formation of Mixed Micelles**

If nothing else happened at this point, the 2-monoglycerides and fatty acids produced by pancreatic lipase would form micelles. The hydrophilic heads would be outward and the fatty acids would be buried on the interior. These micelles are not sufficiently water-soluble to cross the unstirred water layer to get to the brush border of enterocytes. Thus, mixed micelles are formed containing cholesterol, bile acids, and lysolecithin in addition to the 2-monoglycerides and fatty acids, as illustrated below.

![Figure 3.448 Normal (left) and mixed (right) micelles](image)

Mixed micelles are more water-soluble, allowing them to cross the unstirred water layer to the brush border of enterocytes for absorption.
Mixed micelles can cross the unstirred water layer for absorption into the enterocytes.

References & Links
62. 3.5 Macronutrient Digestion Review

The following figures review the digestion of the different macronutrients.

**Carbohydrate Digestion**

![Figure 3.51 Review of carbohydrate digestion](image)

**Protein Digestion**
Lipid Digestion

Lingual Lipase released, minor amount of digestion in stomach

CCK (duodenum) stimulates gall bladder contraction, bile release into duodenum

Gastrin stimulates gastric lipase release, cleaves sn-3 FAs

Liver produces bile, sends to gall bladder in response to secretin (duodenum)

Pancreatic lipase (sn-3 & sn-1) & procolipase (trypsin cleaves) are released from pancreas in response to CCK (duodenum), major site of digestion

Figure 3.53 Review of triglyceride digestion

Cholesterol Ester and Phospholipid Digestion
After digestion, the products below are ready for uptake into the enterocyte.

Figure 3.55 Macronutrient digestion products ready for uptake into the enterocyte

References & Links
63. 3.6 The Large Intestine

We have reached a fork in the road. We could follow the uptake of the digested compounds into the enterocyte or we could finish following what has escaped digestion and is going to continue into the large intestine. Obviously from the title of this section we are going to do the latter. As we learned previously, fiber is a crude term for what has survived digestion and has reached the large intestine.

The ileocecal valve is the sphincter between the ileum and the large intestine. This name should make more sense as we go through the anatomy of the large intestine.
The large intestine consists of the colon, the rectum, and the anus. The colon can be further divided into the cecum (hence the -cecal in ileocecal valve, ileo- refers to ileum), ascending colon, transverse colon, descending colon, and sigmoid colon as shown below.
The large intestine is responsible for absorbing remaining water and electrolytes (sodium, potassium, and chloride). It also forms and excretes feces. The large intestine contains large amounts of microorganisms like those shown in the figure below.
The large intestine can also be referred to as the gut. There are a large number of microorganisms found throughout the gastrointestinal tract that collectively are referred to as the flora, microflora, biota, or microbiota. Technically, microbiota is the preferred term because flora means “pertaining to plants”. There are 10 times more microorganisms in the gastrointestinal tract than cells in the whole human body. As can be seen in the figure below, the density of microorganisms increases as you move down the digestive tract.
As described in the fiber sections, there are two different fates for fiber once it reaches the large intestine. The fermentable, viscous fiber is fermented by bacteria. Fermentation is the metabolism of compounds by the microorganisms in the gut. An example of fermentation is the utilization of the oligosaccharides raffinose and stachyose by microorganisms that results in the production of gas, which can lead to flatulence. Also, some bile acids are fermented by microorganisms to form secondary bile acids that can be reabsorbed. These secondary bile acids represent approximately 20% of the total bile acids in our body. Fermentable fibers can be used to form short-chain fatty acids that can then be absorbed and used by the body. The non-fermentable, non-viscous fiber is not really altered and will be a component of feces, that is then excreted through the rectum and anus. This process involves both an internal and external sphincter that are shown in figure 3.63 above.

Subsection:
3.61 Probiotics & Prebiotics
**References & Links**

Recently there has been increased attention given to the potential of a person’s microbiota to impact health. This is because there are beneficial and non-beneficial bacteria inhabiting our gastrointestinal tracts. Thus, theoretically, if you can increase the beneficial or decrease the non-beneficial bacteria, there may be improved health outcomes. In response to this, probiotics and prebiotics have been identified/developed. A probiotic is a live microorganism that is consumed, and colonizes in the body as shown in the figures below.

A prebiotic is a nondigestible food component that selectively stimulates the growth of beneficial intestinal bacteria. An example of a prebiotic is inulin, which is shown in the figure below.
Figure 3.612 Inulin, an indigestible food component that is a commonly used prebiotic

The net result is the same for both prebiotics and probiotics, an increase in the beneficial/non beneficial microorganism ratio.

Figure 3.613 An effective prebiotic or probiotic should result in an increase in the beneficial bacteria
The following video does a nice job of explaining and illustrating how probiotics work. The NCCAM website is a good source of information if you have further questions on the topic.

---

**Web Links**

- Video: Probiotics (3:40)
- NCCAM: Probiotics

---

Some common examples of probiotics are DanActive® and Activia®.

---

**Web Links**

- DanActive®
- Activia®

---

The claims that companies made about their produce probiotic products have come under scrutiny. Dannon settled with the US Federal Trade Commission to drop claims that its probiotic products will help prevent colds or alleviate digestive problems, as seen in the top link below. General Mills also settled a lawsuit that accused them of a falsely advertising the digestive benefits of Yo-Plus a product it no longer sells, as seen in the second link.

---

**Web Link**

- New Campaign Markets Activia to Wider Audience
  - General Mills Settles Yo-Plus Lawsuit

---

Some examples of prebiotics include inulin, other fructose-containing oligosaccharides and polysaccharides, and resistant starch. Inulin is a polysaccharide that contains mainly fructoses that are joined by beta-bonds, which allows them to survive digestion. The structure of inulin is shown below.
Resistant starch is so named because it is a starch that is resistant to digestion. As a result, it arrives in the colon to be fermented.

**References & Links**


**Links**

- DanActive® – http://www.danactive.com/
- Activia® – http://www.activia.us.com/
General Mills Settles Yo-Plus Lawsuit –
http://www.foodbusinessnews.net/articles/news_home/
Site_News/2013/02/General_Mills_settles_Yo-
Plus.aspx?ID={40F62478-1AA4-49DF-9330-E41E19E946D0}&cck=1

**Video**

Probiotics – http://www.youtube.com/
watch?v=2k8Puxz54FQ&NR=1
65. 5.5 Celiac Disease & Gluten

1 out of every 133 people in the United States has celiac disease. People with celiac disease cannot consume the protein gluten because it causes their body to generate an autoimmune response (immune cells attack the body’s own cells) that causes damage to the villi in the intestine, as shown below.

**Upper Jejunal Mucosal Immunopathology**

![Figure 5.51 Different stages of celiac disease](image)

This damage to the villi impairs the absorption of macronutrients and micronutrients from food.

There are a variety of symptoms for celiac disease that vary depending on age and from person to person. For a listing of all symptoms, see the first link below. The second link describes the difficulty in diagnosing this disease, which is reinforced by the the third video link.

---

**Web Link**

What are the symptoms of celiac disease?  
Celiac Disease, a Common, but Elusive, Diagnosis  
Video: Celiac’s Disease (2:00)
What is gluten?
Gluten is a protein that is bound to starch in the endosperm of grains such as:

- Wheat
- Barley
- Rye
- Triticale
Figure 5.51 Parts of a wheat granule\textsuperscript{3}

The video below does a nice job of providing some more information about this disease.
Gluten-free diets have been increasing in popularity even for people who don't have celiac disease. The thinking among those consuming these diets is that they might be gluten-sensitive, meaning that they experience adverse effects from consuming it. However, as the following videos describes, there is not much evidence to support people being gluten-sensitive.

Web Link

Is Gluten-Sensitivity Real? (3:11)

References & Links

Links
The gluten-free diet: some examples – http://digestive.niddk.nih.gov/ddiseases/pubs/celiac/#symptoms

Videos
Is Gluten-Sensitivity Real? – https://www.youtube.com/watch?v=EXON2IV0v4o
Approximately 10% of people under 40, and 50% of people over 60 years old have a condition known as diverticulosis\textsuperscript{1}. In this condition, diverticula (plural, diverticulum singular), or outpouches, are formed at weak points in the large intestine, primarily in the lowest section of the sigmoid colon, as nicely shown in the figure below and in the video in the web link below.
It is believed that diverticula are formed as a result of a low-fiber diet because people may strain more during bowel movements. Most people with diverticulosis do not know that they have the condition. However, if the pouches become inflamed, then the condition is known as diverticulitis. The most common symptom of this condition is abdominal pain. A liquid diet may be needed until the inflammation is decreased, then fiber is gradually increased\(^1\).

**References & Links**

1. http://www.niddk.nih.gov/health-information/health-topics/digestive-diseases/diverticular-disease/Pages/facts.aspx#1

**Video**

Diverticulosis: https://youtu.be/Mwa1qu9W2mM
Before moving to metabolism, we are going learn about some common digestive problems.

Sections:
5.1 Peptic Ulcers
5.2 Gallstones
5.3 Irritable Bowel Syndrome
5.4 Inflammatory Bowel Disease
5.5 Celiac Disease
5.6 Diverticulosis & Diverticulitis
5.7 Hemorrhoids
Inflammatory bowel disease (IBD) refers to a number of inflammatory conditions in the intestine. The two most common are Crohn's Disease and ulcerative colitis. These two conditions differ mainly in the areas of the intestine that are affected. Crohn's disease can occur anywhere throughout the GI tract, but most commonly occurs in the last part of the ileum. Crohn's disease may also involve all layers of the intestine\(^1\). Ulcerative colitis are ulcers, or sores, in the lining of the colon and/or rectum\(^2\). It is estimated that up to 1 million people have IBD in the United States. Half of these individuals have Crohn's disease, and the other half have ulcerative colitis\(^3\).

The following table in the first link below summarizes the differences between the Crohn's disease and ulcerative colitis. Figure 4 in the second link below illustrates the differences between these two conditions.

### Web Links

- Differences between Crohn's disease and ulcerative colitis
- Ulcerative Colitis vs. Crohn's Disease

The exact causes of these two diseases is not known. One hypothesized cause for Crohn's disease is an overactive immune system that results in the chronic inflammation and collateral damage to the cells of the intestine, resulting in formation of lesions. The following video does a nice job of illustrating this cause.

### Web Link

- Video: Pathology of Crohn's disease
Crohn’s disease and ulcerative colitis present symptoms similar to other gastrointestinal diseases, such as irritable bowel syndrome and GERD.

References & Links
3. http://www.ccfa.org/info/about/crohns

Links
Differences between Chron’s disease and ulcerative colitis – http://www.columbia-stmarys.org/Crohn_vs_Ulcerative_Colitis

Video
Pathology of Chron’s disease – http://www.youtube.com/watch?v=k_6AsumRnU0
5.1 Peptic Ulcers

When the mucus layer of the stomach or duodenum becomes too thin, acid can erode the cells lining these tissues. This results in a lesion known as a peptic ulcer, as shown below.

![Figure 5.11 A peptic ulcer in the duodenum](image)

The first video says that goblet cells secrete mucus in the stomach. This is not correct; they secrete mucus in the intestine. It should be neck cells in the stomach. The second link shows what two ulcers actually look like in the stomach.

**Web Links**

Video: Gastric Ulcers (1:21)
Video: Endoscopy of Two– Giant Gastric Ulcers (0:26)
10% of Americans will develop an ulcer in their lifetime. Despite common beliefs, these ulcers are not caused by stress or spicy foods. Most ulcers are believed to be caused by the acid-resistant bacteria, *Helicobacter pylori*. 30-40% of Americans are infected with this bacteria. *Helicobacter pylori* causes a thinning of the mucus that protects the stomach and duodenum from gastric acid. It is not clear how *Helicobacter pylori* is transmitted, though it may be through contaminated food or water. It might also be spread through contact with vomit, feces, or saliva of an infected person\(^1\).

Prolonged use of nonsteroidal anti-inflammatory drugs (NSAIDS) such as aspirin, ibuprofen, or naproxen (Aleve) are also frequent causes of peptic ulcers. NSAIDs inhibit the production of a protective eicosanoid\(^1\).

**References & Links**


**Videos**

Gastric Ulcers – [http://www.youtube.com/watch?v=98JaiKH2q3E](http://www.youtube.com/watch?v=98JaiKH2q3E)

70. 5.3 Irritable Bowel Syndrome

Up to 20% of Americans may have irritable bowel syndrome (IBS). A syndrome is a group of symptoms, not a disease. In IBS, the colon does not function correctly. The symptoms of IBS are cramping, bloating, gas, diarrhea, and/or constipation. The cause of IBS is unknown. Diet changes, stress reduction, and medicine may help manage the condition. To learn more about IBS, see the reference below.

Reference
5.2 Gallstones

It is estimated that up to 1 million Americans are hospitalized annually as a result of gallstones, making it the most common of all digestive diseases\(^1\). Gallstones are formed when bile hardens in the gallbladder. 80% of gallstones are a result of cholesterol precipitation, while 20% are a result of bile pigment precipitation\(^2\). The cause of gallstones is unknown\(^2\). The way in which gallstones are formed is shown in the following video.

**Web Link**

**Video: Gallstones (0:27)**

The following figure shows a severe case of gallstones.

![Gallstones within a dissected gallbladder](image)

**Figure 5.21 Gallstones within a dissected gallbladder\(^3\)**

Many people do not experience symptoms from gallstones. They are usually discovered during examination for another health condition.
However, some people experience an “attack” or pain that results from blockage of the bile ducts. The gallbladder is not essential, so the primary treatment is cholecystectomy, the removal of the gallbladder. Bile then flows directly from the liver into the small intestine.

**References & Links**


**Video**

Gallstones – [http://www.youtube.com/watch?v=1q3NxfwSENMFeature=rec-HM-fresh+div](http://www.youtube.com/watch?v=1q3NxfwSENMFeature=rec-HM-fresh+div)
72. 5.7 Hemorrhoids

Hemorrhoids are swollen or inflamed veins of the anus or lower rectum. An internal hemorrhoid occurs within the anus, while an external hemorrhoid occurs in the skin surrounding the anus. Symptoms of hemorrhoids include bleeding, pain during bowel movements, and/or itching. It is estimated that “about 75% of people will have hemorrhoids at some point in their lives”.

The first 55 seconds of the following video does a nice job of illustrating what hemorrhoids are and how they develop.

**Web Link**

Video: Hemorrhoids (2:05)
The anus and lower rectum experience high pressure during bowel movements. Thus, hemorrhoids are believed to be caused by straining during bowel movements. To prevent this condition from occurring, it is recommended that people consume a high-fiber diet, drink plenty of water, and exercise to produce regular, large, soft stools. In addition, people should “go” at first urge and not wait until it is more than an urge

References & Links

Video
Hemorrhoids — http://www.youtube.com/watch?v=C8vZolhQCwU
PART VI

CHAPTER 6
73. 6 Macronutrient & Alcohol Metabolism

Now that we have digested, taken up, absorbed, and transported the macronutrients, the next step is to learn how these macronutrients are metabolized. Alcohol is also included at the end of this chapter, even though it is not a macronutrient.

Sections:
6.1 Metabolism Basics
6.2 Carbohydrate Metabolism
6.3 Lipid Metabolism
6.4 Protein Metabolism
6.5 Alcohol Metabolism
Metabolism consists of all the chemical processes that occur in living cells. These processes/reactions can generally be classified as either anabolic or catabolic. Anabolic means to build, catabolic means to breakdown. If you have trouble remembering the difference between the two, remember that anabolic steroids are what are used to build enormous muscle mass.

![Figure 6.11 One of these two is taking anabolic steroids, which one would be your guess?](image)

An anabolic reaction/pathway requires energy to build something. A catabolic reaction/pathway generates energy by breaking down something. This is shown in the example below of glucose and glycogen. The same is true for other macronutrients.
Anabolic and catabolic can also be used to describe conditions in the body. For instance, after a meal there is often a positive energy balance, or there is more energy and macronutrients than the body needs at that time. Thus, some energy needs to be stored and the macronutrients will be used for synthesis, such as amino acids being used for protein synthesis. However, after a fast, or a prolonged period without energy intake, the body is in negative energy balance and is considered catabolic. In this condition, macronutrients will be mobilized from their stores to be used to generate energy. For example, if prolonged enough, protein can be broken down, then the released amino acids can be broken down to be used as an energy source.

A number of the metabolic reactions oxidize or reduce compounds. A compound that is being oxidized loses at least one electron, while a compound that is reduced gains at least 1 electron. To remember the difference, a mnemonic device such as OIL...
(oxidation is lost), RIG (reduction is gained) is helpful. Oxidation-reduction reactions are illustrated in the figure below.

![Figure 6.13 The purple compound is being oxidized, the orange compound is being reduced](image)

Another way to remember oxidation versus reduction is **LEO goes GER** (like a lion)
- Lose Elections = Oxidize
- Gain Elections = Reduce

Iron is a good example we can use to illustrate oxidation-reduction reactions. Iron commonly exists in two oxidation states (Fe$^{3+}$ or Fe$^{2+}$). It is constantly oxidized/reduced back and forth between the two states. The oxidation/reduction of iron is shown below.

- Fe$^{3+}$ + e$^{-}$ → Fe$^{2+}$ Reduced
- Fe$^{2+}$ → Fe$^{3+}$ + e$^{-}$ Oxidized

However, some oxidation reduction reactions are not as easy to recognize. There are some simple rules to help you recognize less
obvious oxidation/reduction reactions that are based upon the gain or loss of oxygen or hydrogen. These are as follows:

Oxidation: gains oxygen or loses hydrogen
Reduction: loses oxygen or gains hydrogen

References
A number of enzymes require cofactors to function. Some also require what other textbooks and resources refer to as coenzymes. But to keep things simple, we are going to include these coenzymes in our definition of cofactors. Thus, cofactors can be either organic or inorganic molecules that are required by enzymes to function. Many organic cofactors are vitamins or molecules derived from vitamins. Most inorganic cofactors are minerals. Cofactors can be oxidized or reduced for the enzymes to catalyze the reactions.

Two common cofactors that are derived from the B vitamins, niacin and riboflavin, are nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD), respectively. The structure of NAD and FAD are shown below.
Figure 6.111 Structure of NAD1 upside down. The atoms are circled to help orient this structure with Figure 6.113.
Both of these cofactors can be reduced; NAD is reduced to form NADH, while FAD is reduced to form FADH2 as shown in the 2 figures below.
An example of a mineral that serves as a cofactor is Fe²⁺ for proline and lysyl hydroxylases. We will discuss later in detail why vitamin C (ascorbic acid) is needed to reduce iron to Fe²⁺ so that it can serve as a cofactor for proline and lysyl hydroxylases.
Iron (Fe2+) is a cofactor for proline and lysyl hydroxylases.

References & Links
76. 6.2 Carbohydrate Metabolism Pathways

There are many metabolic pathways/cycles/processes/reactions that are involved in the synthesis or degradation of carbohydrates and compounds formed from them. Please note that most of these pathways aren't specific to carbohydrates only. Gluconeogenesis will be covered in the protein section, because amino acids are a common substrate used for synthesizing glucose.

**Carbohydrate Pathways/Cycles/Processes/Reactions:**
- **Glycogenes**is: glycogen synthesis
- **Glycogenolysis**: glycogen breakdown
- **Gluconeogenesis**: synthesis of glucose from a non-carbohydrate source
- **Glycolysis**: breakdown of glucose to pyruvate
- **Transition Reaction**: conversion of pyruvate to acetyl-CoA
- **Citric Acid (Tricarboxylic acid (TCA), Kreb's) Cycle**: acetyl-CoA combines with oxaloacetate to form citrate; ATP, NADH, and FADH2 are produced in the cycle
- **Electron Transport Chain**: oxidative phosphorylation, producing ATP from NADH and FADH2

Subsections:
- 6.21 Monosaccharide Metabolism
- 6.22 Glycogenesis & Glycogenolysis
- 6.23 Glycolysis
- 6.24 Transition Reaction
- 6.25 Citric Acid Cycle
- 6.26 Electron Transport Chain
- 6.27 Aerobic Glucose Metabolism Totals
- 6.28 Anaerobic Respiration
Galactose and fructose metabolism is a logical place to begin looking at carbohydrate metabolism, before shifting focus to the preferred monosaccharide glucose. The figure below reminds you that in the liver, galactose and fructose have been phosphorylated.

**Figure 6.21 Uptake of monosaccharides into the hepatocyte**

**Galactose**

In the liver, galactose-1-phosphate is converted to glucose-1-phosphate, before finally being converted to glucose-6-phosphate\(^1\). As shown below, glucose 6-phosphate can then be used in either glycolysis or glycogenesis, depending on the person’s current energy state.
Fructose

Unlike galactose, fructose cannot be used to form phosphorylated glucose. Instead, fructose-1-phosphate is cleaved in the liver to form glyceraldehyde 3-phosphate, a glycolysis (pathway that breaks down glucose) intermediate. This occurs through multiple steps, as depicted below.
**Figure 6.213 Conversion of fructose-1-phosphate to glyceraldehyde 3-phosphate**

**Glucose-6-Phosphate**

Within hepatocytes or myocytes (muscle cells), glucose-6-phosphate can be used either for glycogenesis (glycogen synthesis) or glycolysis (breakdown of glucose for energy production). If the person is in an anabolic state, they will use glucose-6-phosphate for storage. If they are in a catabolic state, they will use it for energy production.
Glucose-6-Phosphate

Anabolic
Glycogenesis
(Storage)

Catabolic
Glycolysis
(Energy Production)

Hepatocyte or myocyte

Figure 6.214 The “fork in the road” for glucose-6-phosphate

References & Links

78. 6.22 Glycogenesis & Glycogenolysis

As discussed earlier, glycogen is the animal storage form of glucose. If a person is in an anabolic state, such as after consuming a meal, most glucose-6-phosphate within the myocytes (muscle cells) or hepatocytes (liver cells) is going to be stored as glycogen. The structure is shown below as a reminder.
Glycogen is mainly stored in the liver and the muscle. It makes up ~6% of the wet weight of the liver and only 1% of muscle wet weight. However, since we have far more muscle mass in our body, there is 3-4 times more glycogen stored in muscle than in the liver. We have limited glycogen storage capacity. Thus, after a
high-carbohydrate meal, our glycogen stores will reach capacity. After glycogen stores are filled, glucose will have to be metabolized in different ways for it to be stored in a different form.

**Glycogenesis**

The synthesis of glycogen from glucose is a process known as glycogenesis. Glucose-6-phosphate is not inserted directly into glycogen in this process. There are a couple of steps before it is incorporated. First, glucose-6-phosphate is converted to glucose-1-phosphate and then converted to uridine diphosphate (UDP)-glucose. UDP-glucose is inserted into glycogen by either the enzyme, glycogen synthase (alpha-1,4 bonds), or the branching enzyme (alpha-1,6 bonds) at the branch points.

![Glycogenesis Diagram](image)

**Figure 6.22 Glycogenesis**

**Glycogenolysis**

The process of liberating glucose from glycogen is known as glycogenolysis. This process is essentially the opposite of glycogenesis with two exceptions: (1) there is no UDP-glucose step, and (2) a different enzyme, glycogen phosphorylase, is involved. Glucose-1-phosphate is cleaved from glycogen by the enzyme, glycogen phosphorylase, which then can be converted to glucose-6-phosphate as shown below.

336 | 6.22 Glycogenesis & Glycogenolysis
References & Links

If a person is in a catabolic state or in need of energy, such as during fasting, most glucose-6-phosphate will be used for glycolysis.

Glycolysis is the breaking down of one glucose molecule (6 carbons) into two pyruvate molecules (3 carbons). During the process, a net of two ATPs and two NADHs are also produced.
The following animation, using ball-and-stick models, allows you to control the 3 steps of glycolysis.

**Web Links**

Glycolysis Animation

### 3 steps of Glycolysis

1. Energy investment step – 2 ATP are added to the 6 carbon molecule.

Figure 6.233 Glycolysis step 1, energy investment

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6.23 Glycolysis | 339
2. Glucose Split – The 6 carbon molecule is split into two 3 carbon molecules.

![Figure 6.234 Glycolysis step 2, glucose split](image)

3. Energy harvesting step – 1 NADH and 2 ATPs are produced from each 3 carbon molecule (there are two 3 carbon molecules formed from each glucose).

![Figure 6.235 Glycolysis step 3, energy harvesting](image)
Thus, from a molecule of glucose, the harvesting step produces a total of four ATPs and two NADHs. Subtracting the harvesting from the investment step, the net output from one molecule of glucose is two ATPs and two NADHs.

The figure below shows the stages of glycolysis, as well as the transition reaction, citric acid cycle, and electron transport chain that are utilized by cells to produce energy. They are also the focus of the next 3 sections.

Figure 6.236 Glycolysis, transition reaction, citric acid cycle, and the electron transport chain

References & Links


Links

80. 6.24 Transition Reaction

If a person is in a catabolic state, or needs energy, how pyruvate will be used depends on whether adequate oxygen levels are present. If there are adequate oxygen levels (aerobic conditions), pyruvate moves from the cytoplasm, into the mitochondria, and then undergoes the transition reaction. If there are not adequate oxygen levels (anaerobic conditions), pyruvate will instead be used to produce lactate in the cytoplasm. We are going to focus on the aerobic pathway to begin with, then we will address what happens under anaerobic conditions in the anaerobic respiration section.

Figure 6.241 Pyruvate fork in the road. What happens depends on whether it is aerobic or anaerobic respiration.
The transition reaction is the transition between glycolysis and the citric acid cycle. The transition reaction converts pyruvate (3 carbons) to acetyl CoA (2 carbons), producing carbon dioxide (CO2) and a NADH as shown below. The figure below shows the transition reaction with CoA and NAD entering, and acetyl-CoA, CO2, and NADH being produced.

![Transition reaction](image)

Figure 6.242 Transition reaction

The acetyl is combined with coenzyme A (CoA) to form acetyl-CoA. The structure of CoA is shown below.

![Structure of coenzyme A](image)

Figure 6.243 Structure of coenzyme A
Thus, for one molecule of glucose, the transition reaction produces 2 acetyl-CoAs, 2 molecules of CO2, and 2 NADHs.

**References & Links**

Acetyl-CoA is a central point in metabolism, meaning there are a number of ways that it can be used. We're going to continue to consider its use in an aerobic, catabolic state (need energy). Under these conditions, acetyl-CoA will enter the citric acid cycle (aka Krebs Cycle, TCA Cycle). The following figure shows the citric acid cycle.

The citric acid cycle begins by acetyl-CoA (2 carbons) combining with oxaloacetate (4 carbons) to form citrate (aka citric acid, 6 carbons). A series of transformations occur before a carbon is given off as carbon dioxide and NADH is produced. This leaves alpha-ketoglutarate (5 carbons). Another carbon is given off as CO2 to
form succinyl CoA (4 carbons) and produce another NADH. In the next step, one guanosine triphosphate (GTP) is produced as succinyl-CoA is converted to succinate. GTP is readily converted to ATP, thus this step is essentially the generation of 1 ATP. In the next step, an FADH2 is produced along with fumarate. Then, after more steps, another NADH is produced as oxaloacetate is regenerated.

Thus, the net output from one cycle is:

- 2 CO2
- 3 NADH
- 1 FADH2
- 1 GTP (converted to ATP)

The two carbons that are given off as CO2 originally came from acetyl-CoA.

The first video and the animation do a good job of explaining and illustrating how the cycle works. The second video is an entertaining rap about the cycle.

Web Links

- Video: Citric acid cycle (0:44)
  - Citric acid cycle animation
- Video: TCA (Kreb’s) Cycle Rap (3:01)

There are two acetyl-CoAs produced from one glucose, so the net from one glucose is the amount generated from two cycles:

- 4 CO2
- 6 NADH
- 2 FADH2
- 2 GTP (converted to ATP)

Through glycolysis, the transition reaction, and the citric acid cycle, multiple NADH and FADH2 molecules are produced. Under aerobic conditions, these molecules will enter the electron transport chain to be used to generate energy through oxidative phosphorylation as described in the next section.
Figure 6.252 The pathways involved in aerobic respiration²

References & Links


Link

Video
Citric acid cycle – http://www.youtube.com/watch?v=hw5nWB0xN0Y
TCA (Kreb’s) Cycle Rap – http://www.youtube.com/watch?v=aMBls_Iw0kE
82. 6.26 Electron Transport Chain

The electron transport chain is located on the inner membrane of the mitochondria, as shown below.

The electron transport chain contains a number of electron carriers. These carriers take the electrons from NADH and FADH2, pass them down the chain of complexes and electron carriers, and ultimately produce ATP. More specifically, the electron transport chain takes the energy from the electrons on NADH and FADH2 to pump protons (H+) into the intermembrane space. This creates a proton gradient between the intermembrane space (high) and the matrix (low) of the mitochondria. ATP synthase uses the energy from this gradient to synthesize ATP. Oxygen is required for this process.

Figure 6.261 The pathways involved in aerobic respiration

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348 | 6.26 Electron Transport Chain
because it serves as the final electron acceptor, forming water. Collectively this process is known as oxidative phosphorylation. The following figure and animation do a nice job of illustrating how the electron transport chain functions.

Figure 6.262 Location of the electron transport chain in the mitochondria

**Web Link**

ETC Animation

2.5 ATP/NADH and 1.5 ATP/FADH2 are produced in the electron transport chain. Some resources will say 3 ATP/NADH and 2 ATP/FADH2, but these values are generally less accepted now.

For one molecule of glucose, the preceding pathways produce:

Glycolysis: 2 NADH
Transition Reaction: 2 NADH
Citric Acid Cycle: 6 NADH, 2 FADH2
Total 10 NADH, 2 FADH2
Multiply that by the amount of ATP per NADH or FADH2 to yield:
10 NADH X 2.5 ATP/NADH = 25 ATP
2 FADH2 X 1.5 ATP/FADH2 = 3 ATP
Total 28 ATP
The first video does a nice job of illustrating and reviewing the
electron transport chain. Note that it uses 3 ATP/NADH and 2 ATP/
FADH2 so the totals from each cycle are different from those listed
above. The second video is a great rap video explaining the steps of
glucose oxidation.

Web Links

Video: Electron Transport (1:43)
Video: Oxidate it or Love it/Electron to the Next One (3:23)

References & Links


Link

ETC Animation – http://www.science.smith.edu/departments/Biology/Bio231/etc.html

Videos

Oxidate it or Love it/Electron to the Next One –
http://www.youtube.com/watch?v=VCpNk92uswY&feature=response_watch
83. 6.27 Aerobic Glucose Metabolism Totals

The table below shows the ATP generated from one molecule of glucose in the different metabolic pathways.

Table. 6.271 ATP generated from one molecule of glucose.

<table>
<thead>
<tr>
<th>Metabolic Pathway</th>
<th>ATP Generated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycolysis</td>
<td>2</td>
</tr>
<tr>
<td>Citric Acid Cycle</td>
<td>2</td>
</tr>
<tr>
<td>Electron Transport Chain</td>
<td>28</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
</tr>
</tbody>
</table>

Notice that the vast majority of ATP is generated by the electron transport chain. If we do the math, \( \frac{28}{32} \times 100 = 87.5\% \) of the ATP from a molecule of glucose is generated by the electron transport chain. Remember that this is aerobic and requires oxygen to be the final electron acceptor. If 3 ATP/NADH and 2 ATP/FADH2 are used instead of 2.5 ATP/NADH and 1.5 ATP/FADH2 that were used above, total ATP and percentage of ATP produced by the electron transport chain would be different. But the takeaway message remains the same. The electron transport chain by far produces the most ATP from one molecule of glucose.

No References
84. 6.28 Anaerobic Respiration

Conditions without oxygen are referred to as anaerobic. In this case, the pyruvate will be converted to lactate in the cytoplasm of the cell as shown below.

Figure 6.281 Pyruvate fork in the road, what happens depends on whether it is aerobic or anaerobic respiration

What happens if oxygen isn't available to serve as the final electron acceptor? As shown in the following video, the ETC becomes backed up with electrons and can't accept them from NADH and FADH2.
This leads to a problem in glycolysis because NAD is needed to accept electrons, as shown below. Without the electron transport chain functioning, all NAD has been reduced to NADH and glycolysis cannot continue to produce ATP from glucose.

Thus, there is a workaround to regenerate NAD by converting pyruvate (pyruvic acid) to lactate (lactic acid) as shown below.
However, anaerobic respiration only produces 2 ATP per molecule of glucose, compared to 32 ATP for aerobic respiration. The biggest producer of lactate is the muscle. Through what is known as the Cori cycle, lactate produced in the muscle can be sent to the liver. In the liver, through a process known as gluconeogenesis, glucose can be regenerated and sent back to the muscle to be used again for anaerobic respiration forming a cycle as shown below.
It is worth noting that the Cori cycle also functions during times of limited glucose (like fasting) to spare glucose by not completely oxidizing it.

**References & Links**


**Video**
What happens when your run out of oxygen? – http://www.youtube.com/watch?v=StXloIW3Gvg
85. 6.3 Lipid Metabolism Pathways

Five lipid metabolic pathways/processes will be covered in the following subsections:

6.31 Lipolysis (Triglyceride Breakdown)
- Breakdown of triglycerides to glycerol and free fatty acids.

6.32 Fatty Acid Oxidation (Beta-Oxidation)
- Breakdown of fatty acids to acetyl-CoA

6.33 De Novo Lipogenesis (Fatty Acid & Triglyceride Synthesis)
- Synthesis of fatty acids from acetyl-CoA and esterification into triglycerides

6.34 Ketogenesis (Ketone Body Synthesis)
- Synthesis of ketone bodies from acetyl-CoA

6.35 Cholesterol Synthesis
Lipolysis is the cleavage of triglycerides to glycerol and fatty acids, as shown below.

There are two primary lipolysis enzymes:
1. Lipoprotein lipase (LPL)
2. Hormone-sensitive lipase (HSL)

Despite performing the same function, at the adipose level, the enzymes are primarily active for seemingly opposite reasons. In the fed state, LPL on the endothelium of blood vessels cleaves lipoprotein triglycerides into fatty acids so that they can be taken up into adipocytes, for storage as triglycerides, or myocytes where they are primarily used for energy production. This action of LPL on lipoproteins is shown in the two figures below.
HSL is an important enzyme in adipose tissue, which is a major storage site of triglycerides in the body. HSL activity is increased by glucagon and epinephrine (“fight or flight” hormone), and decreased by insulin. Thus, in hypoglycemia (such as during a fast) or a “fight or flight” response, triglycerides in the adipose are cleaved, releasing...
fatty acids into circulation that then bind with the transport protein albumin. Thus, HSL is important for mobilizing fatty acids so they can be used to produce energy. The figure below shows how fatty acids can be taken up and used by tissues such as the muscle for energy production.

Figure 6.314 Hormone-sensitive lipase

We are not going to focus on glycerol, but it does have two metabolic fates.
1. It can be broken down in glycolysis
2. It can be used to synthesize glucose (gluconeogenesis)

Figure 6.315 Metabolic fates of glycerol

360 | 6.31 Lipolysis (Triglyceride Breakdown)
References & Links

To generate energy from fatty acids, they must be oxidized. This process occurs in the mitochondria, but long chain fatty acids cannot diffuse across the mitochondrial membrane (similar to absorption into the enterocyte). Carnitine, an amino acid-derived compound, helps shuttle long-chain fatty acids into the mitochondria. The structure of carnitine is shown below.

**Fatty Acid Shuttling**

As shown below, there are two enzymes involved in this process: carnitine palmitoyltransferase I (CPTI) and carnitine palmitoyltransferase II (CPTII). CPTI is located on the outer mitochondrial membrane, CPTII is located on the inner mitochondrial membrane. The fatty acid is first activated by addition of a CoA (forming acyl-CoA), then CPTI adds carnitine. Acyl-Carnitine is then transported into the mitochondrial matrix with the assistance of the enzyme translocase. In the matrix, CPTII removes carnitine from the activated fatty acid (acyl-CoA). Carnitine is recycled back into the cytosol to be used again, as shown in the figure and animation below.
Web Link

Fatty acid transfer from cytoplasm to mitochondria

Fatty Acid Activation

As shown below, the first step of fatty acid oxidation is activation. A CoA molecule is added to the fatty acid to produce acyl-CoA, converting ATP to AMP in the process. Note that in this step, the ATP is converted to AMP, not ADP. Thus, activation uses the equivalent of 2 ATP molecules\(^4\).
Fatty Acid Oxidation

Fatty acid oxidation is also referred to as beta-oxidation because 2 carbon units are cleaved off at the beta-carbon position (2nd carbon from the acid end) of an activated fatty acid. The cleaved 2 carbon unit forms acetyl-CoA and produces an activated fatty acid (acyl-CoA) with 2 fewer carbons, acetyl-CoA, NADH, and FADH2.

To completely oxidize the 18-carbon fatty acid above, 8 cycles of beta-oxidation have to occur. This will produce:
- 9 acetyl-CoAs
- 8 NADH
- 8 FADH2

Those 9 acetyl-CoAs can continue into the citric acid cycle, where they can produce:
- 9 GTP
- 9 FADH2
- 27 NADH

The products of the complete oxidation of a fatty acid are shown below.
Adding up the NADH and FADH2, the electron transport chain ATP production from beta-oxidation and the citric acid cycle looks like this:

\[ \text{NADH} \]

\[
8 \text{ (beta-oxidation)} + 27 \text{ (TCA)} = 35 \text{ NADH} \times 2.5 \text{ ATP/NADH} = 87.5 \text{ ATP}
\]

\[ \text{FADH}_2 \]

\[
8 \text{ (beta-oxidation)} + 9 \text{ (TCA)} = 17 \text{ FADH}_2 \times 1.5 \text{ ATP/FADH}_2 = 25.5 \text{ ATP}
\]

\[ \text{GTP} \]

\[
9 \text{ GTP} = 9 \text{ ATP}
\]

**Total ATP from complete oxidation of an 18 carbon fatty acid:**

\[
87.5 + 25.5 + 9 = 122 \text{ ATP}
\]

Subtract 2 ATP (ATP→AMP) required for activation of the fatty acid:

\[
122 - 2 = 120 \text{ Net ATP}
\]

Compared to glucose (32 ATP) you can see that there is far more energy stored in a fatty acid. This is because fatty acids are in more
reduced form and thus, they yield 9 kcal/g instead of 4 kcal/g like carbohydrates.\(^4\)

The following animation reviews lipolysis and beta-oxidation.

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**Web Link**

Fatty Acid Metabolism

**References & Links**


**Links**


Fatty Acid Metabolism – http://www.wiley.com/legacy/college/boyer/0470003790/animations/fatty_acid_metabolism/fatty_acid_metabolism.htm
88. 6.33 De novo Lipogenesis (Fatty Acid Synthesis)

De novo in Latin means “from the beginning.” Thus, de novo lipogenesis is the synthesis of fatty acids, beginning with acetyl-CoA. Acetyl-CoA has to first move out of the mitochondria, where it is then converted to malonyl-CoA (3 carbons). Malonyl-CoA then is combined with another acetyl-CoA to form a 4 carbon fatty acid (1 carbon is given off as CO2). The addition of 2 carbons is repeated through a similar process 7 times to produce a 16 carbon fatty acid\(^1\).

![Figure 6.331 Fatty acid synthesis](https://en.wikipedia.org/wiki/Mitochondrion)

Most fatty acids synthesized will be esterified into triglycerides for storage.

**References**

89. 6.34 Ketone Body Synthesis

In cases where there is not enough glucose available for the brain (very low carbohydrate diets, starvation), the liver can use acetyl-CoA, primarily from fatty acids (but also certain amino acids), to synthesize ketone bodies (ketogenesis). The structures of the three ketone bodies; acetone, acetoacetic acid, and beta-hydroxybutyric acid, are shown below.
Figure 6.341 The three ketone bodies from top to bottom (acetone, acetoacetic acid, and beta-hydroxybutyric acid)
After they are synthesized in the liver, ketone bodies are released into circulation where they can travel to the brain. The brain converts the ketone bodies to acetyl-CoA that can then enter the citric acid cycle for ATP production, as shown below.

If there are high levels of ketones secreted, it results in a condition known as ketosis or ketoacidosis. The high level of ketones in the blood decreases the blood's pH, meaning it becomes more acidic. It is debatable whether mild ketoacidosis is harmful, but severe ketoacidosis can be lethal. One symptom of this condition is fruity or sweet smelling breath, which is due to increased acetone exhalation.

References & Links

Figure 6.342 The production, release, use, or exhalation of ketone bodies

---

370  | 6.34 Ketone Body Synthesis
90. 6.35 Cholesterol Synthesis

Acetyl-CoA is also used to synthesize cholesterol. As shown below, there are a large number of reactions and enzymes involved in cholesterol synthesis.

Figure 6.351 Cholesterol synthesis pathway

1
Simplifying this, acetyl-CoA is converted to acetoacetyl-CoA (4 carbons) before forming 3-hydroxy-3-methylglutaryl-CoA (HMG-CoA). HMG-CoA is converted to mevalonate by the enzyme HMG-CoA reductase. This enzyme is important because it is the rate-limiting enzyme in cholesterol synthesis.

A rate-limiting enzyme is like a bottleneck in a highway, as shown below, that determines the flow of traffic past it.

*Figure 6.352 Cholesterol synthesis simplified*
Rate-limiting enzymes limit the rate at which a metabolic pathway proceeds. The pharmaceutical industry has taken advantage of this knowledge to lower people’s LDL levels with drugs known as statins. These drugs inhibit HMG-CoA reductase and thus decrease
cholesterol synthesis. Less cholesterol leads to lower LDL levels, and hopefully a lower risk of cardiovascular disease.

The brand name of the statins approved for use in the US are⁴:

- Lipitor
- Lescol
- Mevacor
- Pravachol
- Crestor
- Zocor
- Livalo

The first link below talks about the new cholesterol guidelines, in which statins are prescribed at set therapeutic doses based on assessed cardiovascular risk rather than treating LDL and HDL to target levels. The second link is to the online calculator that can be used to estimate individual’s risk based on results from the Framingham Heart Study. The third link talks about a drug that was effective at lowering LDL, increasing HDL, but did not improve cardiovascular disease outcomes. This finding is consistent with the new cholesterol guidelines deemphasizing HDL and LDL target levels. The fourth link below describes some new cholesterol lowering drugs, which have shown some promising preliminary results.

**Web Links**

3 Things to Know About the New Cholesterol Guidelines
AHA Heart Attack Risk Assessment
Dashing Hopes, Study Shows a Cholesterol Drug Had No Effect on Heart Health
Tests of Cholesterol Drugs Offer Hope of Reducing Heart Attacks and Strokes

The body synthesizes approximately 1 gram of cholesterol a day, whereas it is recommended that we consume less than 0.3 gram a day. A number of tissues synthesize cholesterol, with the liver accounting for ~20% of synthesis. The intestine is believed to be
the most active among the other tissues that are responsible for the other 80% of cholesterol synthesis⁵.

References & Links

Links
6.4 Protein Metabolism

Section 2.22 described how proteins are synthesized. Thus, this section will focus on how proteins and amino acids are broken down. There are four protein metabolic pathways that will be covered in this section:

- **Transamination**: transfer of an amino group from one amino acid to another
- **Deamination**: removal of an amino group, normally from an amino acid.
- **Gluconeogenesis**: synthesis of glucose from a non-carbohydrate source.
- **Protein Turnover/Degradation**: liberation of amino acids from proteins.

Subsections:
- 6.41 Transamination, Deamination, & Ammonia Removal as Urea
- 6.42 Gluconeogenesis
- 6.43 Protein Turnover/Degradation
92. 6.41 Transamination, Deamination & Ammonia Removal as Urea

The first step in catabolizing, or breaking down, an amino acid is the removal of its amine group (−NH₃). Amine groups can be transferred or removed through transamination or deamination, respectively.

**Transamination**

Transamination is the transfer of an amine group from an amino acid to a keto acid (amino acid without an amine group), thus creating a new amino acid and keto acid as shown below.

![Figure 6.411 Generic transamination reaction where the top keto acid is converted to an amino acid, while the bottom amino acid is converted to a keto acid](image)

Keto acids and/or carbon skeletons are what remains after amino acids have had their nitrogen group removed by deamination or transamination. Transamination is used to synthesize nonessential amino acids.

**Deamination**
Deamination is the removal of the amine group as ammonia (NH₃), as shown below.

![Deamination of cytosine to uracil (nucleotides, not amino acids)](image)

The potential problem with deamination is that too much ammonia is toxic, causing a condition known as hyperammonemia. The symptoms of this condition are shown in the following figure.
Our body has a method to safely package ammonia in a less toxic form to be excreted. This safer compound is urea, which is produced by the liver using 2 molecules of ammonia (NH₃) and 1 molecule of carbon dioxide (CO₂). Most urea is then secreted from the liver and incorporated into urine in the kidney to be excreted from the body, as shown below.
Figure 6.414 Production of urea helps to safely remove ammonia from the body.\textsuperscript{4-6}

References

5. http://upload.wikimedia.org/wikipedia/commons/b/b0/Kidney_section.jpg
Gluconeogenesis is the synthesis of glucose from noncarbohydrate sources. Certain amino acids can be used for this process, which is the reason that this section is included here instead of the carbohydrate metabolism section. Gluconeogenesis is glycolysis in reverse with an oxaloacetate workaround, as shown below. Remember oxaloacetate is also an intermediate in the citric acid cycle.

Not all amino acids can be used for gluconeogenesis. The ones that can be used are termed glucogenic (red), and can be converted to either pyruvate or a citric acid cycle intermediate. Other amino acids can only be converted to either acetyl-CoA or acetoacetyl-...
CoA, which cannot be used for gluconeogenesis. However, acetyl-CoA or acetoacetyl-CoA can be used for ketogenesis to synthesize the ketone bodies, acetone and acetoacetate. Thus, these amino acids are instead termed ketogenic (green).

Fatty acids and ketogenic amino acids cannot be used to synthesize glucose. The transition reaction is a one-way reaction, meaning that acetyl-CoA cannot be converted back to pyruvate. As a result, fatty acids can't be used to synthesize glucose, because beta-oxidation produces acetyl-CoA. Even if acetyl-CoA enters the citric acid cycle, the carbons from it will eventually be completely oxidized and given off as CO2. The net result is that these carbons are not readily available to serve as keto-acids or carbon skeletons for amino acid synthesis. Some amino acids can be either glucogenic or ketogenic, depending on how they are metabolized. These amino acids are referred to as glucogenic and ketogenic (pink).

References
Proteins serve a number of functions in the body, but what happens when cells, enzymes, etc. have completed their lifespan? They are recycled.

Figure 6.43 Recycling symbol

Proteins are broken down to amino acids that can be used to
synthesize new proteins. There are 3 main systems of protein degradation:

1. Ubiquitin-proteasome degradation
2. Lysosome degradation
3. Calpain degradation

1. **Ubiquitin-Proteasome Degradation**

   Proteins that are damaged or abnormal are tagged with the protein ubiquitin. There are multiple protein subunits involved in the process (E1-E3), but the net result is the production of a protein (substrate) with a ubiquitin tail, as shown below.

   ![Ubiquitination of a protein (substrate)](image)

   Figure 6.432 Ubiquitination of a protein (substrate)

   This protein then moves to the proteasome for degradation. Think of the proteasome like a garbage disposal. The ubiquitinated “trash” protein is inserted into the garbage disposal where it is broken down into its component parts (primarily amino acids). The following video illustrates this process nicely.

   **Web Link**

   Video: Proteasome Degradation (0:44)
2. Lysosome Degradation

The lysosomes are organelles that are found in cells. They contain a number of proteases that degrade proteins.

**Cell Structure**

![Cell Structure Diagram]

Figure 6.43 Lysosomes are organelles within the cell

3. Calpain Degradation

The last degradation system is the calpain system, which is not as well understood, but does require calcium.

**References & Links**


**Video**

Proteasome Degradation – https://www.youtube.com/watch?v=w2Qd6v-4Ilc
The other energy source is alcohol. The alcohol we consume contains two carbons and is known as ethanol.

![Structure of ethanol](image)

Ethanol is passively absorbed by simple diffusion into the enterocyte. Ethanol metabolism occurs primarily in the liver, but 10–30% is estimated to occur in the stomach. For the average person, the liver can metabolize the amount of ethanol in one drink (1/2 ounce) per hour. There are three ways that alcohol is metabolized in the body.

1. Catalase – an enzyme that we will cover again in the antioxidants section. Catalase is estimated to metabolize less than 2% of ethanol, so it is not shown below or discussed further.

2. Alcohol dehydrogenase (ADH) – This is the major ethanol-metabolizing enzyme that converts ethanol and NAD to acetaldehyde and NADH, respectively. Aldehyde dehydrogenase (ALDH) uses NAD, CoA, and acetaldehyde to create acetyl-CoA and...
to produce another NADH. The action of ADH is shown in the figure below.

![Diagram of Alcohol Metabolism]

**MEOS – Microsomal Ethanol Oxidizing System**

*Figure 6.52 Ethanol Metabolism*¹,⁵

3. Microsomal ethanol oxidizing system (MEOS) – When a person consumes a large amount of alcohol the MEOS, is the overflow pathway, that also metabolizes ethanol to acetaldehyde. It is estimated that the MEOS metabolizes 20% of ethanol³, and it differs from ADH in that it uses ATP to convert reduced nicotinamide adenine dinucleotide phosphate (NADPH + H⁺) to NADP⁺. The action of the MEOS is shown in the figure above.

At high intakes or with repeated exposure, there is increased synthesis of MEOS enzymes resulting in more efficient metabolism, also known as increased tolerance. ADH levels do not increase based on alcohol exposure. MEOS also metabolizes a variety of other compounds (drugs, fatty acids, steroids) and alcohol competes for the enzyme's action. This can cause the metabolism of drugs to slow and potentially reach harmful levels in the body³.

Females have lower stomach ADH activity and body H2O concentrations. As a result, a larger proportion of ethanol reaches
circulation, thus, in general, females have a lower tolerance for alcohol. About 50% of Taiwanese, Han Chinese, and Japanese populations have polymorphisms in ALDH which cause the enzyme to have low activity. This leads to buildup of acetaldehyde and undesirable symptoms such as: flushing, dizziness, nausea, and headaches. The following short video explains what happens when the MEOS system gets involved in alcohol metabolism.

**Web Link**

**Video: MEOS Overflow Pathway**

**References & Links**


**Video**

MEOS Overflow Pathway – http://nutrition.jbpub.com/resources/animations.cfm?id=20&debug=0
96. 7 Integration of Macronutrient & Alcohol Metabolism

Understanding the different metabolic pathways is an important step. However, an integrated understanding of the interconnectedness and tissue specificity of metabolism is where this knowledge really becomes powerful. To this end, we will first cover how the different pathways feed into one another and then talk about the metabolic capabilities of the different tissues in the body. We will then discuss what happens metabolically during different conditions or when consuming certain diets.

Sections:

7.1 Integration of Macronutrient & Alcohol Metabolic Pathways
7.2 Liver Macronutrient & Alcohol Metabolism
7.3 Extrahepatic Macronutrient & Alcohol Metabolism
7.4 Metabolic Conditions
7.1 Integration of Macronutrient and Alcohol Metabolic Pathways

If you were to draw all the macronutrient and alcohol metabolic pathways covered in chapter 6, hopefully it would look something like the figure below. In this figure:

- Carbohydrate pathways are orange
- Triglyceride/fatty acid pathways are purple
- Protein/amino acid pathways are green
- Nonclassified pathways are gray

Figure 7.11 Integrated macronutrient and alcohol metabolism

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394 | 7.1 Integration of Macronutrient and Alcohol Metabolic
To simplify, we are going to remove the glycerol and cholesterol pathways so that we can focus on integrating the other pathways in macronutrient and alcohol metabolism.

Thus, we are left with the following simplified figure:
Notice that acetyl-CoA is the central metabolite in integrated metabolism that connects many different pathways. For example, carbohydrates can be broken down to acetyl-CoA that can then be used to synthesize fats and ultimately triglycerides.

References & Links
**7.2 Liver Macronutrient and Alcohol Metabolism**

The liver is the organ that has the greatest macronutrient metabolic capability; there are a number of metabolic functions that only the liver performs. However, there are two major macronutrient metabolic processes, lactate synthesis and ketone body breakdown, that the liver will not normally perform, as shown in the figure below.

Figure 7.21 Ketone body breakdown and lactate synthesis are major macronutrient metabolic pathways that the liver does not normally perform\(^1\)

But aside from those two pathways, the liver performs all the other metabolic pathways that you have learned about that are listed and shown below:
- Glycogen synthesis and breakdown
- Glycolysis
- Gluconeogenesis
- Alcohol oxidation
- Ketone body synthesis
- Fatty acid synthesis and breakdown
- Triglyceride synthesis and breakdown
- Protein synthesis and breakdown
- Urea synthesis
- VLDL synthesis
- Glucose-6-phosphatase

Figure 7.22 Metabolic capability of the liver

The liver is the only tissue that performs the following functions:

- Ketone body synthesis
- Urea synthesis
- VLDL synthesis
- The liver is also the primary, but not exclusive site, of the
following functions:

- Alcohol oxidation (also occurs in the stomach)
- Gluconeogenesis (also occurs in the kidney(s))
- Glucose-6-phosphatase activity (also occurs in the kidney(s))
- Lactate breakdown (also occurs in muscle)

Glucose-6-phosphatase is important because it removes the phosphate from glucose-6-phosphate so that glucose can be released into circulation. Kidneys can perform gluconeogenesis and has glucose-6-phosphatase. However, it is estimated that 90% of glucose formed from gluconeogenesis is produced by the liver; the remaining 10% is produced by the kidney(s). It is also important to note that the muscle does not have this enzyme, so it cannot release glucose into circulation.

**References & Links**

99. 7.3 Extrahepatic Macronutrient Metabolism

Because the liver is so important in metabolism, the term extrahepatic has been defined to mean “located or occurring outside of the liver”. We are next going to consider extrahepatic tissue metabolism.

I’m kind of a big deal. How many of you have a name to designate other things besides yourself?

Figure 7.31 The liver “is kind of a big deal”

To start considering the metabolic capabilities of the extrahepatic tissues, we start by removing pathways that only or mostly occur in the liver:
- Alcohol oxidation
- Gluconeogenesis
- Ketone body synthesis
- Urea synthesis
- Lactate breakdown
- Glucose-6-phosphatase

These metabolic processes are crossed off in the figure below.
We are left with metabolic capabilities that are listed and shown below.

Glycogen synthesis and breakdown
Glycolysis
Fatty acid synthesis and breakdown
Triglyceride synthesis and breakdown
Protein synthesis and breakdown
7.3 Extrahepatic Tissues

We will use this figure as the base for metabolic capabilities of the different extrahepatic tissues to compare what pathways other tissues can perform versus all the pathways performed by extrahepatic tissues.

In an effort to keep this simple, we are going to focus on four extrahepatic tissues in the following subsections:

7.31 Muscle Macronutrient Metabolism
7.32 Adipose Macronutrient Metabolism
7.33 Brain Macronutrient Metabolism
7.34 Red Blood Cell Macronutrient Metabolism

References & Links
100. 7.31 Muscle Macronutrient Metabolism

Compared to extrahepatic tissues as a whole, in the muscle the following pathways are not performed or are not important:
- Fatty acid synthesis
- Ketone body breakdown

These pathways are crossed out in the figure below.

Removing those pathways, the following metabolic pathways make up the muscle metabolic capability:
- Glycogen synthesis and breakdown
- Glycolysis

Figure 7.311 The metabolic pathways that are not performed or important in the muscle, compared to extrahepatic tissues as a whole.

7.31 Muscle Macronutrient Metabolism | 403
Muscle is a major extrahepatic metabolic tissue. It is the only extrahepatic tissue with significant glycogen stores. However, unlike the liver, the muscle cannot secrete glucose after it is taken up (no glucose-6-phosphatase). Thus, you can think of the muscle as being selfish with glucose. It either uses it for itself initially or stores it for its later use.

References & Links
101. 7.32 Adipose Macronutrient Metabolism

It probably does not surprise you that the major function of the adipose is to store energy as triglycerides. Compared to extrahepatic tissues as a whole, in the adipose the following pathways are not performed or are not important:

- Glycogen synthesis and breakdown
- Lactate synthesis
- Ketone body breakdown
- Fatty acid breakdown
- Protein synthesis and breakdown
- Citric acid cycle (not much since it is not an active tissue needing energy)

These pathways are crossed out in the figure below.
Removing those pathways, we are left with metabolic capabilities listed below and depicted in the following figure:

- Glycolysis
- Fatty acid synthesis
- Triglyceride synthesis and breakdown
Fatty acid synthesis only occurs in the adipose and liver. In the adipose, fatty acids are synthesized and most will be esterified into triglycerides to be stored. In the liver, some fatty acids will be esterified into triglycerides to be stored, but most triglycerides will be incorporated into VLDL so that they can be used or stored by other tissues.

**References & Links**
Fatty acid breakdown does not occur to any great extent in the brain because of the low activity of an enzyme in the beta-oxidation pathway limits the pathway’s activity. Compared to the extrahepatic tissues as a whole, in the brain the following pathways are not performed or are not important:

- Glycogen synthesis and breakdown
- Lactate synthesis
- Fatty acid synthesis and breakdown
- Triglyceride synthesis and breakdown
- Protein synthesis and breakdown

These pathways are crossed out on the figure below.

Figure 7.331 The metabolic pathways that are not performed or important in the brain compared to extrahepatic tissues as a whole are crossed out.
Fatty acid breakdown does not occur to any great extent in the brain because low activity of an enzyme in the beta-oxidation pathway limits the activity of this pathway\(^2\).

By removing those pathways the only pathways left are:
- Glycolysis
- Ketone body breakdown

Thus, due to its limited metabolic capabilities, the brain needs to receive either glucose or ketone bodies to use as an energy source.

**References & Links**
Red blood cells are the most limited of the extrahepatic tissues because they do not contain a nucleus or other cell organelles, most notably mitochondria.

As a result, compared to the extrahepatic tissues, in red blood cells the following pathways are not performed or are not important:
- Glycogen synthesis and breakdown
- Lactate breakdown
- Fatty acid synthesis and breakdown
- Triglyceride synthesis and breakdown
- Protein synthesis and breakdown

Figure 7.341 Red blood cells do not contain mitochondria\(^1\)
Ketone body breakdown

These pathways are crossed off in the figure below.

If all those pathways are removed, only glycolysis is left, where pyruvate is converted to lactate.

Figure 7.342 The metabolic pathways that are not performed or important in the red blood cells, compared to extrahepatic tissues as a whole are crossed off.
Thus, red blood cells are one-trick ponies, only being able to perform glycolysis and produce lactate.
Figure 7.344 Red blood cells are one-trick ponies

References & Links
You have learned about the pathways and the tissue metabolic capabilities, so now we're going to apply that knowledge to three conditions: fasting, the Atkins diet, and the Ornish/Pritikin diet, as ways to illustrate how you can use this knowledge. In fasting, we're going to be considering what is happening metabolically during a prolonged period without food. This is a catabolic condition. The Atkins diet is a carbohydrate-restricted diet, so we are going to consider what happens metabolically when someone is eating a diet that essentially only contains protein and lipids over an extended period of time. This is an anabolic condition. Finally the Ornish/Pritikin diet is a very low fat diet, so we're going to consider what happens metabolically when someone is eating a diet that is essentially only carbohydrates and protein over an extended period of time. This is an anabolic condition. For each of these conditions, we're going to consider what is happening in the liver, muscle, adipose, and brain.

Now that you should have an understanding of the glycemic response and macronutrient metabolism, you should be able to understand the broader effects of insulin and glucagon that are summarized in the following tables. Knowing what hormone is elevated in the different conditions helps you to understand the metabolism that occurs in different conditions.

Table 7.41 Insulin’s effects on targets in tissues

1.4 7.4 Metabolic Conditions
Effect | Tissue | Target
--- | --- | ---
↑ Glucose Uptake | Muscle, Adipose | ↑ GLUT4
↑ Glucose Uptake | Liver | ↑ Glucokinase
↑ Glycogen Synthesis | Liver, Muscle | ↑ Glycogen Synthase
↓ Glycogen Breakdown | Liver, Muscle | ↓ Glycogen Phosphorylase
↑ Glycolysis, Transition Reaction | Liver, Muscle | ↑ Phosphofructokinase-1
↑ Fatty Acid Synthesis | Liver | ↑ Fatty Acid Synthase
↑ Triglyceride Synthesis | Adipose | ↑ Lipoprotein Lipase

Table 7.42 Glucagon's effects on targets in tissues

Effect | Tissue | Target
--- | --- | ---
↑ Glycogen Breakdown | Liver | ↑ Glycogen Phosphorylase
↓ Glycogen Synthesis | Liver | ↓ Glycogen Synthase
↑ Gluconeogenesis | Liver | Multiple Enzymes
↓ Glycolysis | Liver | ↓ Phosphofructokinase-1
↑ Ketone Body Synthesis | Liver | ↑ Acetyl-CoA Carboxylase
↑ Triglyceride Breakdown | Adipose | ↑ Hormone-Sensitive Lipase

Subsections:
7.41 Fasting
7.42 Atkins Diet
7.43 Ornish/Pritikin Diet

References & Links
In this condition a person has been fasting for an extended period of time (18 hours or longer). As a result, the person is in a catabolic state with low blood glucose levels, which leads the pancreas to secrete glucagon.

The liver will break down glycogen to secrete glucose for other tissues to use until its stores are exhausted. Amino acids and lactate from muscle will be used for gluconeogenesis to synthesize glucose that will also be secreted. Glycolysis will not be occurring to any great extent to spare glucose for use by other tissues. From the breakdown of amino acids, there will be an increase in the synthesis and secretion of urea from the liver to safely rid the body of ammonia from the amino acids. Fatty acids that are received from the adipose will be broken down to acetyl-CoA and used to synthesize ketone bodies that are secreted for tissues, such as the brain, that cannot directly use fatty acids as a fuel.

The muscle will break down glycogen to glucose until glycogen stores are exhausted, and receive glucose from the liver that enters glycolysis, forming pyruvate. Glucose will be used for anaerobic (lactate) and aerobic (pyruvate) respiration. Pyruvate will enter the transition reaction to form acetyl-CoA. The acetyl-CoA will then enter the citric acid cycle, and NADH and FADH2 produced will enter the electron transport chain to generate ATP. Once there isn’t enough glucose for the muscle to use, fatty acids taken up from the adipose and from breakdown of muscle triglyceride stores will be broken down to acetyl-CoA. The acetyl-CoA will then enter the citric acid cycle, and NADH and FADH2 produced will enter the electron transport chain to generate ATP. Amino acids from protein breakdown and lactate (Cori Cycle) will be secreted to be used by the liver for gluconeogenesis.

The adipose tissue will break down triglycerides to fatty acids and
release these for use by the muscle and the liver. It will not be taking up anything.

**No References**
In this condition, assume a person just started into phase I of the Atkins Diet and he/she has just consumed a meal of all protein and fat with no carbohydrates. As a result, this person is in an anabolic state, but blood glucose levels are low, meaning the pancreas will secrete glucagon.

Liver glycogen stores will be broken down to secrete glucose for other tissues. Glycolysis will not be occurring to any great extent, in order to spare glucose for other tissues. Using amino acids from digestion and lactate from muscle, gluconeogenesis will synthesize glucose that will also be secreted. From the breakdown of amino acids, there will be an increase in the synthesis and secretion of urea from the liver to safely rid the body of ammonia from the amino acids. Amino acids will also be used for protein synthesis. Some triglycerides from chylomicron remnants taken up will be broken down to fatty acids. These will then be broken down to acetyl-CoA and used to synthesize ketone bodies that are secreted for tissues, such as the brain, that cannot directly use fatty acids as a fuel. Other triglycerides will be packaged into VLDL and secreted from the liver.

The muscle is going to break down glycogen to glucose, and receive glucose from the liver that enters glycolysis, forming pyruvate. Glucose will be used for anaerobic (lactate) and aerobic (pyruvate) respiration. After glycogen is used up, most glucose will be used for anaerobic respiration to spare glucose. In aerobic respiration, pyruvate will enter the transition reaction to form acetyl-CoA. The acetyl-CoA will then enter the citric acid cycle, and NADH and FADH2 produced will enter the electron transport chain to generate ATP. Once there is not enough glucose for the muscle to use, fatty acids will be cleaved from and taken up from chylomicrons, chylomicron remnants, VLDL, IDL, and LDL and broken down to acetyl-CoA. The acetyl-CoA will then enter the citric acid cycle, and NADH and FADH2 produced will enter the
electron transport chain to generate ATP. Amino acids taken up will be used for protein synthesis, and lactate will be secreted for the liver to use for gluconeogenesis (Cori cycle).

In the adipose, fatty acids that are cleaved from chylomicrons, chylomicron remnants, VLDL, IDL, and LDL are also going to be taken up. These fatty acids will be used to synthesize triglycerides for storage. With glucagon levels high in this condition, hormone-sensitive lipase would be active. However, since this is an anabolic state, the net effect would be uptake of fatty acids after cleavage by lipoprotein lipase. The adipose won’t be secreting anything under this condition.

No References
In this condition, assume a person is on the Ornish/Pritikin diet and just consumed a meal containing carbohydrates, with minimal but adequate amount of protein and no fat. As a result, this person is in an anabolic state with high blood glucose levels, meaning the pancreas will secrete insulin.

The liver will take up glucose and synthesize glycogen until its stores are filled. After these stores are full, glucose can be broken down through glycolysis to pyruvate, then form acetyl-CoA in the transition reaction. Because we are in the fed or anabolic state, acetyl-CoA will be used for fatty acid synthesis, and the fatty acids will be used for triglyceride synthesis. However, evidence suggests that this de novo lipogenesis pathway does not occur to any great extent in humans\(^1\). These triglycerides will be packaged into VLDL and secreted from the liver. Amino acids will also be taken up and used for protein synthesis as needed. Because there is plenty of glucose, gluconeogenesis and ketone body synthesis will not be operating to any great extent.

The muscle will take up glucose and synthesize glycogen until those stores are filled. Some glucose will go through glycolysis to produce pyruvate, then form acetyl-CoA in the transition reaction. The acetyl-CoA will enter the citric acid cycle, and NADH and FADH\(_2\) produced will enter the electron transport chain to generate ATP. Fatty acids that are cleaved from VLDL, IDL, and LDL are also going to be taken up. These fatty acids will be used to synthesize triglycerides for storage. Whatever amino acids are taken up will be used for protein synthesis. The muscle will not be secreting anything in this condition.

The adipose is going to take up glucose that will enter glycolysis, where pyruvate will be produced, then acetyl-CoA will be produced in the transition reaction. Because we are in the fed or anabolic state, the acetyl-CoA will be used for fatty acid synthesis, and the
fatty acids will be used for triglyceride synthesis. However, evidence suggests that de novo lipogenesis does not occur to any great extent in humans\(^1\). Fatty acids that are cleaved from VLDL, IDL, and LDL are going to be taken up and primarily used to synthesize triglycerides for storage. The adipose won’t be secreting anything under this condition.

The brain will have plenty of glucose available for its use, so it is not going to have to use ketone bodies like it would during fasting and during prolonged Atkins diet consumption.

**References & Links**

Micronutrients consist of vitamins and minerals. In this chapter, an overview of vitamins and minerals will be presented followed by a description of the dietary reference intakes (DRIs), which are used as benchmarks of micronutrient intake.

Sections:
8.1 Vitamins
8.2 Minerals
8.3 Vitamins and Minerals Functional Categories
8.4 Dietary Reference Intakes (DRIs)
The name vitamin comes from Casimir Funk, who in 1912 thought vital amines (NH₃) were responsible for preventing what we know now are vitamin deficiencies. He coined the term vitamines to describe these compounds. Eventually it was discovered that these compounds were not amines and the ‘e’ was dropped to form vitamins.

Vitamins are classified as either fat-soluble or water-soluble. The fat-soluble vitamins are:

- Vitamin A
- Vitamin D
- Vitamin E
- Vitamin K

The water-soluble vitamins are vitamin C and the B vitamins, which are shown in the table below.

Table 8.11 The B vitamins and their common names

<table>
<thead>
<tr>
<th>Vitamin</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Thiamin</td>
</tr>
<tr>
<td>B2</td>
<td>Riboflavin</td>
</tr>
<tr>
<td>B3</td>
<td>Niacin</td>
</tr>
<tr>
<td>B5</td>
<td>Pantothenic Acid</td>
</tr>
<tr>
<td>B6*</td>
<td>Pyridoxine</td>
</tr>
<tr>
<td>B7</td>
<td>Biotin</td>
</tr>
<tr>
<td>B9</td>
<td>Folate</td>
</tr>
<tr>
<td>B12*</td>
<td>Cobalamin</td>
</tr>
</tbody>
</table>

*Normally used instead of common names

A common question from students about B vitamins is: “Why are
there so many B vitamins? It is not like they ran out of letters in the alphabet to name them.”

Before they even knew that vitamins existed, a scientist named E.V. McCollum recognized that a deficiency in what he called ‘fat-soluble factor A’ resulted in severe ophthalmia (inflammation of the eye). In addition, a deficiency in ‘water-soluble factor B’ resulted in beriberi (a deficiency discussed more later).

Figure 8.11 Factor A deficiency led to ophthalmia, factor B deficiency led to beriberi

Factor A is what we now know as vitamin A. However, researchers soon realized that factor B actually consisted of two factors that they termed B1 and B2. Then they realized that there are multiple components in B2, and they began identifying the wide array of B vitamins that we know today

You might be thinking “but the numbers on the B vitamins still do not add up.” You are right, vitamins B4, B8, B10, and B11 were discovered and then removed leaving us with the B vitamins shown in Table 8.11.

Relative to other scientific milestones, the discovery of vitamins is a fairly recent occurrence, as shown in the table below.
Table 8.12 Vitamin, year proposed, isolated, structure determined, and synthesis achieved up to 1944

<table>
<thead>
<tr>
<th>Vitamin</th>
<th>Year Proposed</th>
<th>Isolated</th>
<th>Structure Determined</th>
<th>Synthesis Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thiamin</td>
<td>1901</td>
<td>1926</td>
<td>1936</td>
<td>1936</td>
</tr>
<tr>
<td>Vitamin C</td>
<td>1907</td>
<td>1926</td>
<td>1932</td>
<td>1933</td>
</tr>
<tr>
<td>Vitamin A</td>
<td>1915</td>
<td>1939</td>
<td>1942</td>
<td>–</td>
</tr>
<tr>
<td>Vitamin D</td>
<td>1919</td>
<td>1931</td>
<td>1932</td>
<td>1932</td>
</tr>
<tr>
<td>Vitamin E</td>
<td>1922</td>
<td>1936</td>
<td>1938</td>
<td>1938</td>
</tr>
<tr>
<td>Niacin</td>
<td>1926</td>
<td>1937</td>
<td>1937</td>
<td>1867*</td>
</tr>
<tr>
<td>Biotin</td>
<td>1926</td>
<td>1939</td>
<td>1942</td>
<td>1943</td>
</tr>
<tr>
<td>Vitamin K</td>
<td>1929</td>
<td>1939</td>
<td>1942</td>
<td>1943</td>
</tr>
<tr>
<td>Pantothenic Acid</td>
<td>1931</td>
<td>1939</td>
<td>1939</td>
<td>1940</td>
</tr>
<tr>
<td>Folate</td>
<td>1931</td>
<td>1939</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Riboflavin</td>
<td>1933</td>
<td>1934</td>
<td>1935</td>
<td>1935</td>
</tr>
<tr>
<td>Vitamin B6</td>
<td>1934</td>
<td>1936</td>
<td>1938</td>
<td>1939</td>
</tr>
</tbody>
</table>

* Was established long before it was known to be a vitamin

A number of B vitamins serve as cofactors/coenzymes. The following table lists the cofactors/coenzymes formed from B vitamins that will be discussed in more detail in the following subsections.

Table 8.13 Cofactors/coenzymes formed from B vitamins
<table>
<thead>
<tr>
<th>Vitamin</th>
<th>Cofactors/Coenzymes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thiamin</td>
<td>Thiamin Pyrophosphate (TPP)</td>
</tr>
<tr>
<td></td>
<td>Flavin Adenine Dinucleotide (FAD),</td>
</tr>
<tr>
<td>Riboflavin</td>
<td>Flavin Mononucleotide (FMN)</td>
</tr>
<tr>
<td></td>
<td>Nicotin Adenine Dinucleotide (NAD),</td>
</tr>
<tr>
<td>Niacin</td>
<td>Nicotin Adenine Dinucleotide Phosphate (NADP)</td>
</tr>
<tr>
<td>Pantothenic Acid</td>
<td>Coenzyme A</td>
</tr>
<tr>
<td>Vitamin B6</td>
<td>Pyridoxal Phosphate (PLP)</td>
</tr>
<tr>
<td>Biotin</td>
<td>-</td>
</tr>
<tr>
<td>Folate</td>
<td>Tetrahydrofolate (THF)</td>
</tr>
<tr>
<td>Vitamin B12</td>
<td>Adenosylcobalamin, Methylcobalamin</td>
</tr>
</tbody>
</table>

**References & Links**
8.2 Minerals

Minerals are elements that are essential for body functions that can’t be synthesized in the body. Some people refer to them as elements instead of minerals, and the names can be used interchangeably. However, in the nutrition community, they are more commonly referred to as minerals. Minerals can be divided up into three different categories:

- Macrominerals
- Trace Minerals (aka Microminerals)
- Ultratrace Minerals

There is not an exact, agreed on definition for how the different categories are defined, but in general they are defined by the amount required and found in the body such that:

Macrominerals > Trace Minerals > Ultratrace Minerals

Table 8.21 Alphabetical listing of the 20 minerals and their chemical symbols

<table>
<thead>
<tr>
<th>Macrominerals</th>
<th>Trace Minerals</th>
<th>Ultratrace Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca)</td>
<td>Chromium (Cr)</td>
<td>Arsenic (As)</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>Copper (Cu)</td>
<td>Boron (B)</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>Fluoride (F)</td>
<td>Nickel (Ni)</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>Iodine (I)</td>
<td>Silicon (Si)</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>Iron (Fe)</td>
<td>Vanadium (V)</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>Manganese (Mn)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molybdenum (Mo)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selenium (Se)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zinc (Zn)</td>
<td></td>
</tr>
</tbody>
</table>

a Chlorine ion, Cl-
b Phosphate in body, PO4

The table below shows the estimated amount of the macrominerals, trace minerals, and ultratrace minerals found in the body.

<table>
<thead>
<tr>
<th>Macrominerals</th>
<th>Trace Minerals</th>
<th>Ultratrace Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>1200 g</td>
<td>Iron</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>780 g</td>
<td>Fluoride</td>
</tr>
<tr>
<td>Potassium</td>
<td>110-140 g</td>
<td>Zinc</td>
</tr>
<tr>
<td>Sodium</td>
<td>100 g</td>
<td>Copper</td>
</tr>
<tr>
<td>Chloride</td>
<td>95 g</td>
<td>Selenium</td>
</tr>
<tr>
<td>Magnesium</td>
<td>25 g</td>
<td>Manganese</td>
</tr>
</tbody>
</table>

Minerals are elements. The figure below shows the distribution of minerals in the periodic table, which you should be familiar with from your chemistry education.

Figure 8.21 Minerals are elements, this figure shows their position within the periodic table.

8.2 Minerals | 431
References & Links

There are two common ways to teach about vitamins and minerals in nutrition classes. The traditional way is to start with fat-soluble vitamins and go down through the vitamins alphabetically (i.e. vitamin A, vitamin D, vitamin E, vitamin K). However, this method leads students to learn about vitamins and minerals more individually instead of how they work together. For instance, it makes sense to cover calcium with vitamin D, and iron with copper and zinc. We are going to cover vitamins and minerals based on their function rather than covering them by whether they are a water-soluble vitamin or trace mineral. The hope is that you will gain a more integrative understanding of vitamins and minerals from this approach.

Here are the different functional categories that we are going to cover. Notice that some micronutrients fit into more than one functional category. Each vitamin and mineral will be covered only in one section, with some mention of its overlap in other section(s) in certain cases.
<table>
<thead>
<tr>
<th>Antioxidants</th>
<th>Macronutrient Metabolism</th>
<th>1-Carbon Metabolism</th>
<th>Blood</th>
<th>Bones &amp; Teeth</th>
<th>Electrolytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitamin E</td>
<td>Thiamin</td>
<td>Folate</td>
<td>Vitamin K</td>
<td>Vitamin D</td>
<td>Sodium</td>
</tr>
<tr>
<td>Vitamin C</td>
<td>Riboflavin</td>
<td>Vitamin B12</td>
<td>Iron</td>
<td>Calcium</td>
<td>Potassium</td>
</tr>
<tr>
<td>Selenium</td>
<td>Niacin</td>
<td>Vitamin B6</td>
<td>Vitamin B6</td>
<td>Vitamin K</td>
<td>Chloride</td>
</tr>
<tr>
<td>Iron</td>
<td>Pantothenic Acid</td>
<td>Folate</td>
<td>Phosphorus</td>
<td>Phosphorus</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>Vitamin B6</td>
<td>Vitamin B12</td>
<td>Magnesium</td>
<td>Magnesium</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>Biotin</td>
<td>Copper</td>
<td>Fluoride</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Vitamin B12</td>
<td>Calcium</td>
<td>Vitamin A</td>
<td>Iron</td>
<td></td>
</tr>
<tr>
<td>Riboflavin</td>
<td>Vitamin C</td>
<td>Iodine</td>
<td>Copper</td>
<td>Zinc</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manganese</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnesium</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**No References**
112. 8.4 Dietary Reference Intakes (DRIs)

Dietary Reference Intakes (DRIs) are more than numbers in the table, even though that is often how many people view them. The link below takes you to the tables that many people commonly associate with the DRIs. These tables have been updated to include the new RDAs for vitamin D and calcium.

---

**Web Link**

[DRI Tables](#)

Most of you are probably familiar with Dietary Guidelines. DRIs and Dietary Guidelines provide different information for different audiences.

Dietary Guidelines provide **qualitative** advice to the **public** about diet and chronic disease prevention and maintaining health.

DRIs provide **quantitative** advice to **professionals** about amounts of nutrients or food components to be of benefit.

DRIs are a collective term to refer to these components:
- Estimated Average Requirement (EAR)
- Recommended Dietary Allowance (RDA)
- Adequate Intake (AI)
- Tolerable Upper Intake Level (UL)

A number of people refer to the UL as simply the “upper limit”, leaving off “tolerable”.

The RDA is the measure that professionals use to assess the quality of people’s diets. It is the requirement estimated to meet the needs of 97.5% of the population. But the RDA is calculated using the EAR. Therefore, the EAR needs to be set before an RDA can be set. There must be applicable research in order to set an EAR. An EAR is the estimated requirement for 50% of the population (hence
the average in its name), as shown in the figure below. On the left vertical axis is the risk of inadequacy, and on the bottom of the figure is the observed level of intake that increases from left to right. We will talk about the right axis label in a later figure. Notice that for the EAR, the risk for inadequacy is 0.5 (50%) whereas the RDA the risk of inadequacy is 0.025 (2.5%).

Figure 8.41 The EAR meets the needs of 50% of the population, RDA meets the needs of 97.5% of the population.

The figure below shows the EAR on the normal distribution and splits out the different standard deviations as percents. Notice that for 50% of population, their adequate intake is below the EAR and 50% of the population their adequate intake is above the EAR.
Figure 8.42 The EAR meets the needs of 50% of the population as depicted in this normal distribution. SD – standard deviation

If an EAR is set, the formula for setting the RDA is:

\[ \text{EAR} + 2 \text{ Standard Deviations} = \text{RDA} \]

The following figure shows the distribution and how the percentages and standard deviation changes from the EAR. Only 2.5% of the population will have a need above the RDA for a particular nutrient.
For nutrients lacking the research evidence needed to set an EAR, an AI is set instead. An AI is a level that appears to be adequate in a defined population or subgroup. As you can see, the EAR is adequate for 50% (0.5) of the population and is lower than the RDA. The RDA is adequate for 97.5% (0.025) of the population, and higher than the EAR. The AI level of intake is believed to be between the EAR/RDA and the UL, but since it is not research-based, it is not exactly known where this level falls as shown below.
The last of the DRIs is the Tolerable Upper Intake Level (UL). This is the highest level of daily nutrient intake that is unlikely to pose risk of adverse health effects to almost all individuals in the population. To set this, the committee first sets a no observed adverse effect level (NOAEL) and/or the lowest observed adverse effect level (LOAEL). The UL is then set lower based on a number of uncertainty/safety factors off the NOAEL or LOAEL as shown below. The right vertical axis is used to represent the risk of an adverse event. Notice the NOAEL at the point where no adverse effects have been reported. The LOAEL is somewhere above the NOAEL. The UL is set at a level where it is believed that people will not experience the selected adverse effect.
How are Americans doing in meeting the DRIs? The following figure shows the percentage of Americans that are not meeting the EAR for some of the earlier micronutrients that had DRIs set. Keep in mind that the EAR is lower than the RDA.
As you can see, a large percentage of Americans don’t meet the EAR for vitamin E, magnesium, vitamin A, and vitamin C. Also, keep in
mind that this also does not include micronutrients that have AI instead of EARs and RDAs.

References & Links


Link

PART IX
CHAPTER 9
This chapter will describe what antioxidants are and then discuss the three major antioxidant micronutrients: vitamin E, vitamin C and selenium.

9.1 Antioxidants
9.2 Vitamin E
9.3 Vitamin C
9.4 Selenium
The antioxidant vitamins and minerals are:

- Vitamin E
- Vitamin C
- Selenium
- Iron
- Copper
- Zinc
- Manganese
- Riboflavin

In this section, we are going to cover vitamin E, vitamin C, and selenium in detail because being an antioxidant is their primary function. Iron, copper, zinc, and manganese are cofactors for the antioxidant enzymes catalase and superoxide dismutase, as shown below.

![Antioxidant enzymes that use minerals as cofactors](image-url)
Superoxide dismutase converts superoxide into hydrogen peroxide. Catalase converts hydrogen peroxide into water. Iron, copper, and zinc will be covered in more detail in the blood, bones, and teeth chapter (chapter 11). Manganese will be covered in the macronutrient metabolism chapter.

Riboflavin, in the cofactor FAD, is an important cofactor for several antioxidant enzymes, but it will be covered in more depth in the macronutrient metabolism micronutrients chapter (Chapter 10).

Subsections:
9.11 Free Radicals & Oxidative Stress
9.12 What is an Antioxidant?
9.13 Meaningful Antioxidant(s)
9.14 Too Much of a Good Thing? Antioxidants as Pro-oxidants
Before you can understand what an antioxidant is, it is important to have an understanding of oxidants. As you have learned already, oxidation is the loss of an electron as shown below.

Some important terms to understand:

**Free Radical** – a molecule with an unpaired electron in its outer orbital.

The following example shows normal oxygen losing an electron from its outer orbital and thus, becoming an oxygen free radical.
Free radicals are highly reactive because they actively seek an electron to stabilize the molecule.

**Reactive Oxygen Species (ROS)** – an oxygen-containing, free radical species.

Some of the most common ROS are (● symbolizes radical):
- Superoxide (O2●)
- Hydroxyl Radical (●OH)
- Hydrogen Peroxide Radical (HO2●)
- Peroxyl Radical (ROO2●)
- Alkoxyl Radical (RO●)
- Ozone (O3)
- Singlet Oxygen (1O2)
- Hydrogen Peroxide (H2O2)

**Oxidative Stress** – the imbalance between the production of ROS/free radicals and the body’s ability to quench them.

The following video does a good job illustrating how free radicals can be formed and quenched by antioxidants.

---

**Web Link**

Video: How Antioxidants Work (4:31), watch first minute
The following figure shows that inflammation caused by hitting your thumb with a hammer, exposure to UV light, radiation, smoking, and air pollution are all sources of free radicals.

Free radicals can be generated by a variety of sources that can be classified as endogenous (within the body) and exogenous sources (outside the body). The link below is a figure that shows how ROS can be generated from each of these sources.

**Web Link**

Sources and - Cellular Responses to Reactive Oxygen Species

So, we have these free radicals searching for an electron, what’s the big deal? The problem arises if the free radicals oxidize LDL, proteins, or DNA as shown below.
Free radicals can attack LDL, proteins, and DNA. Oxidized LDL is more atherogenic, meaning it is more likely to contribute to atherosclerosis (hardening of the arteries) than normal LDL. Protein oxidation is believed to be involved in the development of cataracts. Cataracts are the clouding of the lens of the eye. If you would like to see what it looks like, see the link below.

**Web Link**

**Cataract Vision Simulator**

If a nucleotide in DNA is attacked, it can result in a mutation. A mutation is a change in the nucleotide or base pair sequence of DNA. Mutations are a common occurrence in cancer.

**References & Links**

2. [http://www.genome.gov/Pages/Hyperion(DIR)/VIP/Glossary/Illustration/amino_acid.cfm?key=amino%20acids](http://www.genome.gov/Pages/Hyperion(DIR)/VIP/Glossary/Illustration/amino_acid.cfm?key=amino%20acids)

**Videos**

How Antioxidants Work – [https://www.youtube.com/watch?v=lG3O0XIXvwx](https://www.youtube.com/watch?v=lG3O0XIXvwx)
Links

Sources and Cellular Responses to Reactive Oxygen Species – http://www.nature.com/nature/journal/v408/n6809/fig_tab/408239a0_F1.html

9.12 What is an Antioxidant?

We are ready to move on to antioxidants, which as their name indicates, combat free radicals, ROS, and oxidative stress. As a humorous introduction, the link below is to a cartoon that shows Auntie Oxidant kicking free radicals out of the bloodstream.

**Web Link**

*Auntie Oxidant*

But it’s not quite that simple. You have probably heard the saying “take one for the team.” Instead of taking one for the team, antioxidants “give one for the team.” The ‘giving’ is the donation of an electron from the antioxidant to a free radical, in order to regenerate a stable compound, as shown below.

*Figure 9.121 Regeneration of normal oxygen from oxygen free radical by the donation of an electron from an antioxidant*
Donating an electron is how vitamins act as antioxidants. Minerals, on the other hand, are not antioxidants themselves. Instead, they are cofactors for antioxidant enzymes.

These antioxidant enzymes include:

Superoxide dismutase (SOD): uses copper, zinc, and manganese as cofactors (there is more than one SOD enzyme); converts superoxide to hydrogen peroxide and oxygen\(^1\).

Catalase: uses iron as a cofactor; converts hydrogen peroxide to water\(^1\).

Glutathione peroxidase (GPX): is a selenoenzyme that converts hydrogen peroxide to water. It can also convert other reactive oxygen species (ROSs) to water\(^1\).

The action of these enzymes is shown below.

Figure 9.122 Antioxidant enzymes that use minerals as cofactors

Antioxidants are thought to work in concert with one another, forming what is known as the antioxidant network. An example of the antioxidant network is shown below. Alpha-tocopherol (major form of vitamin E in our body) is oxidized, forming an alpha-
tocopherol radical. This donation of an electron stabilizes reactive oxygen species. Ascorbate (vitamin C) is then oxidized, forming dehydroascorbate to regenerate (reduce) alpha-tocopherol. Ascorbate is then regenerated by the selenoenzyme thioredoxin reductase. This demonstrates how antioxidants can function as a network to regenerate one another so they can continue to function as antioxidants.

Figure 9.123 The theorized antioxidant network

References & Links

Link
Auntie Oxidant – http://www.ibiblio.org/Dave/Dr-Fun/df200005/df20000523.jpg
There is a lot of confusion among the public on antioxidants. For the most part, this is for a good reason. Many food companies put antioxidant numbers on the packages that sound good to consumers, who have no idea how to interpret them. Thus, it is increasingly important to have an understanding of what a meaningful antioxidant actually is.

A meaningful antioxidant has two characteristics (these are based on the assumption that the compound is an antioxidant):

1. Found in appreciable amounts right location where there are free radicals/ROS that need to be quenched
2. It is not redundant with another antioxidant that is already serving as an antioxidant

What do these mean? Let’s consider the example of lycopene and vitamin E (alpha-tocopherol), which are both fat-soluble antioxidants. In vitro antioxidant assays have found that lycopene is 10-fold more effective in quenching singlet oxygen than alpha-tocopherol. However, when you look at the concentrations found in the body, there is far more alpha-tocopherol than lycopene. For example:

LDL on average contains 11.6 molecules of alpha tocopherol and 0.9 molecules of lycopene. Thus, if we divide alpha tocopherol by lycopene 11.6/0.9 we find that there is on average 12.9 times more alpha-tocopherol than lycopene.

Other examples in the body:
Prostate – 162-fold higher alpha-tocopherol than lycopene concentrations
Skin – 17 to 269-fold higher alpha-tocopherol than lycopene concentrations
Plasma – 53-fold higher alpha tocopherol than lycopene concentrations\(^1\)

Thus, despite the fact that lycopene is a better antioxidant \textit{in vitro}, since the concentration of alpha-tocopherol is so much higher in tissues (locations of need), it is likely the more meaningful antioxidant. In addition, if lycopene and alpha-tocopherol have similar antioxidant functions (fat-soluble antioxidants), lycopene's potential antioxidant action is redundant to alpha-tocopherol's antioxidant function and thus, also less likely to be a meaningful antioxidant. Indeed, further examination of the literature has not suggested that lycopene can act as an antioxidant \textit{in vivo}, even though it is a good one \textit{in vitro}\(^1\).

You may be wondering “What about the in vitro antioxidant assays, like the oxygen radical absorbance capacity (ORAC) assay that some food and supplement companies are including on their labels?” This is an example of how some companies/businesses use ORAC values to market their product(s). However, the USDA removed its table of ORAC values “due to mounting evidence that the values indicating antioxidant capacity have no relevance to the effects of specific bioactive compounds, including polyphenols on human health\(^2\).”

\underline{Web Link}

\underline{Sozo Coffee ORAC Comparison}

However, going back to the two characteristics of meaningful antioxidants, there really is no evidence that shows that a high ORAC score leads to any benefit \textit{in vivo}. This is because the measure also doesn’t take into account characteristics such as bioavailability. Bioavailability is the amount of a compound that is absorbed or reaches circulation. Many of these purported super antioxidants have not been shown to be absorbed or maintained in the body in a way that would suggest that they would be meaningful antioxidants. 5 years after it was removed, industry and suppliers think it has
been a good thing that it is no longer used as indicated in the following article.

Web Link

Saying goodbye to ORAC was a good thing for industry, suppliers say

References & Links


Link

Sozo Coffeee ORAC Comparison – http://www.sozoglobal.com/products/?sec=1

Saying goodbye to ORAC was a good thing for industry, suppliers say – http://www.nutraingredients-usa.com/Suppliers2/Saying-goodbye-to-ORAC-was-a-good-thing-for-industry-suppliers-say
Chapter 1 described a clinical trial that found that high-dose beta-carotene supplementation increased lung cancer risk in smokers. This is an example of findings that support that high doses of antioxidants may be “too much of a good thing”, causing more harm than benefit. The parabolic, or U-shaped figure, below displays how the level of nutrient concentration or intake (x-axis) relates to an antioxidant measure (y-axis). The lowest level of antioxidant intake or tissue concentration results in nutrient deficiency if the antioxidant is essential (vitamins and minerals). Intake levels above deficient, but less than optimal, are referred to as low suboptimal. Suboptimal means the levels are not optimal. Thus, low suboptimal and high suboptimal sandwich optimal. The high suboptimal level is between optimal and where the nutrient becomes toxic.
An example of where this phenomenon has been shown to occur is in the dog prostate with toenail selenium concentrations, which are a good indicator of long-term selenium status\(^1\). Researchers found that when they plotted prostate DNA damage (antioxidant measure) against toenail selenium status (nutrient concentration or intake) that it resulted in a U-shaped curve like the one shown above\(^1\). Thus, it is good to have antioxidants in your diet, but too much can be counterproductive.

**References & Links**


There are 8 different forms of vitamin E: 4 tocopherols and 4 tocotrienols. The difference between tocopherols and tocotrienols is that the former have a saturated tail, while the latter have an unsaturated tail. Within tocopherols and tocotrienols, the difference between the different forms is the position of the methyl groups on the ring. The 4 different forms within the tocopherol and tocotrienols are designated by the Greek letters: alpha, beta, gamma, and delta. The difference in these structures is shown in the figures below.

For reasons that will be covered in a later subsection, the primary form of vitamin E found in the body is alpha-tocopherol. The major, and possibly only, function of vitamin E is as an antioxidant. When it serves as an antioxidant it forms an alpha-tocopherol radical, as shown below.
Alpha-tocopherol is believed to be the first part of an antioxidant network (shown below) where it is oxidized to donate an electron to stabilize reactive oxygen species. Alpha-tocopherol radical can then be reduced by the donation of an electron from ascorbate.

To help protect the antioxidant function of alpha-tocopherol (by preventing the formation of alpha-tocopherol radical) in foods and during digestion, some manufacturers have added compounds to this site of alpha-tocopherol through ester bonds. These are referred to as alpha-tocopherol derivatives or alpha-tocopherol esters. The most common forms are alpha-tocopherol acetate, alpha-tocopherol succinate, and alpha-tocopherol phosphate.
Alpha-tocopherol derivatives, such as acetate in alpha-tocopherol acetate, are cleaved prior to absorption in the small intestine by esterases, meaning that alpha-tocopherol is absorbed, not the alpha-tocopherol derivative.

Subsections:
9.21 Alpha-Tocopherol: Natural vs. Synthetic
9.22 Absorption, Metabolism & Excretion of Vitamin E
9.23 Dietary Vitamin E & Amounts Found in Body
9.24 Vitamin E Deficiency & Toxicity
9.25 Vitamin E DRI & IUs

References & Links
In addition to being found naturally in foods, alpha-tocopherol can also be synthesized. It is important to know whether alpha-tocopherol is natural or synthetic because the stereochemistry differs between these forms. Alpha-tocopherol contains 3 chiral centers (non-superimposable mirror images) designated as R or S. If this is a new topic to you or you would like a refresher, the following link is a fun, animated chirality game.

**Web Link**

[Chirality Game](#)

The 3 chiral centers in alpha-tocopherol are located at the 2, 4', and 8' positions. You can see the full numbering of tocopherols in the link below. In short, the rings are normal numbers and the tail are prime numbers.

**Web Link**

[Tocopherol Numbering](#)

The figure below shows the 3 chiral centers without the other numbers.
In natural alpha-tocopherol, all 3 chiral centers are in the R configuration. Thus, it is designated RRR-alpha-tocopherol. The R's represent the 2, 4', and 8' positions of alpha-tocopherol, respectively, as shown below.

Synthetic alpha-tocopherol is a racemic (equal) mixture of all the
different stereochemical possibilities at the three chiral centers. These are:

- RRR
- RRS
- RSS
- RSR
- SRR
- SSR
- SSS
- SRS

The two forms of alpha-tocopherol are designated (these are placed before alpha-tocopherol to indicate whether it is natural or synthetic) as listed below:

1. **Natural**
   - New designation: RRR-alpha-tocopherol (because all 3 positions are RRR)
   - Old designation: d-alpha-tocopherol

2. **Synthetic**
   - New designation: all-rac-alpha-tocopherol (because it is a racemic mixture)
   - Old designation: dl-alpha-tocopherol

The old d and dl designations were describing the chemical structure that are sometimes still used. Keep in mind the natural and synthetic are describing the stereochemistry of alpha-tocopherol and not whether it is naturally derived. For example, there are natural alpha-tocopherol derivatives where the derivatives are added through synthetic procedures.

**References & Links**

1. [http://lpi.oregonstate.edu/mic/vitamins/vitamin-E](http://lpi.oregonstate.edu/mic/vitamins/vitamin-E)

**Link**

You might be saying to yourself, “who cares about natural versus synthetic alpha-tocopherol.” But the small change in stereochemistry makes a big difference in how alpha-tocopherol is maintained in the body.

All forms of vitamin E (tocopherols, tocotrienols) are absorbed equally. Fat-soluble vitamins are handled like lipids and thus are incorporated into chylomicrons that have triglycerides removed by lipoprotein lipase. The chylomicron remnants containing the different forms of vitamin E are then taken up by the liver. The figure below shows the absorption, metabolism, and excretion of vitamin E.

![Figure 9.221 The absorption, metabolism, and excretion of vitamin E](image)
The liver contains a protein called alpha-tocopherol transfer protein (alpha-TTP), which is responsible for maintaining higher levels of alpha-tocopherol in the body. Alpha-TTP preferentially binds to 2R alpha-tocopherol and helps facilitate its incorporation into VLDL. 2R means any form of alpha-tocopherol in which the 2 position is in the R conformation. The following table summarizes the forms of alpha-tocopherol that bind well to alpha-TTP, and those that don’t bind well to alpha-TTP.

Table 9.221 Alpha-tocopherol isomers and binding to alpha-TTP

<table>
<thead>
<tr>
<th>Do not bind well to alpha-TTP</th>
<th>Bind well to alpha-TTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRR</td>
<td>RRR</td>
</tr>
<tr>
<td>SSR</td>
<td>RRS</td>
</tr>
<tr>
<td>SSS</td>
<td>RSS</td>
</tr>
<tr>
<td>SRS</td>
<td>RSR</td>
</tr>
</tbody>
</table>

Other forms of vitamin E (gamma-tocopherol, tocotrienols) also don’t bind well to alpha-TTP and thus, are found in lower levels than alpha-tocopherol in the body. The following graph shows plasma vitamin E levels from a study in which subjects were given 150 mg each of RRR-alpha-tocopherol, all-rac-alpha-tocopherol, or gamma-tocopherol^1.
Figure 9.22 Plasma vitamin E concentrations in response to a 150 mg dose of RRR-alpha-tocopherol, all-rac-alpha-tocopherol, or gamma-tocopherol. Adapted from reference 1

As you can see in the figure, there was a greater rise in the plasma alpha-tocopherol levels after receiving RRR-alpha-tocopherol vs. all-rac-alpha-tocopherol. This is not a surprise because approximately 50% of all-rac-alpha-tocopherol is 2R alpha-tocopherol that binds well with alpha-TTP. You can also see that the plasma gamma-tocopherol concentration is much lower than either natural or synthetic alpha-tocopherol.

From VLDL and subsequent lipoproteins, vitamin E reaches tissues, with most vitamin E in the body being found in the adipose tissue. There are two main routes of vitamin E excretion. The major route of excretion is through bile that is then excreted in feces. The second route is in the urine after vitamin E is chain-shortened in a process similar to beta-oxidation to make them more water-soluble.

Reference

1. Traber MG, Elsner A, Brigelius-Floh R. (1998) Synthetic as compared with natural vitamin E is preferentially excreted as alpha-
The best food sources of vitamin E are primarily oils and nuts. As you can see below, the forms of vitamin E that nuts and oils contain varies, with the two major forms being alpha and gamma-tocopherol. Soybean, corn, and flaxseed oils are good sources of gamma-tocopherol. Palm and canola oils contain almost equal amounts of alpha-tocopherol and gamma-tocopherol. Safflower oil, almonds, sunflower oil, and wheat germ oil are good sources of alpha-tocopherol. Beta-tocopherol and delta-tocopherol are found in lower levels in foods. Tocotrienols, for the most part, are not found in high levels in the diet. The amount of tocopherols in different nuts and oils are shown in the figure below.

Figure 9.23.1 Tocopherol distribution in plant products
Three-fourths of the oil Americans consume is soybean oil. As a result, it is estimated that we consume 2-4 times more gamma-tocopherol than alpha-tocopherol. Europeans consume more olive, sunflower, and canola oil and thus are believed to consume at least 2 times more alpha-tocopherol than gamma-tocopherol.

Despite Americans’ higher intake of gamma tocopherol compared to other countries, our serum concentrations do not differ much as illustrated in the table below.

Table 9.231 International serum gamma-tocopherol and alpha-tocopherol concentrations (uM/L)

<table>
<thead>
<tr>
<th>Location</th>
<th>Gamma-tocopherol</th>
<th>Alpha-tocopherol</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA 1*</td>
<td>2-7</td>
<td>15-20</td>
</tr>
<tr>
<td>USA 2</td>
<td>5.4</td>
<td>22.3</td>
</tr>
<tr>
<td>USA 3</td>
<td>2.5</td>
<td>21.8</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>2.7</td>
<td>28.6-31.8</td>
</tr>
<tr>
<td>France</td>
<td>1.05-1.28</td>
<td>26.7</td>
</tr>
<tr>
<td>Ireland</td>
<td>1.74-1.87</td>
<td>26.3</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>2.3</td>
<td>23.9-25.5</td>
</tr>
<tr>
<td>Spain</td>
<td>0.88-1.14</td>
<td>27.4-28.3</td>
</tr>
<tr>
<td>Italy</td>
<td>1.29</td>
<td>24.3</td>
</tr>
<tr>
<td>Sweden</td>
<td>3.2</td>
<td>23.8</td>
</tr>
<tr>
<td>Lithuania</td>
<td>1.64</td>
<td>21.7</td>
</tr>
<tr>
<td>Austria</td>
<td>1.48</td>
<td>21.1</td>
</tr>
</tbody>
</table>

There are 3 different studies that have reported serum levels in the United States.

Tissue concentrations, for the most part, also indicate a greater accumulation of alpha-tocopherol than gamma-tocopherol as shown in the table below.

Table 9.232 Tissue gamma-tocopherol and alpha-tocopherol concentrations (nM/g)
<table>
<thead>
<tr>
<th>Tissue</th>
<th>Gamma-tocopherol</th>
<th>Alpha-tocopherol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>180</td>
<td>127</td>
</tr>
<tr>
<td>Adipose</td>
<td>176</td>
<td>440</td>
</tr>
<tr>
<td>Muscle</td>
<td>107</td>
<td>155</td>
</tr>
</tbody>
</table>

**Reference**

Vitamin E deficiency is extremely rare. Depletion studies require years on a vitamin E-deficient diet to cause deficiency\(^1\). Deficiency primarily occurs in people with lipid malabsorption problems or Ataxia with Isolated Vitamin E Deficiency (AVED). Individuals with AVED have a mutation in their alpha-TTP that prevents it from functioning correctly. The primary symptoms of vitamin E deficiency are neurological problems.

High levels of vitamin E intake do not result in a noted toxicity. However, higher levels of intake are associated with decreased blood coagulation. In particular, hemorrhagic stroke has been linked to high vitamin E levels. The link below shows that in this condition a blood vessel ruptures or leaks in the brain.

**Web Link**

**Hemorrhagic Stroke**

It is believed that this increased bleeding risk is due to a vitamin E metabolite that has anti-vitamin K activity. This potential antagonism will be described more in the vitamin K section.

**References & Links**


**Link**

Hemorrhagic Stroke – http://heart.arizona.edu/heart-health/preventing-stroke/lowing-risks-stroke
Before 2001, all forms of vitamin E contributed to the RDA, using a measure called alpha-tocopherol equivalents. In 2001, the Dietary Reference Intake (DRI)\(^2\) committee decided only 2R forms of alpha-tocopherol should be used to estimate the requirement, because these forms bind to alpha-TTP. Thus, other forms of vitamin E (gamma-tocopherol\(^1\), tocotrienols etc.) do not count toward the requirement and the unit is now mg of alpha-tocopherol. As a result, soybean, corn, and flaxseed oils, which are good sources of gamma-tocopherol, are no longer considered to be good sources of vitamin E. The figure below is a reminder of the tocopherol content of different nuts and oils.

Figure 9.251 Only the yellow bars count toward the 2001 DRI requirement

Another level of complexity is added by the introduction of international units (IU). IUs are a unit that are used to describe the bioactivity of different compounds, including 4 vitamins: A, D, E, and
C. It would be less confusing if these units were not used. However, most supplements use IUs. IUs are not as common on food items.

For vitamin E, IUs are specific for alpha-tocopherol and adjusted for the molecular weight of the different forms (alpha-tocopherol acetate etc.). The conversion factors for converting IU to mg of alpha-tocopherol are:

- 0.67 for RRR-alpha-tocopherol (and its esters)
- 0.45 for all-rac-alpha-tocopherol (and its esters)

Here are some example calculations showing how to use these conversion factors:

Example 1. For a supplement containing 100 IU of RRR-alpha-tocopherol:

\[
100 \text{ IU} \times 0.67 = 67 \text{ mg alpha-tocopherol}
\]

Example 2. For a supplement containing 100 IU of all-rac-alpha-tocopherol:

\[
100 \text{ IU} \times 0.45 = 45 \text{ mg alpha-tocopherol}
\]

**References & Links**

9.3 Vitamin C

Vitamin C is well-known for being a water-soluble antioxidant. Humans are one of the few mammals that don't synthesize vitamin C, making it an essential micronutrient. Other mammals that don't synthesize vitamin C include primates, guinea pigs, and other less prevalent species.

Vitamin C's scientific names are ascorbic acid or ascorbate and the oxidized form is dehydroascorbic acid or dehydroascorbate. The structure of vitamin C is shown below.

![Structure of ascorbic acid](image)

Figure 9.31 Structure of ascorbic acid
When ascorbic acid is oxidized, it forms semidehydroascorbate (1 degree of oxidation) and then dehydroascorbate (2 degrees of oxidation). The structure of dehydroascorbic acid is shown below.

![Figure 9.32 Structure of dehydroascorbic acid](image)

The figure below shows the reaction through which ascorbic acid can stabilize or quench 2 free radicals. The 2 circled hydrogens are lost and replaced by double bonds when ascorbic acid is oxidized to dehydroascorbic acid. Reducing dehydroascorbic acid back to ascorbic acid is the opposite reaction.
Ascorbic acid is believed to be a part of an antioxidant network (shown below) where it is oxidized to reduce alpha-tocopherol radicals\(^4\). Dehydroascorbic acid can be reduced by thioredoxin reductase, a selenoenzyme, to regenerate ascorbic acid.

Subsections:
- 9.31 Absorption and Tissue Accumulation of Vitamin C
- 9.32 Enzymatic Functions
9.33 Vitamin C Deficiency – Scurvy
9.34 Vitamin C Toxicity, Linus Pauling, & the Common Cold

References & Links
Vitamin C is found in foods primarily as ascorbic acid (80-90%), but dehydroascorbic acid (10-20%) is also present. The bioavailability of vitamin C is high at lower doses as shown below, but drops to less than 50% at higher doses.

Table 9.31 Bioavailability of vitamin C

<table>
<thead>
<tr>
<th>Dose (mg)</th>
<th>% Bioavailability</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>112</td>
</tr>
<tr>
<td>500</td>
<td>73</td>
</tr>
<tr>
<td>1250</td>
<td>49</td>
</tr>
</tbody>
</table>

Ascorbic acid is actively absorbed by the sodium vitamin C cotransporter (SVCT). This active transport is driven by the sodium electrochemical gradient created by sodium-potassium ATPase. Ascorbic acid then diffuses into the capillary and ultimately enters general circulation. Vitamin C generally circulates as ascorbic acid.
Accumulation

Most water-soluble vitamins are not stored in the body. Vitamin C is not stored, but is accumulated in certain tissues in the body where it can be 5-100 times higher than found in the plasma. The table below shows the concentrations of vitamin C in different tissues and fluids.

Table 9.3-2 Human tissue & fluid ascorbic acid concentrations

<table>
<thead>
<tr>
<th>Organ/Tissue</th>
<th>Vitamin C Concentration*</th>
<th>Organ/Tissue</th>
<th>Vitamin C Concentration*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pituitary Gland</td>
<td>40-50</td>
<td>Lungs</td>
<td>7</td>
</tr>
<tr>
<td>Adrenal Gland</td>
<td>30-40</td>
<td>Skeletal Muscle</td>
<td>3-4</td>
</tr>
<tr>
<td>Eye Lens</td>
<td>25-31</td>
<td>Testes</td>
<td>3</td>
</tr>
<tr>
<td>Liver</td>
<td>10-16</td>
<td>Thyroid</td>
<td>2</td>
</tr>
<tr>
<td>Brain</td>
<td>13-15</td>
<td>Cerebrospinal Fluid</td>
<td>3.8</td>
</tr>
<tr>
<td>Pancreas</td>
<td>10-15</td>
<td>Plasma</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Spleen</td>
<td>10-15</td>
<td>Saliva</td>
<td>0.1-9.1</td>
</tr>
<tr>
<td>Kidneys</td>
<td>5-15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 9.311 Ascorbic acid (Asc) absorption

484 | 9.31 Vitamin C Absorption & Tissue Accumulation
How does the body accumulate such high levels of vitamin C? There are 2 primary mechanisms:

1. Ascorbic Acid (Ascorbate) uptake using sodium-dependent vitamin C transporter (SVCT) 1 or 2
2. Ascorbic Acid (Ascorbate) Recycling

Ascorbic Acid (Ascorbate) transport using sodium-dependent vitamin C transporter (SVCT) 1 or 2

As shown below, SVCT 1 and SVCT 2 transport ascorbic acid or ascorbate into the cell against the concentration gradient (represented by the orange wedge in the figure below). Like absorption, this uptake is driven by the action of sodium-potassium ATPase. This mechanism is saturable, meaning that at high concentrations it reaches a threshold where it cannot take up ascorbic acid any faster. Thus, there is a limit to how much can be taken up through this mechanism.

![Figure 9.312 Ascorbic acid (Asc) uptake using SVCT 1 and 2 against the ascorbic acid concentration gradient](image-url)
**Ascorbic Acid (Ascorbate) Recycling**

In ascorbic acid recycling, ascorbic acid is oxidized to dehydroascorbic acid (DHA). DHA is then transported into the cell moving with its concentration gradient using GLUT1 or 3. Once inside the cell, DHA is reduced back to ascorbic acid, thus maintaining the DHA gradient. As a result, the cell is able to accumulate high levels of ascorbic acid. The figure below depicts ascorbic acid recycling. 

![Ascorbic Acid Recycling Diagram](image)

*Figure 9.313 Ascorbic acid recycling*

**References & Links**


In addition to its antioxidant function, vitamin C is also a cofactor for a number of enzymes. The enzymes proline hydroxylase and lysyl hydroxylase are important in the formation of the protein collagen. Hydroxylase means that the enzymes add alcohol (hydroxyl, -OH) to the amino acids proline and lysine, as shown below.

![Figure 9.321 Proline hydroxylase adds an alcohol group (circled) to proline forming hydroxyproline](image1)

![Figure 9.322 Lysyl hydroxylase adds an alcohol group (circled) to lysine forming hydroxylysine](image2)

As shown below, proline and lysyl hydroxylases require ferrous iron (Fe2+) to function. But in the course of the hydroxylating proline or lysine, ferrous iron (Fe2+) is oxidized to ferric iron (Fe3+). Ascorbic
Acid is required to reduce Fe$^{3+}$ to Fe$^{2+}$, forming semidehydroascorbic acid in the process. With Fe$^{2+}$, the enzyme is then able to continue to hydroxylate proline and lysine.

**Figure 9.323** Ascorbic acid reduces iron so that it can continue to serve as a cofactor for proline and lysyl hydroxylases

Why should you care about collagen formation? Because collagen is estimated to account for 30% or more of total body proteins$^5$. Collagen contains a number of hydroxylated prolines and lysines that are needed for collagen strands to properly cross-link. This cross-linking is important for collagen to wind together like a rope, forming the strong triple helix known as tropocollagen. This process is shown in the following animation, as well as in the figure below.
But if there isn’t enough ascorbic acid available, the collagen strands are underhydroxylated and instead of forming strong tropocollagen, the underhydroxylated collagen is degraded as shown below.
This weak collagen then results in the symptoms seen in the vitamin C deficiency, scurvy, that will be discussed in the next subsection. Ascorbic Acid is also needed for:

- Carnitine synthesis
- Tyrosine synthesis and catabolism
- Serotonin (neurotransmitter) synthesis
- Other hormone and neurotransmitter synthesis

The figure below shows how ascorbic acid is needed for dopamine hydroxylase, which ultimately produces the hormone epinephrine.

![Dopamine beta-hydroxylase requires ascorbic acid to produce norepinephrine](image)

**Figure 9.326** Dopamine beta-hydroxylase requires ascorbic acid to produce norepinephrine

**References & Links**

128. 9.33 Vitamin C Deficiency (Scurvy)

Why should you care about the functions of vitamin C? Because they explain the symptoms of vitamin C deficiency. While it is rare in the United States, vitamin C deficiency, known as scurvy, displays symptoms that are a result of weak collagen, that in turn, weakens connective tissue throughout the body. Symptoms of scurvy include bleeding gums, pinpoint hemorrhages, and corkscrew hairs as shown in the figure and link below.

Figure 9.331 Bleeding gums that occur in scurvy

Web Link

–Corkscrew Hairs

Additional symptoms include impaired wound and fracture healing, easy bruising, and loose or decaying teeth. Scurvy can be fatal if not
treated. Scurvy was the first discovered nutrition deficiency in 1746 by James Lind, who is shown below.

Figure 9.332 Dr. James Lind discovered that scurvy was caused by a nutrition deficiency

Keep in mind as you read the description below that suggesting scurvy was due to a diet deficiency, at that time, sounded like flu was caused by not consuming green beans. Sounds pretty crazy, right?
Lind was a surgeon on a British navy ship. Frequently during voyages the sailors would develop scurvy for reasons that weren’t understood at the time. It was known that citrus fruits could cure or prevent scurvy, but it was believed this was due to their acidity. Lind performed clinical trials comparing citrus juice to dilute sulfuric acid and vinegar and found that only citrus juice caused the sailors to recover, as depicted in the link below. As a result of the discovery, the British sailors became known as “Limeys” because they would drink lime juice to prevent the development of the disease⁴.

**Web Link**

*Curing Scurvy*

**References & Links**


**Links**


Vitamin C does not have a toxicity per se, but in some people over 2 grams/day can lead to diarrhea and gastrointestinal distress. In addition, high intake of vitamin C increases excretion of uric acid (urate) and oxalic acid (oxalate). The structure of these 2 compounds are shown below.

Figure 9.341 Structure of uric acid\(^1\)
These compounds are the primary components of 2 types of kidney stones\(^3\). The figures below show the most common sites of pain in someone with kidney stones.
The following video describes what kidney stones are and the symptoms that can occur if someone has kidney stones. The second link shows some pictures of kidney stones.

**Web Links**

- Video: Kidney Stones (1:16)
- Kidney Stones

Calcium oxalate is one of the primary forms of kidney stones with uric acid stones being more rare. However, a link between excretion of these compounds and actual stone formation hasn't been established. Nevertheless, high-dose vitamin C supplementation should be approached with some caution, since it is not clear whether it increases the risk of forming kidney stones.

**Linus Pauling and the common cold**

The person who popularized taking megadoses of vitamin C was
Dr. Linus Pauling. Dr. Pauling was a chemist, and is the only person to receive 2 unshared Nobel Prizes. The Nobel Prize is a prestigious award, and Dr. Pauling was close to solving the structure of DNA. This would have likely netted him another Nobel prize, but Watson and Crick beat him to it.

Figure 9.344 Linus Pauling
Later in his life Pauling became convinced that megadoses of vitamin C could prevent the common cold. In 1970 his book *Vitamin C and the Common Cold* was released and became a bestseller. Later he came to believe that vitamin C could prevent cardiovascular disease, cancer, and combat aging\(^7\). However, critics of his beliefs countered that all megadose supplementation was doing was creating “expensive urine”. This refers to the fact that the RDA is only 75-90 mg/day for adults and Pauling recommended taking 1-2 grams of vitamin C daily\(^8\). Thus, with vitamin C being water-soluble, most of the vitamin C that people on the regimen were paying to consume was being excreted in the urine, thus making it “expensive”.

A recent review of vitamin C and colds found that that routine megadoses of vitamin C do not reduce the risk of the common cold in most individuals. However, there is some evidence that it might benefit people exposed to brief periods of severe physical exercise (marathon runners) or cold environments (skiers and soldiers in subarctic conditions). There has been little research conducted in children, so it is not known whether vitamin C supplementation is beneficial in this age group\(^9\).

**References & Links**

8. http://www.health.harvard.edu/newsletter_article/
excerpts_from_vitamin_c_and_the_common_cold_by_linus_pauling


**Video**
Kidney Stones – [https://www.youtube.com/watch?v=l6ewFJ-iQtw](https://www.youtube.com/watch?v=l6ewFJ-iQtw)

**Links**
Selenium can be divided into 2 categories: organic and inorganic. The organic forms contain carbon, while the inorganic forms do not. The primary inorganic forms of selenium are selenite (SeO3) and selenate (SeO4). Selenite and selenate are not commonly found alone in nature; they are usually complexed with sodium to form sodium selenite (Na2SeO3) and sodium selenate (Na2SeO4).

Selenomethionine is the most common organic form of selenium. The structure of selenomethionine is shown above the structure of the amino acid methionine in the figure below.

In comparing the structures of selenomethionine or methionine, you can see that the only difference is that selenium has been substituted for the sulfur (S) atom in methionine. Selenocysteine is
considered the 21st amino acid by some, because there is a codon that directs its insertion into selenoproteins. Like selenomethionine versus methionine, the only difference between selenocysteine and cysteine is the substitution of selenium for sulfur. The last organic form is methylselenocysteine (aka Se-methylselenocysteine). Notice that its structure is like selenocysteine, but with a methyl group added (like the name suggests).

The selenium content of plants is dependent on the soil where they are grown. As shown below, soil selenium levels vary greatly throughout the United States, meaning that the selenium content of plant foods also greatly vary.

Figure 9.42 United States soil selenium levels

The above map is interactive, so to see the soil selenium levels in a certain county or state, click on it in the link below.

Web Link

– USGS Soil Selenium Levels

Inorganic forms of selenium are commonly used in supplements. Selenomethionine is the most common organic form of selenium in supplements and food. It is found in cereal grains such as wheat,
corn, and rice as well as soy. Yeast are typically used to produce selenomethionine for supplements.

It should be noted that selenomethionine accumulates at much higher levels in the body than other forms of selenium. This is because it can be nonspecifically incorporated into body proteins in place of methionine. However, despite accumulating at higher levels, selenomethionine is less effective than the methylselenocysteine in decreasing cancer incidence or growth in animal models. However, methylselenocysteine is not commonly consumed, because it is a form that plants accumulate to prevent selenium from becoming toxic to themselves. Thus, plants need to be grown in the presence of high selenium levels to accumulate meaningful amounts of methylselenocysteine.

Subsections:
9.41 Selenoproteins
9.42 Selenium Absorption, Excretion, Toxicity & Its Questionable Deficiency

References & Links

Link
As mentioned earlier, selenium’s antioxidant function is not due to the mineral itself, but a result of selenoproteins. This is illustrated in the figure below, where the different colored circles represent amino acids in the crescent shaped enzyme. In most enzymes, the mineral is a cofactor that is external to the enzyme, as shown on the left. Selenoenzymes contain selenocysteine as an amino acid in the active site of the enzyme. Thus, in selenoenzymes, selenium does not serve as a cofactor, which is different than most minerals required for enzyme function.

25 human selenoproteins, containing the amino acid selenocysteine, have been identified. The following table lists these selenoproteins along with their function.

Table 9.4I The 25 Human Selenoproteins1-3
<table>
<thead>
<tr>
<th>Selenoprotein</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glutathione peroxidase 1 (GPX1)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Glutathione peroxidase 2 (GPX2)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Glutathione peroxidase 3 (GPX3)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Glutathione peroxidase 4 (GPX4)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Glutathione peroxidase 6 (GPX6)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Iodothyronine 5′-deiodinase-1 (DI1)</td>
<td>Plasma T3 production</td>
</tr>
<tr>
<td>Iodothyronine 5′-deiodinase-2 (DI2)</td>
<td>Local T3 production</td>
</tr>
<tr>
<td>Iodothyronine 5′-deiodinase-3 (DI3)</td>
<td>T3 degradation</td>
</tr>
<tr>
<td>Thioredoxin reductase (TR1)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Thioredoxin reductase (TR2)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Thioredoxin reductase (TR3)</td>
<td>Antioxidant enzyme</td>
</tr>
<tr>
<td>Selenophosphate synthetase 2 (SPS2)</td>
<td>Selenophosphate synthesis</td>
</tr>
<tr>
<td>Selenoprotein 15 (Sep15)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein H (SepH)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein I (SepI)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein K (SepK)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein M (SepM)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein N (SepN)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein O (SepO)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein P (SepP)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein R (SepR)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein S (SepS)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein T (SepT)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein V (SepV)</td>
<td>Unknown</td>
</tr>
<tr>
<td>Selenoprotein W (SepW)</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Hopefully from looking at the table, you see that the glutathione peroxidase enzymes and thioredoxin reductases are antioxidant enzymes. The iodothyronine 5′-deiodinases are involved in the metabolism of thyroid hormones, which will be discussed further in
the iodine section. For the vast majority of the other selenoproteins, their function isn’t known, so they were named selenoprotein and given a letter. As described earlier and shown below, glutathione peroxidase converts hydrogen peroxide into water.

\[ \text{Superoxide Dismutase (SOD)} \]
\[ \text{Cu, Zn, Mn} \]

\[ \text{Hydrogen Peroxide (H}_2\text{O}_2) \]

\[ \text{Catalase (Fe)} \]

\[ \text{Glutathione Peroxidase (GPX)} \]
\[ \text{Se} \]

\[ \text{Water (H}_2\text{O)} \]

\[ \text{Superoxide (O}_2^\cdot) \]

**Figure 9.412 Antioxidant enzymes that use minerals as cofactors}^3**

Remember that thioredoxin reductase can regenerate ascorbate from dehydroascorbate in the theorized antioxidant network (shown below).

**Figure 9.413 The theorized antioxidant network}^4**

506 | 9.41 Selenoproteins
References & Links


Selenium is highly absorbed. Thus, selenium levels in the body are not regulated by absorption, but rather by urinary excretion. Organic selenium forms may be absorbed slightly better than inorganic forms, as one study found that 98% of a dose of selenomethionine was absorbed, compared to 84% of selenite. Selenium is primarily excreted in the urine, but at high levels it can be expired, producing garlic odor breath.

Selenium toxicity can be a problem, especially for animals living in or around a body of water in an area with high soil selenium levels. This is because runoff from the soil causes selenium to collect in the water in high levels and then starts working its way up the food chain and causing problems, as shown in the following link.

**Web Link**

–Selenium Toxicity

In humans, the initial symptoms are nausea, fatigue, and diarrhea. If continued, the person may develop hair and nail brittleness, rash or skin lesions, and nervous system abnormalities.

The questionable selenium deficiency is Keshan disease. This disease occurred primarily in the mountainous regions of China, causing heart lesions. Below is a topographical map of China to give you an idea of what areas are mountainous.
You can see in the link below the areas where Keshan disease occurred. For the most part, you can see that these 2 areas overlay.

Web Links

Distribution of Keshan Disease–

However, sodium selenate supplementation failed to totally eradicate Keshan disease like you would expect if it was caused by selenium deficiency. The incidence of Keshan disease also fluctuated seasonally and annually, which is unusual for a deficiency and more consistent of an infectious disease. Research found coxsackievirus in the heart of Keshan disease victims. They isolated this virus and used it to perform the experiment illustrated below.
One group of mice was fed an adequate selenium diet and another group a deficient selenium diet. They were then infected with coxsackievirus that was mostly avirulent, but also contained some virulent viruses. A virulent virus is one that causes a disease, and an avirulent virus is one that doesn’t cause a disease (some vaccines use avirulent viruses). After a period of time, they found that the selenium deficient animals developed severe heart pathology, while the selenium adequate animals did not develop heart pathology. They then isolated the virus from the hearts of the mice from both groups and found that the coxsackievirus from the deficient animals hearts had become mostly virulent. They then took it one step further as shown in the figure below.

Figure 9.422 Keshan disease experiment
They took the isolated virus from the selenium-deficient mouse hearts and infected selenium adequate animals with it. The selenium adequate animals developed the severe heart pathology like the selenium-deficient animals had previously.

What’s going on? They found mutations in the virus from the selenium-deficient animals that they believe caused it to become virulent. They believe that high oxidative stress in these animals leads to mutations in the virus, causing it to become virulent.

Who cares? Research has found similar results with vitamin E. Researchers are also examining the effects on other viruses such as influenza (flu) and HIV. If they find a similar phenomenon occurring in other viruses, it means that you and your friend who eats a horrible diet (eats no fruit and vegetables) could be exposed to a virus. You don't know you were exposed because your immune system fights off the virus. However, your friend gets sick. He/she can serve as a host in which the virus mutates making it more virulent, which when you're exposed a second time, may make you sick.

References & Links

Links
Selenium Toxicity – http://www.sci.sdsu.edu/salton/SeTooMuchTooLittle.html
Distribution of Keshan Disease – http://pubs.acs.org/cen/80th/selenium.html
10 Macronutrient Metabolism

Micronutrients

The macronutrient metabolism vitamins and minerals are:

- Thiamin
- Riboflavin
- Niacin
- Pantothenic Acid
- Vitamin B6
- Biotin
- Vitamin B12
- Vitamin C
- Iodine
- Manganese
- Magnesium

All but three of these will be covered in this section. Vitamin B12 will be covered in the one-carbon metabolism chapter, vitamin C was covered in the antioxidant chapter, and magnesium is going to be covered in the electrolyte chapter. We're left with iodine, manganese, and many of the B vitamins. We'll cover the 2 minerals followed by the B vitamins with the order for the sections as follows:

10.1 Iodine
10.2 Manganese
10.3 Thiamin
10.4 Riboflavin
10.5 Niacin
10.6 Pantothenic Acid
10.7 Vitamin B6
10.8 Biotin
Why is iodine first in this chapter? Not only is it the only non-B vitamin in this chapter, but there is also a connection between selenium (last antioxidant in the previous chapter) and iodine. Iodine’s only, yet critical, function is that it is required for thyroid hormone synthesis. The figure below shows that the thyroid gland is a butterfly-shaped organ found in the neck. The parathyroid glands are also found within the thyroid gland.

**Thyroid and Parathyroid Glands**

![Thyroid and Parathyroid Glands](image)

*Figure 10.11 Location of thyroid and parathyroid glands*¹

Iodine is found in foods primarily as iodide (I⁻), some bread dough has iodate (IO₃⁻) added to help with gluten cross-linking². This used to be more commonly used in the past than it is now. Like selenium, iodide concentrations of the soil vary greatly, causing food concentrations to greatly fluctuate. Sea water is high in iodine, thus foods of marine origin, such as seaweed and seafood, are good dietary sources of iodine. Dairy products also tend to be good
sources of iodide because it is added to cattle feeds. Cattle receive iodine-containing medications, and iodide-containing sanitizing solutions are used in dairy facilities\(^3,4\).

For most Americans, we consume ample iodine through the consumption of iodized salt. Consumption of 1/2 teaspoon of iodized salt meets the RDA for iodine. There is a global logo for iodized salt. However, I must admit that I don't recall ever seeing it myself.

The other link below is to a page that contains a scorecard map that depicts access to iodized salt worldwide. It also contains a Youtube video that displays the reduction in iodine deficiency over the last 2 decades.

**Web Link**

Global Iodized Salt Icon
Global Iodine Scorecard

Salt is iodized with either potassium iodide (KI) or potassium iodate (KIO\(_3\)). The positives of each are:

**Potassium iodide**

- Less expensive
- Higher iodine content (76% vs. 59% for KIO\(_3\))
- More soluble

**Potassium Iodate**

- More stable

The U.S. uses potassium iodide, but the form, and amount, used varies from country-to-country. Most Americans' salt intake comes from processed foods, many of which are made with non-iodized salt. Iodine is well absorbed (~90%). Some dietary compounds interfere with thyroid hormone production or utilization. These compounds are known as goitrogens\(^5\). However, it is not believed
that goitrogens are of clinical importance unless there is a coexisting iodine deficiency$^5$.

Some examples of foods that contain goitrogens are$^{3,4,6}$.

**Cassava**

*Figure 10.12 Cassava plants are typically grown in tropical and subtropical environments* $^6$
Figure 10.13 The cassava roots are what are typically eaten, but first they must be peeled. These are unprocessed.
Figure 10.14 Peeled cassava roots

Millet
Figure 10.15 Millet growing in a field

Figure 10.16 Millets
Cruciferous Vegetables (broccoli, cabbage, Brussels sprouts):

- Onions
- Garlic
- Soybeans
- Peanuts

Subsections:

10.11 Thyroid Hormone
10.12 Iodine Deficiency & Toxicity

References & Links

Links
135. 10.11 Thyroid Hormone

The thyroid accumulates most absorbed iodine, keeping it for use to synthesize thyroid hormone. The following video shows the thyroid and describes its function.

Web Link

A YouTube element has been excluded from this version of the text. You can view it online here:
https://library.achievingthedream.org/herkimernutrition/?p=162

Video: Thyroid (0:37)

As mentioned in the video, the two primary forms of thyroid hormone are triiodothyronine (T3) and thyroxine (T4).
T4 is the primary circulating form, and is really a prohormone that is converted to the active T3 form.

The enzymes that metabolize thyroid hormones are known as deiodinases. There are three deiodinases (Type I, Type II, Type III) that are selenoenzymes whose location and function are summarized in the table below.
Table 10.11 Location and function of the three deiodinases

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Tissues</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deiodinase Type I (D1I)</td>
<td>Liver, kidney, thyroid gland</td>
<td>Plasma T3 production</td>
</tr>
<tr>
<td>Deiodinase Type II (D1I2)</td>
<td>Brain, pituitary, brown adipose</td>
<td>Local T3 production</td>
</tr>
<tr>
<td>Deiodinase Type III (D1I3)</td>
<td>Brain, placenta</td>
<td>T3 degradation</td>
</tr>
</tbody>
</table>

Thyroid hormone regulates the basal metabolic rate and is important for growth and development. Thyroid hormone is particularly important for brain development, but hypothyroidism (low thyroid hormone) also leads to decreased muscle mass and skeletal development.

References & Links

Video
Thyroid – http://www.youtube.com/watch?v=7V0HB4cKIMw
There are two iodine deficiency disorders (IDD): goiter and cretinism. Goiter is a painless deficiency condition that results from the enlargement of the thyroid to help increase its ability to take up iodine. A couple of pictures of goiter are shown below.
10.12 Iodine Deficiency & Toxicity
A more serious consequence of iodine deficiency occurs during pregnancy to the fetus. Iodine deficiency during this time can lead to the mental and physical retardation known as cretinism. This condition is characterized by severe hypothyroidism, stunted growth, speech loss, and paralysis\(^3,4\). The following links show some examples of individuals with cretinism.

**Web Link**

[Cretinism](#)

The World Health Organization calls iodine deficiency “the world’s most prevalent, yet easily preventable, cause of brain damage\(^5\).” By saying it is easily preventable, they are referring to the ability of salt iodization to prevent brain development problems. The following New York Times article talks about how salt iodization may be the cheapest way to raise the world’s IQ.
Iodine toxicity is rare, but like iodine deficiency, it can result in thyroid enlargement, and hypothyroidism or hyperthyroidism. Acute toxicity results in gastrointestinal irritation, abdominal pain, nausea, vomiting, and diarrhea⁶.

**References & Links**

**Links**
- Cretinism – http://www.gsi.ir/Images/MedicalGeology/cretinism1.jpg
- In Raising the World’s I.Q., the Secret’s in the Salt – http://www.nytimes.com/2006/12/16/health/16iodine.html?_r=1&pagewanted=all
10.2 Manganese

We know far less about manganese than many other minerals. Like many minerals it serves as a cofactor for a number of enzymes that are discussed in more detail below.

The enzyme superoxide dismutase uses manganese as a cofactor to convert superoxide to hydrogen peroxide as shown below.

In addition, both the enzymes involved in the gluconeogenesis oxaloacetate workaround use manganese as cofactors as shown below.
Figure 10.22 Both enzymes of the oxaloacetate workaround in gluconeogenesis use manganese as cofactors.

One enzyme in the urea cycle uses manganese as a cofactor.
Enzymes critical to the production of proteoglycans, which are essential components of cartilage and bone, use manganese as a cofactor.\textsuperscript{5}
Absorption of manganese is not well understood but is believed to be pretty low (<5%). The main route (90%) of excretion is via bile excreted in feces. Deficiency and toxicities of manganese are extremely rare. The deficiency is so rare in humans that there isn't much information available on the symptoms of the condition. Symptoms in those who were deliberately made deficient include vomiting, dermatitis, changes in hair color, & skeletal defects. Toxicity symptoms include neurological disorders similar to schizophrenia and Parkinson's disease. In Chilean miners exposed to Mn-containing dust the toxicity was named Manganese Madness.

References & Links
Thiamin (Vitamin B1) structurally consists of 2 rings that are bridged together as shown below.

![Figure 10.31 Structure of thiamin](image)

Since it was one of the original vitamins, (remember vitamine), it was originally named thiamine. The -e has since been dropped in its spelling. Thiamin is sensitive to heat, so prolonged heating causes the cleavage of thiamin between the 2 rings destroying its activity.

Like most of the B vitamins, thiamin’s primary function is as a cofactor for enzymes. It is not thiamin alone that serves as a cofactor but instead thiamin diphosphate (thiamin + 2 phosphates), which is more commonly referred to as thiamin pyrophosphate (TPP). The structure of thiamin pyrophosphate is shown below.
In plants, thiamin is found in its free form, but in animals it is mostly thiamin pyrophosphate. These phosphates must be cleaved before thiamin is taken up into the enterocyte. Thiamin uptake and absorption is believed to be an efficient process that is passive when thiamin intake is high and active when thiamin intakes are low. There are two thiamin transporters (THTR), THTR1 and THTR2, that are involved in thiamin uptake and absorption. THTR1 is found on the brush border and basolateral membrane, while THTR2 is only found on the brush border membrane as shown below.
Like most water-soluble vitamins there is little storage of thiamin.

Subsections:

10.31 Thiamin Functions
10.32 Thiamin Deficiency & Toxicity

References & Links
There are three functions of thiamin\(^1\):

1. Cofactor for decarboxylation reactions (TPP)
2. Cofactor for the synthesis of pentoses (5-carbon sugars) and NADPH (TPP)
3. Membrane and nerve conduction (Not as a cofactor)

**Decarboxylation Reactions**

A decarboxylation reaction is one that results in the loss of carbon dioxide (CO\(_2\)) from the molecule as shown below.

![Decarboxylation reaction](https://example.com/figure10.31)

The transition reaction and one reaction in the citric acid cycle are decarboxylation reactions that use TPP as a cofactor. The figure below shows the transition reaction and citric acid cycle.
As shown below the conversion of pyruvate to acetyl CoA in the transition reaction is a decarboxylation reaction that requires TPP as a cofactor. CO$_2$ (circled) is produced as a result of this reaction.
A similar TPP decarboxylation reaction occurs in the citric acid cycle converting alpha-ketoglutarate to succinyl-CoA. CO$_2$ (circled) is given off as a result of this reaction.
TPP also functions as a cofactor for the decarboxylation of valine, leucine, and isoleucine (branched-chain amino acids).1

**Synthesis of Pentoses and NADPH**

TPP is a cofactor for the enzyme transketolase. Transketolase is a key enzyme in the pentose phosphate (aka hexose monophosphate shunt) pathway. This pathway is important for converting 6-carbon sugars into 5-carbon sugars (pentose) that are needed for synthesis of DNA, RNA, and NADPH. In addition, pentoses such as fructose are converted to forms that can be used for glycolysis and gluconeogenesis.4 Transketolase catalyzes multiple reactions in the pathway as shown below.

![Legend](image)

![Diagram](image)

*Figure 10.315 Transketolase in the pentose phosphate pathway uses TPP as a cofactor*5

542 | 10.31 Thiamin Functions
Membrane and Nerve Conduction

In addition to its cofactor roles, thiamin, in the form of thiamin triphosphate (TTP, 3 phosphates), is believed to contribute in some unresolved way to nervous system function\(^1\).

References & Links

2. https://commons.wikimedia.org/wiki/File:Decarboxylation_reaction.png
Thiamin deficiency is rare in developed countries, but still occurs in poorer countries where white (aka polished) rice is a staple food. During the polishing process, thiamin, and many other nutrients, are removed. Some people also have a mutation in THTR1 that causes them to become thiamin deficient. Thiamin deficiency is known as beriberi, which, when translated, means “I can’t, I can’t.” The symptoms of beriberi are illustrated in the link below.

Web Link

Beriberi

There are two major forms of beriberi: dry and wet. Dry beriberi affects the nervous system, with symptoms such as loss of muscle function, numbness, and/or tingling. Wet beriberi affects the cardiovascular system resulting in pitting edema, along with enlargement of the heart. A picture of a person with beriberi is shown below.
Another group that is at risk for thiamin deficiency is alcoholics. There are three reasons why alcoholics are prone to becoming deficient:

1. Alcohol displaces foods that are better sources of thiamin
2. Liver damage decreases TPP formation
3. Increased thiamin excretion

The thiamin deficiency found in alcoholics is known as Wernicke-Korsakoff Syndrome. Symptoms of this condition include paralysis.
or involuntary eye movement, impaired muscle coordination, memory loss and confusion\(^3\). The following video shows some of the symptoms of this condition.

**Web Link**

A YouTube element has been excluded from this version of the text. You can view it online here:

https://library.achievingthedream.org/herkimernutrition/?p=167

**Video: Wernicke-Korsakoff Syndrome (First 1:50)**

Thiamin toxicity has never been reported as a result of oral intake. Thus, there is little worry about thiamin toxicity\(^4\).

**References & Links**


546 | 10.32 Thiamin Deficiency & Toxicity

**Links**


Wernicke-Korsakoff Syndrome – [http://www.youtube.com/watch?v=wDcyBXJAZNM](http://www.youtube.com/watch?v=wDcyBXJAZNM)
A student once asked this question:

“I started taking the Mega Man Sport Multi-vitamin from GNC and about an hour or two after consumption, with a meal, my pee is bright, practically neon yellow. What does that mean?”

Since this question is leading off the riboflavin section, you have probably surmised that riboflavin is somehow involved. Indeed, flavin means yellow in Latin, and riboflavin is bright yellow as shown below.
Riboflavin is also a water-soluble B vitamin, so the student was excreting large amounts of riboflavin in his urine, leading it to become “bright, practically neon yellow.” The structure of riboflavin is shown below.
Riboflavin is important for the production of two cofactors: flavin adenine dinucleotide (FAD) & flavin mononucleotide (FMN).

FAD has been introduced before, but structurally you can see where riboflavin is within the compound below.
The 2 circled nitrogens are the sites that accept hydrogen to become FADH$_2$ as illustrated below.

Figure 10.44 Addition of two hydrogens to the rings of FAD to form FADH$_2$
The structure of FMN as shown below, is similar to FAD, except that it only contains one phosphate group (versus 2) and doesn’t have the ring structures off the phosphate groups that are found in FAD.

![Figure 10.45 The structure of FMN](image)

Riboflavin is photosensitive, meaning that it can be destroyed by light. This was a problem in the old days when the milkman
delivered milk in clear glass bottles. These have now been replaced by cartons or opaque plastic containers to help protect the riboflavin content of the milk.

Figure 10.46 Milk is no longer packaged in clear glass bottles to help protect its riboflavin from light destruction

Riboflavin in foods is free, protein-bound, or in FAD or FMN. Only free riboflavin is absorbed so it must be cleaved, or converted before absorption\(^6\). Riboflavin is highly absorbed through an unresolved process, though it is believed a carrier is involved\(^7\). As you would guess from the description above, riboflavin is primarily excreted in the urine.

Subsections:

10.41 Riboflavin Functions
10.42 Riboflavin Deficiency & Toxicity

References & Links
142. 10.41 Riboflavin Functions

Riboflavin is required for the production of FAD and FMN. Below are some of the functions of FAD and FMN$^1$:

1. Citric Acid Cycle
2. Electron Transport Chain
3. Fatty Acid Oxidation
4. Niacin Synthesis
5. Vitamin B6 Activation
6. Neurotransmitter Catabolism
7. Antioxidant Enzymes

1. **Citric Acid Cycle** – FAD is reduced to FADH$_2$ in the citric acid cycle when succinate is converted to fumarate by succinic dehydrogenase as circled below.
Figure 10.41: The citric acid cycle requires FAD$^2$

2. **Electron Transport Chain** – Under aerobic conditions, the electron transport chain is where the FADH$^2$ is used to produce ATP. Complex I of the electron transport chain includes an FMN molecule. The electron transport chain is shown below.
3. Fatty Acid oxidation – During fatty acid oxidation FAD is converted to FADH2 as shown below.
4. **Niacin synthesis** – As you will hear more about in the niacin section, niacin can be synthesized from tryptophan as shown below. An intermediate in this synthesis is kynurenine, and one of the multiple steps between kynurenine to niacin requires FAD.

![Niacin synthesis from tryptophan requires FAD](image)

5. **Vitamin B6 Activation** – The enzyme that creates the active form of vitamin B6 (pyridoxal phosphate) requires FMN.
6. Neurotransmitter Catabolism – The enzyme monoamine oxidase (MAO) requires FAD. This enzyme shown below is important in the catabolism of neurotransmitters such as dopamine and serotonin.
Figure 10.416 Catabolism of dopamine involves monoamine oxidase, an enzyme that requires FAD.
Catabolism of serotonin involves monoamine oxidase, an enzyme that requires FAD.
7. **Antioxidant Enzymes** – The antioxidant enzymes glutathione reductase and thioredoxin reductase both require FAD as a cofactor. Thioredoxin reductase is a selenoenzyme. The function of glutathione reductase is shown in the following link. Glutathione reductase can reduce glutathione that can then be used by the selenoenzyme glutathione peroxidase to convert hydrogen peroxide to water.

**Web Link**

The Glutathione Oxidation Reduction (Redox) Cycle

In addition to the functions listed above, FAD is also used in folate activation, choline catabolism, and purine metabolism\(^1\).

**References & Links**

4. [https://commons.wikimedia.org/wiki/](https://commons.wikimedia.org/wiki/) File:Nicotinic_acid_biosynthesis2.png

**Links**

Ariboflavinosis, riboflavin deficiency, is a rare condition that often occurs with other nutrient deficiencies. The symptoms of this condition are shown in the figure below.

Figure 10.421 The symptoms of riboflavin deficiency

Sore red eyes and lids
Angular stomatitis
Glossitis of tongue
Cheilosis of lips
Scrotal dermatitis
The most notable symptoms include angular stomatitis (aka angular cheilitis, like cheilosis), which is a lesion that forms at the corners of the mouth as shown below.

![Angular Cheilitis](image)

Figure 10.42 Angular Cheilitis

Glossitis is the inflammation of the tongue, which can be
accompanied by redness or inflammation of the oral cavity. Dermatitis is also frequently a symptom\textsuperscript{3,4}.

There has been no toxicity of riboflavin reported.

**References & Links**

There are two forms of niacin: nicotinic acid and nicotinamide (aka niacinamide), that have a carboxylic acid group or amide group, respectively. The structure of nicotinic acid and nicotinamide are shown below.

Figure 10.51 Structure of nicotinic acid\textsuperscript{1}
Niacin is important for the production of two cofactors: nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP+). The structure of NAD is shown below; you can clearly see the nicotinamide at the top right of the molecule.
NAD is reduced to form NADH, as shown below.

Figure 10.53 Structure of NAD^3
The structure of NADP+ is exactly the same as NAD, except it has an extra phosphate group off the bottom of the structure, as shown below.

\[
\text{NAD}^+ + H^+ + 2e^- \xrightarrow{\text{Reduction}} \text{NADH}
\]

*Figure 10.54 Reduction of NAD to NADH*
Figure 10.55 Structure of NADP$^+$

570 | 10.5 Niacin
Like NAD, NADP+ can be reduced to NADPH.

Niacin is unique in that it can be synthesized from the amino acid tryptophan as shown below. An intermediate in this synthesis is kynurenine. Many reactions occur between this compound and niacin, and riboflavin and vitamin B6 are required for two of these reactions.

![Figure 10.56 Tryptophan can be used to synthesize niacin](image)

To account for niacin synthesis from tryptophan, niacin equivalents (NE) were created by the DRI committee to account for the amount of niacin in foods as well as their tryptophan content. It takes approximately 60 mg of tryptophan to make 1 mg of niacin. Thus, the conversions to niacin equivalents are:

1 mg Niacin = 1 NE
60 mg Tryptophan = 1 NE

The tryptophan levels of most foods is not known, but a good estimate is that tryptophan is 1% of amino acids in protein. Thus, lets take peanut butter, smooth style, with salt as an example.

The peanut butter contains 13.403 mg of niacin and 25.09 g of protein.

Step 1: Calculate the amount of tryptophan:
25.09 g X 0.01 (the numerical value of 1%) = 0.2509g of tryptophan

Step 2: Convert Grams to Milligrams
0.2509 g X 1000 mg/g = 250.9 mg of tryptophan

Step 3: Calculate NE from tryptophan
250.9 mg of tryptophan/(60 mg of tryptophan/1 NE) = 4.182 NE

Step 4: Add NEs together
13.403 NE (from niacin) + 4.182 (from tryptophan) = 17.585 NE
Most niacin we consume is in the form of nicotinamide and nicotinic acid\(^9\), and in general is well absorbed using an unresolved carrier\(^10\). However, in corn, wheat, and certain other cereal products, niacin bioavailability is low. In these foods, some niacin (~70% in corn) is tightly bound, making it unavailable for absorption. Treating the grains with a base frees the niacin and allows it to be absorbed. After absorption nicotinamide is the primary circulating form\(^7,9\).

Subsections:
10.51 Niacin Functions
10.52 Niacin Deficiency & Toxicity

References & Links
Approximately 200 enzymes require NAD or NADP+. We will go through some selected functions of NAD and NADP+. The following figures and legends show and describe the functions of NAD and NADP+. 
Figure 10.51 NAD is required for glycolysis\textsuperscript{1}
Figure 10.512 NAD is required for the transition reaction and at three different points in the citric acid cycle.

Figure 10.513 NAD is required for fatty acid oxidation.
Figure 10.514 Alcohol oxidation; NAD is required by alcohol dehydrogenase, and the MEOS uses NADPH.

MEOS – Microsomal Ethanol Oxidizing System

HMG CoA reductase, the rate-limiting enzyme in cholesterol synthesis, uses NADPH. NADPH is also used by the antioxidant enzyme glutathione reductase as shown in the link below.

Figure 10.515 Fatty acid synthesis uses NADPH.
Web Link

–The Glutathione Oxidation Reduction (Redox) Cycle

References & Links


Links

Pellagra is a niacin deficiency. This is no longer a common deficiency in developed countries, but was in the U.S. in the early 1900s. This was because corn was a staple crop, meaning it was what people primarily consumed. The bioavailability of niacin from corn is poor unless treated with a base to release the bound niacin. The symptoms of pellagra are the 3 D's:

- Dementia
- Dermatitis
- Diarrhea

Some refer to 4 D's in which the 4th D is death if the condition is not managed. The following pictures show the symptoms of pellagra.
Figure 10.521 The 3 D's of pellagra\textsuperscript{1}
Figure 10.52 A man with pellagra; notice the dermatitis on his arms

The link below shows another picture of a person suffering from dermatitis as a result of pellagra.

**Web Link**

–Pellagra

Dietary niacin toxicity is rare. However, nicotinic acid (not
nicotinamide) can improve people’s lipid profiles when consumed at levels far above the RDA. For instance the RDA & upper limit (UL) is 14 or 16 (women & men) and 35 mg (both), respectively. Many people are taking 1-2 grams (up to 6 g/day) to get the benefits in their plasma lipid profiles as shown in the table below.

Table 10.521 Effects of nicotinic acid (>1.5 g/day) on plasma lipid profile\(^3\)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLDL</td>
<td>↓ 25-40%</td>
</tr>
<tr>
<td>LDL</td>
<td>↓ 6-22%</td>
</tr>
<tr>
<td>HDL</td>
<td>↑ 18-35%</td>
</tr>
<tr>
<td>Total Cholesterol</td>
<td>↓ 21-44%</td>
</tr>
<tr>
<td>Triglycerides</td>
<td>↓ 21-44%</td>
</tr>
</tbody>
</table>

It should be pointed out that there are special supplements for this purpose that include a slower release nicotinic acid that helps prevent the toxicity symptoms (nicotinamide is not toxic). A slow (aka long or extended) release form of niacin for people with atherosclerosis is Niaspan®. The link below is to Niaspan’s site.

Web Link

Niaspan®

A study found that Niaspan plus a statin was no better than a statin alone in preventing heart attacks, despite improvements in HDL and triglyceride levels. This result challenged the understanding of the importance of HDL and triglyceride levels to heart attack risk. The link below explains this study’s results.

Web Link

Niacin Drugs Don’t Reduce Heart Attack Risk

The most well known of the toxicity symptoms is “niacin flush”,
which is a dilation of capillaries accompanied by tingling that can become painful. This symptom is noted to occur at lower levels than the other toxicity symptoms\(^6\). Other symptoms include:

- Gastrointestinal Distress
- Liver Damage

A nicotinic acid receptor GPR109A, which is present in adipocytes and immune cells, has been believed to mediate niacin flush, but the beneficial effects on lipid profiles do not appear to be mediated by this receptor\(^7,8\). It is not clear at this time the mechanism of action for the improvements in lipid profiles\(^7\).

**References & Links**


**Links**

10.6 Pantothenic Acid

Pantothenic acid has two roles in the body:
1. It is part of coenzyme A (CoA)
2. It is part of acyl carrier protein

**1. Coenzyme A**

The structure of pantothenic acid is shown alone below and circled within coenzyme A.

![Figure 10.61 The structure of pantothenic acid](image1)

![Figure 10.62 The structure of coenzyme A (CoA) with the pantothenic acid circled](image2)

The functions of CoA are shown and described below.

584 | 10.6 Pantothenic Acid
Figure 10.63 Acetyl-CoA is a central point in metabolism, and contains CoA.

Figure 10.64 CoA is used in fatty acid oxidation. The fatty acid is activated by adding CoA, forming acyl-CoA.
2. Acyl Carrier Protein

Acyl carrier protein, is also important in fatty acid synthesis. Most pantothenic acid in food is found as CoA, which is cleaved prior to absorption. It is then taken up into the enterocyte through the sodium-dependent multivitamin transporter (SMVT) as shown below. Approximately 50% of pantothenic acid is absorbed; it is excreted primarily in urine.
Deficiency of pantothenic acid is very rare. Pantothenic acid supplementation did relieve the symptoms (burning feet and numbness of toes) of “burning feet syndrome” in prisoners in World War II. It is believed pantothenic acid deficiency was the cause of this syndrome. Other symptoms noted are vomiting, fatigue, weakness, restlessness, and irritability. No toxicity has been reported.

References & Links
Vitamin B6 is composed of three compounds: pyridoxine, pyridoxal, and pyridoxamine. Pyridoxine contains a methylhydroxyl group (−CH3OH), pyridoxal an aldehyde (−CHO), and pyridoxamine an aminomethyl group (−CH3NH2), as shown below.

Figure 10.71 Structure of pyridoxine

![Figure 10.71 Structure of pyridoxine]
Figure 10.72 Structure of pyridoxal

Figure 10.73 Structure of pyridoxamine
All three forms can be activated by being phosphorylated. The phosphorylated forms can be interconverted to the active, or the cofactor form of vitamin B6, pyridoxal phosphate (PLP). This active form has a phosphate group added in place of a hydroxyl group. The enzyme that catalyzes this reaction requires FMN (riboflavin cofactor), as shown below.

![Pyridoxine to Pyridoxal Phosphate Reaction](image)

Figure 10.74 Vitamin B6 activation\(^1\,^4\)

In animal products, vitamin B6 is found in its cofactor forms, PLP and pyridoxamine phosphate (PMP). The latter cofactor is less common than PLP. In plants, vitamin B6 is primarily found as pyridoxine, with up to 75% being pyridoxine glucoside, which is believed to be the plant storage form\(^6\). Pyridoxine glucoside has a glucose added to pyridoxine as shown below.
Vitamin B6 is well absorbed from foods (~75%) through passive diffusion. PLP and PMP are dephosphorylated before uptake into the enterocyte. Some of the pyridoxamine glucoside is cleaved to form free pyridoxine, but some pyridoxine glucoside is absorbed intact. Pyridoxine glucoside absorption is lower (~50%) than pyridoxine alone. The primary circulating forms of vitamin B6 are pyridoxal and PLP. Vitamin B6 is primarily excreted in the urine, and like many other B vitamins, vitamin B6 is destroyed during cooking or heating.

Subsections:
10.71 Vitamin B6 Functions
10.72 Vitamin B6 Deficiency & Toxicity

References & Links

Vitamin B6 Functions

PLP is a cofactor for over 100 different enzymes, most are involved in amino acid metabolism. In fact, without PLP, all amino acids would be essential because we would not be able to synthesize nonessential amino acids. Below are some of the functions of PLP and PMP:

**Figure 10.711 Transaminases require PLP or PMP**

**Figure 10.712 Some deaminases require PLP**
PLP is required for decarboxylase enzymes that are involved in the synthesis of the neurotransmitters GABA, serotonin, histamine, and dopamine. As an example, DOPA decarboxylase uses PLP to convert L-DOPA to dopamine as shown below1.
Figure 10.714 DOPA decarboxylase uses PLP to synthesize dopamine.
PLP is also required by gamma-aminolevulinic acid (ALA) synthetase that is involved in heme synthesis, as shown below. Heme will be discussed in more detail in the iron section.

![Figure 10.715 ALA synthetase uses PLP in the heme synthesis pathway](image)

PLP is also used in one of the multiple reactions that occurs between kynurenine and niacin in its synthesis from tryptophan.

![Figure 10.716 PLP is required for niacin synthesis from tryptophan](image)

In addition, PLP is also involved in:
- Carnitine Synthesis
- 1-Carbon Metabolism

**References & Links**
Vitamin B6 deficiency is rare, but symptoms include:
- Skin or scalp ailments (seborrheic dermatitis)
- Microcytic hypochromic anemia (small cells, low color)
- Convulsions
- Depression
- Confusion

Given what we know about the functions of vitamin B6 most of these symptoms make sense.

The microcytic hypochromic anemia is a result of decreased heme synthesis. The neurological symptoms are due to the decreased production of neurotransmitters\(^1\).

Vitamin B6, unlike many of the B vitamins, can produce toxicity. High doses of vitamin B6, taken for an extended period of time, can lead to neurological damage\(^2\). There are some potential uses of vitamin B6 supplementation that are important to be done with consultation with a physician.

One of the conditions that people take vitamin B6 for is carpal tunnel syndrome. The following video does a nice job of explaining and showing how this condition occurs.

---

**Web Link**

[Video: Carpal Tunnel Syndrome (1:02)]

While the evidence is not conclusive, it appears that vitamin B6 supplementation may be beneficial to those suffering from carpal tunnel syndrome and may be tried alone, or in combination with other complementary treatments, before surgery is undertaken\(^3,4\).

Morning sickness that occurs early in pregnancy is another condition where vitamin B6 supplementation is utilized. The
evidence again is not clear on whether it is beneficial\textsuperscript{5,6}, but The American College of Obstetricians and Gynecologists suggests that vitamin B6 may be tried first to treat nausea and vomiting during pregnancy\textsuperscript{7}. In 2013, the FDA approved doxylamine-pyridoxine (Diclegis) for use in pregnancy\textsuperscript{8}. It is not known exactly what causes morning sickness, but it is believed that lower circulating vitamin B6 levels are associated with increased morning sickness severity\textsuperscript{9}.

The last condition that vitamin B6 is commonly supplemented for is premenstrual syndrome (PMS). A systematic literature review found that it is inconclusive whether vitamin B6 supplementation is beneficial in managing PMS\textsuperscript{10}.

References & Links

10. Whelan A, Jurgens T, Naylor H. (2009) Herbs, vitamins and...

**Video**

Carpal Tunnel Syndrome – http://www.youtube.com/watch?v=rewDQgqU5Hg

600 | 10.72 Vitamin B6 Deficiency & Toxicity
The 2 primary dietary forms of biotin are free biotin and biocytin (aka biotinyllysine). The structure of biotin is shown below.

Figure 10.81 Structure of biotin

Biocytin is biotin bound to lysine as seen in its structure below.

Figure 10.82 Structure of biocytin
Free biotin is believed to be highly absorbed. Before uptake, biocytin is acted on by the enzyme biotinidase, forming free biotin and lysine. Free biotin is then taken up into the enterocyte through the sodium-dependent multivitamin transporter (SMVT), as shown below\(^1,4,5\).

![Diagram showing the process of biotin absorption](image)

Figure 10.83 Free biotin is taken up into the enterocyte by the SMVT.

Most biotin is excreted in the urine.

Subsections:
10.81 Biotin Functions
10.82 Epigenetics
10.83 Biotin Deficiency & Toxicity

**References & Links**
Biotin is an important cofactor for carboxylase enzymes. As the name sounds, these enzymes add carboxylic acid groups (–COOH) to whatever compound they act on. In fatty acid synthesis, biotin is required by the enzyme that forms malonyl CoA from acetyl-CoA, as shown below.

Figure 10.811 The conversion of acetyl CoA to malonyl CoA in fatty acid synthesis requires biotin.

Another biotin-requiring carboxylase is one that converts pyruvate to oxaloacetate in gluconeogenesis as shown below.
In addition to these two functions, biotin is also important for histone biotinylation and the breakdown of isoleucine, leucine, methionine, and threonine\(^1\).

Histone biotinylation is an epigenetic modification that is described in the next section.

Biotin is an effective treatment for brittle nail syndrome, but it has not been shown to improve healthy nails\(^4\). There is little evidence to suggest that biotin improves healthy hair as well\(^5\).

References & Links


What is epigenetics? Epigenetics means “above the genome.” The nucleotide sequence of the human genome is known, and there is surprisingly little difference between individuals. However, the 2 main epigenetic modifications play a major role in determining what genes are expressed:

- DNA methylation
- Histone modification

These epigenetic modifications are illustrated in the following link.

**Web Link**

– Epigenetic modifications

DNA methylation is the addition of a methyl group to a DNA base, which decreases gene transcription. Conversely, demethylation increases gene transcription.

DNA does not exist simply as long strands of double helix, instead it is packaged and shaped so that it can fit in the nucleus of our cells. The first part of this packaging is that DNA is wrapped around proteins called histones as shown below.
Histone modification occurs when there are additions or subtractions to the histones themselves. The most common is acetylation (addition of an acetyl group) or deacetylation of histones. The structure of acetyl is shown below.
Histone acetylation causes the DNA structure to open up so that transcription can occur. Histone deacetylation causes the DNA to become more tightly packed, preventing transcription from occurring.

Together, these modifications to DNA and histones are known as the epigenetic code. The following two videos do a good job explaining epigenetics and tying together its two different methods of modification:
How does this relate to biotin? Histones can be biotinylated, or have biotin added to the histone. However, it should be noted that histone biotinylation is rare (<0.001% of human histones H3 and H4), so it is questionable how much impact this action has.

References & Links

Links
Epigenetic modifications - http://www.nature.com/nature/journal/v441/n7090/images/441143a-i2.0.jpg

Videos
A Tale of Two Mice - https://www.youtube.com/watch?v=OOiCu5kzGxg
Histone Modifications - http://www.youtube.com/watch?v=eYrQ0EhVCYA
Biotin deficiency is very rare. Symptoms of biotin deficiency include:

Skin rash
Hair loss
Neurological Impairments

There are a couple of ways that a person could develop a deficiency in biotin. First, a very small number of people are born with a mutation in biotinidase that results in them not being able to cleave biocytin for absorption. Another way is through the consumption of raw eggs. Drinking raw eggs is not something that most people do. However, some people do it to imitate Sylvester Stallone's movie character Rocky, who consumed them as part of his boxing training regimen. If you are not familiar with this movie the link below shows you how Rocky consumed his raw eggs.

Web Link

– Video: Rocky Raw Eggs (1:21)

The potential problem with consuming raw eggs routinely is that raw egg whites contain a protein called avidin which binds biotin and prevents its absorption. However, it would take more than two dozen egg whites consumed daily over many months to cause a deficiency, making this an unlikely occurrence. Cooking denatures avidin and prevents it from binding biotin, meaning that cooked eggs are not a concern.

No toxicity of biotin has been reported.

References & Links


Videos
Rocky Raw Eggs – http://www.youtube.com/watch?v=NhkdLHSKo9s
Three B vitamins are involved in what is known as 1-carbon metabolism. This is the movement of 1 carbon units, generally methyl groups (CH3). It is similar to the movement of the amino group that occurs in transamination. As shown in the figure below, folate, vitamin B12, and vitamin B6 are the B vitamins involved in 1-carbon metabolism.

Figure 11.1 One-carbon metabolism depiction. 5-methyl tetrahydrofolate (THF) donates a methyl group to cobalamin forming methylcobalamin. Methylcobalamin donates a methyl group to homocysteine, forming methionine (amino acid). Alternatively, vitamin B6 can be utilized to convert homocysteine into cysteine.

Vitamin B6 has been covered already in the previous chapter, so this chapter is going to focus on folate and vitamin B12. We will examine this figure in pieces, so that hopefully by the time this chapter is completed, you will understand the role of all these vitamins in 1-carbon metabolism.

Sections:
11.1 Folate & Folic Acid
11.2 Vitamin B12
11.3 B Vitamins, Homocysteine, & Cardiovascular Disease
Folate is a B vitamin that exists in either its reduced form (folate) or oxidized form (folic acid). When folate is used in this section, we are referring to the reduced form, not the vitamin itself. Another key distinction between the 2 terms is that folic acid refers to the synthetic form, while folate refers to the natural form. Folic acid is only found in certain foods because they have been fortified with it, not because they produce it. The structure of folic acid is shown below.

Another key difference between folate and folic acid is the number of glutamates in their tails. Notice that glutamate is boxed in the structure of folic acid above. Folic acid always exists as a monoglutamate, meaning it only contains 1 glutamate. On the other hand, about 90% of the folate found in foods are polyglutamates, meaning there is more than 1 glutamate in their tail. Folic acid is more stable than folate, which can be destroyed by heat, oxidation, and light. Table 11.11 summarizes the key differences between folate and folic acid.
Table 11.11 Comparison of folate to folic acid

<table>
<thead>
<tr>
<th>Folate</th>
<th>Folic Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Form</td>
<td>Oxidized Form</td>
</tr>
<tr>
<td>Natural</td>
<td>Synthetic</td>
</tr>
<tr>
<td>Polyglutamate</td>
<td>Monoglutamate</td>
</tr>
<tr>
<td></td>
<td>More Stable</td>
</tr>
</tbody>
</table>

The bioavailability of folate was believed to be much lower than folic acid. To account for these differences, the DRI committee created dietary folate equivalents (DFEs) to set the RDAs. DFEs are defined as follows:

1 DFE = 1 ug food folate = 0.6 ug food folic acid = 0.5 ug folic acid on an empty stomach

DFE = ug food folate + (ug folic acid X 1.7)

The 1.7 came from research suggesting that folic acid from food was 85% bioavailable, compared to 50% for folate (85%/50% = 1.7). This was established in 1998 by the DRI committee, and it is likely that these conversions & the requirements will change based on the newer evidence suggesting folate's bioavailability from food is higher (80% of folic acid) than previously believed. With this data, the new conversion factor for folic acid would be 1.25 (100%/80%). This conversion factor means that food folate levels are probably contributing more towards our dietary needs than currently being estimated by the DFE, but the DRI for folate/folic acid has not been updated.

Before folate (polyglutamates) can be taken up into the enterocyte, the extra glutamates must be cleaved prior to uptake into the enterocyte by the reduced folate transporter (RFT, aka reduced folate carrier). Folic acid, because it is a monoglutamate, requires no cleavage for uptake before it is taken up through the RFT. Once inside the enterocyte, the monoglutamate form is methylated and transported into circulation through an unresolved carrier. This series of events is depicted in the figure below.

11.1 Folate & Folic Acid | 617
Thus, the methylated monoglutamate form is the circulating form. This is transported to the liver where it is converted back to the polyglutamate form for storage. Folate is excreted in both the urine and feces\(^5\).

Subsections:
11.11 Folate Functions
11.12 Folate Deficiency & Toxicity

References & Links
5. Shils ME, Shike M, Ross AC, Caballero B, Cousins RJ, editors.


**157. II.11 Folate Functions**

The major function of folate is that it participates in 1-carbon metabolism. As described earlier, this is the transfer of 1-carbon units from 1 compound to another. The cofactor form of folate is tetrahydrofolate (THF). As is shown in the figure below, in order for THF to be formed, a methyl group is transferred to cobalamin (vitamin B12) from 5-methyl THF (THF plus a methyl group), forming methyl-cobalamin. You can see this on the left side of the figure below.

![Figure 11.11 One-carbon metabolism](image)

There are 2 major cofactor functions of THF:\(^1\):

1. **DNA Synthesis**
   
   THF is required for the synthesis of DNA bases (purines and pyrimidines).\(^1\) As shown in the link below, N10-formyl-THF (a form of THF) is needed in 2 reactions (3 and 9) in purine synthesis.

   **Web Link**
   
   - [Purine Synthesis](link)

---

620 | 11.11 Folate Functions
2. Amino Acid Metabolism

THF is a cofactor for enzymes that metabolize histidine, serine, glycine, and methionine\(^1\). The following link shows that THF is a cofactor for serine hydroxymethyltransferase, the enzyme that converts serine to glycine.

**Web Link**

–Serine to Glycine

**References & Links**


**Links**

Folate deficiency is a vitamin deficiency that affects some Americans. The hallmark symptom of folate deficiency is megaloblastic (aka macrocytic) anemia. Megaloblastic anemia, as the name suggests, is characterized by large, nucleated (most red blood cells do not have a nucleus), immature red blood cells. This occurs because folate is needed for DNA synthesis; without it red blood cells are not able to divide properly\(^1\). As a result, fewer and poorer functioning red blood cells are produced that cannot carry oxygen as efficiently as normal red blood cells\(^2\).

A maternal folate deficiency can lead to neural tube defects in infants. The exact cause of neural tube defects is unknown, but folate supplementation has been shown to decrease the incidence of neural tube defects\(^3\). The most common of these neural tube defects is spina bifida (1 out of 2500 babies born in the United States), which is a failure of the neural tube to close and the spinal cord and its fluid protrude out the infant’s back, as shown below\(^4,5\).
The neural tube closes 21-28 days after conception\(^1\), and with 50% of pregnancies estimated to be unplanned, many women aren’t aware they are pregnant during this period\(^{1,2}\). Thus, it is recommended that women of childbearing age consume 400 \(\mu\)g of folic acid daily\(^1\). In addition, in 1998 the FDA mandated that all refined cereals and grains be fortified with 140 \(\mu\)g folic acid /100 grams of product\(^7\). As you can see below, spina bifida prevalence rates declined during the optional fortification years and declined further once fortification became mandatory in the United States.
However, more recent research has found that folic acid supplementation begun before conception reduced the occurrence and severity of neural tube defects. The following link is an interesting account of the history that led up to the folic acid fortification. It is debatable whether folic acid fortification was fully responsible for the decrease in spina bifida rates shown above, but the rates are lower than they were pre-fortification.

**Web Link**

Folic Acid Fortification: Fact and Folly

Folate/Folic acid is not toxic, but it can mask a vitamin B12 deficiency and prevent its diagnosis. This effect will be discussed further in the vitamin B12 deficiency section.

**References & Links**

8. http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6401a2.htm

**Link**

Folic Acid Fortification: Fact and Folly – http://www.fda.gov/AboutFDA/WhatWeDo/History/ProductRegulation/SelectionsFromFDLIUpdateseriesonFDAHistory/ucm091883.htm
Vitamin B12 is unique among vitamins in that it contains an element (cobalt) and is found almost exclusively in animal products. Neither plants nor animals can synthesize vitamin B12. Instead, vitamin B12 in animal products is produced by microorganisms within the animal that the products came from. Animals consume the microorganisms in soil or bacteria in ruminant animals that produce vitamin B12\(^1\). Some plant products, such as fermented soy products (tempeh, miso) and the sea algae supplement, spirulina, are advertised as being good sources of B12. However, fermented soy products are not a reliable vitamin B12 source\(^2\) and spirulina contains a pseudovitamin B12 compound that is not bioavailable\(^3\). For vegans, supplements, nutritional yeast, and fortified products like fortified soy milk can help them meet their vitamin B12 needs\(^4\).

Vitamin B12’s scientific name is cobalamin, which makes sense when you consider it contains cobalt and many amine groups, as shown in the figure below.
The other feature that is important in cobalamin is the circled R group. This is what differs between the different cobalamins, whose names and R groups are shown in the following table.

Table 11.21 Different cobalamin forms
<table>
<thead>
<tr>
<th>R Group</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>Cyanocobalamin</td>
</tr>
<tr>
<td>OH</td>
<td>Hydroxocobalamin</td>
</tr>
<tr>
<td>H2O</td>
<td>Aquocobalamin</td>
</tr>
<tr>
<td>NO2</td>
<td>Nitritocobalamin</td>
</tr>
<tr>
<td>5′-deoxyadenosyl</td>
<td>Adenosylcobalamin*</td>
</tr>
<tr>
<td>CH3</td>
<td>Methylcobalamin*</td>
</tr>
</tbody>
</table>

*Cofactor Forms

The 2 cofactor forms are adenosylcobalamin and methylcobalamin. We can convert most cobalamins into these 2 cofactor forms. Most foods contain adenosylcobalamin, hydroxocobalamin, or methylcobalamin. The most common form found in supplements is cyanocobalamin, with some also using methylcobalamin. Cyanocobalamin is a synthetic form of the vitamin B12.

The uptake, absorption, and transport of vitamin B12 is a complex process. The following descriptions explain, and figures illustrate, this process.

Vitamin B12 is normally bound to protein in food. Salivary glands in the mouth produce haptocorrin (formerly known as R protein), which travels with the food into the stomach. In the stomach, acid converts pepsinogen into pepsin, and the protein intrinsic factor is released from the parietal cells.
As pepsin frees B12 from protein, haptocorrin binds to the newly freed vitamin B12 (haptocorrin + B12). Intrinsic factor escapes digestion and, along with haptocorrin + B12, exits the stomach and enters the duodenum\(^1\,\text{,}^8\).
In the duodenum, pancreatic proteases break down haptocorrin, and again vitamin B12 is freed. Intrinsic factor then binds vitamin B12 (intrinsic factor + B12); intrinsic factor + B12 continues into the ileum to prepare for absorption\(^1,8\).

![Figure 11.24 Vitamin B12 in the duodenum\(^8,9\)](image)

In the ileum, intrinsic factor + B12 is believed to be endocytosed by cubulin (aka intrinsic factor receptor), forming an endosome inside the enterocyte. Intrinsic factor is broken down in the enterocyte, freeing vitamin B12. The free vitamin B12 is then bound to transcobalamin II (TC II + B12); TC II + B12 moves into circulation\(^8\).
The liver is the primary storage site for vitamin B12. Unlike most other water-soluble vitamins, the liver is able to maintain significant stores of vitamin B12. Uptake into the liver occurs through the binding of TC II + B12 to the TC II Receptor and the endocytosis of both the compound and the receptor. Vitamin B12 is once again freed after degradation of TC II. Vitamin B12 is primarily stored in the liver as adenosylcobalamin.
The overall bioavailability of vitamin B12 is believed to be approximately 50%\(^3\), with the different cobalamin forms having similar bioavailabilities\(^7\). Sublingual supplements of vitamin B12 have been found to be equally efficacious as oral supplements\(^7\). Excretion occurs mostly through bile, with little loss in urine\(^6\).

Subsections:

11.21 Vitamin B12 Functions
11.22 Vitamin B12 Deficiency & Toxicity

**References & Links**


Vitamin B12 Functions

Vitamin B12 is a cofactor for 2 enzymes:
1. Methionine synthase
2. Methylmalonyl mutase

**Methionine Synthase**

Methionine synthase is an important enzyme in 1-carbon metabolism that uses methylcobalamin as its cofactor and converts homocysteine to methionine by adding a methyl group. Methionine then is converted to other compounds that serve as methyl donors, as shown below.

These methyl donors can donate methyl groups for methylating DNA, an epigenetic modification.

**Methymalonyl mutase**

This enzyme uses adenosylcobalamin as its cofactor, and is important in the breakdown of odd chain fatty acids (5 carbons etc.). As you know, odd chain fatty acids are less common than even chain...
fatty acids, but this enzyme is required to properly handle these less common fatty acids\(^1\).

**Demyelination**

In addition to its role as a cofactor for enzymes, vitamin B12 is also important for preventing degradation of the myelin sheath that surrounds neurons, as shown below.

![Myelin Sheath](image)

*Figure 11.212 Vitamin B12 is needed to maintain the myelin sheath that surrounds neurons*\(^2\)

The mechanism through which vitamin B12 prevents demyelination is not known\(^3\).

**References & Links**

There are 2 primary symptoms of vitamin B12 deficiency:

Megaloblastic (Macrocytic) Anemia

Neurological Abnormalities

**Megaloblastic (Macrocytic) Anemia**

This is the same type of anemia that occurs in folate deficiency that is characterized by fewer, enlarged, immature red blood cells. In vitamin B12 deficiency, this can occur because there is not enough cobalamin to convert 5-methyl THF to THF (illustrated in Figure 11.211). Thus, THF is not available for normal DNA synthesis and the red blood cells do not divide correctly.

**Neurological Abnormalities**

Vitamin B12 deficiency also results in nerve degeneration and abnormalities that can often precede the development of anemia. These include a decline in mental function and burning, tingling, and numbness of legs. These symptoms can continue to worsen and deficiency can be fatal\(^1\).

The most common cause of vitamin B12 deficiency is pernicious anemia, a condition of inadequate intrinsic factor production that causes poor vitamin B12 absorption. This condition is common in people over the age of 50 because they have the condition atrophic gastritis\(^2\). Atrophic gastritis is a chronic inflammatory condition that leads to the loss of glands in the stomach, as shown in the figure in the following link.

---

**Web Link**

[Atrophic Gastritis](#)

The loss of glands leads to decreased intrinsic factor production. It is estimated that ~6% of those age 60 and over are vitamin B12 deficient....
deficient, with 20% having marginal status. In addition to the elderly, vegans are also at risk for vitamin B12 deficiency because they do not consume animal products. However, the deficiency may take years to develop in adults because of stores and recycling of vitamin B12. Deficiency has the potential to occur much quicker in infants or young children on vegan diets because they do not have stores that adults do.

**Folate/Folic Acid masking vitamin B12 deficiency**

As mentioned above, folate and vitamin B12 lead to the same megaloblastic (macrocytic) anemia. If high levels of folate or folic acid (most of the concern is with folic acid since it is fortified in foods and commonly taken in supplements) is given during vitamin B12 deficiency, it can correct this anemia. This is referred to as masking because it does not rectify the deficiency, but it “cures” this symptom. This is problematic because it does not correct the more serious neurological problems that can result from vitamin B12 deficiency. There are some people who are concerned about the fortification of cereals and grains with folic acid because people who are B12 deficient might not develop macrocytic anemia, which makes a vitamin B12 deficiency harder to diagnose.

No toxicity of vitamin B12 has been reported.

**References & Links**


**Links**

Homocysteine is a sulfur containing, non-proteinogenic (not used for making proteins) amino acid whose structure is shown in the figure below.

![Figure 11.31 Structure of homocysteine](image)

Elevated circulating homocysteine levels have been found in people with cardiovascular disease. Folate, vitamin B6, and vitamin B12 contribute to the conversion of homocysteine to methionine by providing methyl groups, thereby decreasing homocysteine levels, as illustrated in the figure below. Thus, based on these facts, it was hypothesized that intake of these B vitamins may decrease the risk of cardiovascular disease.
Research has found that intake of these B vitamins does decrease circulating homocysteine levels. However, most studies have not found that it results in improved cardiovascular disease outcomes\(^2\)\(^-\)\(^4\). It is debated why B vitamin intake has not resulted in improved outcomes. Some think it is because the studies have not focused on individuals with elevated homocysteine levels\(^2\), while others believe that homocysteine is a biomarker or indicator of cardiovascular disease, not a causative or contributing factor to cardiovascular disease development\(^3\).

**References & Links**


163. 12 Blood, Bones & Teeth
Micronutrients

This chapter is a collection of vitamins and minerals that are involved in the structure or function of blood, bones and teeth. The individual sections are:

12.1 Vitamin D
12.2 Calcium
12.3 Phosphorus
12.4 Fluoride
12.5 Vitamin K
12.6 Vitamin A
12.7 Iron
12.8 Zinc
12.9 Copper
164. 12.1 Vitamin D

Vitamin D is unique among the vitamins in that it is part vitamin, part hormone. It is considered part hormone for two reasons: (1) we have the ability to synthesize it, and (2) it has hormone-like functions. The amount synthesized, however, is often not enough to meet our needs. Thus, we need to consume this vitamin under certain circumstances, meaning that vitamin D is a conditionally essential micronutrient.

There are two major dietary forms of vitamin D: the form produced by plants and yeast is vitamin D2 (ergocalciferol), and the form made by animals is vitamin D3 (cholecalciferol). The structures of these two forms are shown below. Notice that the only difference is the presence of a double bond in D2 that is not in D3.
We synthesize vitamin D3 from cholesterol, as shown below. In the skin, cholesterol is converted to 7-dehydrocholesterol. In the presence of UV-B light, 7-dehydrocholesterol is converted to vitamin D3. Synthesized vitamin D will combine with vitamin D-binding protein (DBP) to be transported to the liver. Dietary vitamin D2 and D3 is transported to the liver via chylomicrons and then taken up in chylomicron remnants. Once in the liver, the enzyme 25-hydroxylase (25-OHase) adds a hydroxyl (-OH) group at the 25th carbon, forming 25-hydroxy vitamin D (25(OH)D, calcidiol). This is
the circulating form of vitamin D, thus 25(OH)D blood levels are measured to assess a person's vitamin D status. The active form of vitamin D is formed with the addition of another hydroxyl group by the enzyme 1alpha-hydroxylase (1alpha-OHase) in the kidney, forming 1,25 hydroxy vitamin D (1,25(OH)2D). The synthesis and activation of vitamin D is shown in the figures below.

Figure 12.12 Vitamin D synthesis and activation

Figure 12.12 Vitamin D synthesis and activation[^4]
However, there are a number of other tissues that have been found to have 1alpha-hydroxylase activity. Therefore, these tissues can activate circulating 25(OH)D to 1,25(OH)2D for their own use.

Vitamin D2 and D3 were once thought to be equivalent forms of vitamin D, but research has found that D3 supplementation increases 25(OH)D levels more than D2 supplementation.\(^7,8\)
Subsections:
12.11 Environmental Factors That Impact Vitamin D3 Synthesis
12.12 Dietary or Supplemental Vitamin D
12.13 Response to Low Blood Calcium
12.14 Response to High Blood Calcium
12.15 Vitamin D Receptor
12.16 Vitamin D Deficiency, Toxicity, & Insufficiency

References & Links
Environmental Factors That Impact Vitamin D3 Synthesis

There are a number of environmental factors that affect vitamin D3 synthesis:
- Latitude
- Season
- Time of Day
- Skin Color
- Age
- Clothing
- Sunscreen

**Latitude**
The latitude a person is at affects that person’s ability to synthesize vitamin D3. There is an inverse relationship between distance from the equator and UV light exposure. Thus, with increased distance from the equator (increased latitude), there is decreased UV light exposure and vitamin D3 synthesis. The link below shows the latitude and longitude lines of the United States.

---

**Web Link**

United States Latitude and Longitude Lines

**Seasons**

Seasons also make a difference in vitamin D3 synthesis. In Boston (42° N), vitamin D synthesis only occurs from March-October, because during late fall and winter not enough UV-B reaches the earth’s surface to synthesize vitamin D3. However, in Los Angeles (34° N), vitamin D3 synthesis occurs year round. The difference is
the angle of the sun relative to latitude and how many UV-B photons are absorbed before they reach the earth's surface\textsuperscript{1}.

\textbf{Time}

Time of day is also an important factor in affecting vitamin D3 synthesis. Vitamin D3 synthesis increases in the morning before peaking at noon, then declines the rest of the day\textsuperscript{1}.
Skin pigmentation

Another factor that plays an important role in vitamin D3 synthesis is skin pigmentation. As shown in the figure below, skin pigmentation tends to be darker around the equator to help protect inhabitants from the harmful effects of sun exposure.

Skin color is the result of increased production of the pigment melanin, as shown in the link below.
Very dark skin color can provide a sun protection factor (SPF) 8–30 for those individuals who never burn. These individuals will require approximately 5- to 10-times greater sunlight exposure than a light-skinned, white person to synthesize the same amount of vitamin D3.

**Age**

Age also plays a factor in vitamin D3 synthesis. Aging results in decreased 7-dehydrocholesterol concentrations in the skin, resulting in an approximately 75% reduction in the vitamin D3 synthesis capability by age 70.

![Figure 12.114 Aging decreases vitamin D synthesis](image)

**Clothing**

Clothing is another factor that influences vitamin D3 synthesis. More clothing means that less sun reaches your skin, and thus less vitamin D3 synthesis.
Sunscreen, “Sensible Sun Exposure”, and Tanning

There is quite a spirited debate on sunscreen, sun exposure, skin cancer, and vitamin D synthesis. On one side are the vitamin D researchers, on the other side are dermatologists. Vitamin D research found that SPF 8 sunscreen almost totally blocked vitamin D3 synthesis\(^5\). However, the SPF value equals \(1/(\# \text{ photons that reach your skin})\) meaning that SPF 30 means 1/30 UV photons reach your skin. Thus, vitamin D3 synthesis shouldn’t be totally blocked. In addition, studies indicate that consumers apply 1/2 or less of the amount required to get the listed SPF protection\(^5\). Researchers recommend sun exposure on the face, arms, and hands for 10-15 minutes 2-3 times per week between 10 AM-3 PM\(^3,6\). However, dermatologists do not like “sensible sun exposure” because this is also the peak time for harmful sun exposure. Dermatologists say that “sensible sun exposure” appeals to those who are looking for a reasons to support tanning and are at highest risk (primarily young, fair-skinned females) of sun damage. They argue that vitamin D can be provided through supplementation\(^5\).
What about tanning beds? Not all tanning beds provide UV-B rays that are needed for vitamin D3 synthesis. In fact, some advertise that they only use UV-A rays that are safer, even though this is not the case. Virtually every health organization advises against using tanning beds, because the risks are far greater than the potential benefits.

References & Links

Links
United States Latitude and Longitude Lines – http://modernsurvivalblog.com/survival-skills/basic-map-reading-latitude-longitude/
Because of the possible double-edged sword of sun exposure for synthesizing vitamin D3, consuming vitamin D from the diet or supplements is the alternative.

However, there are a limited number of food naturally rich in vitamin D. Good sources of vitamin D are fatty fish (salmon, tuna, etc.) and their oils (such as cod liver oil). The amount in fatty fish varies greatly with wild-caught salmon being the highest. One study showed that farmed salmon contained almost 75% less vitamin D than wild-caught salmon1. It is not known whether this disparity exists between other types of farmed and wild-caught fish varieties.

Table 12.121 Vitamin D content of fish1

<table>
<thead>
<tr>
<th>Fish</th>
<th>Vitamin D (IU/oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Fish</td>
<td>280 ± 68</td>
</tr>
<tr>
<td>Cod</td>
<td>104 ± 24</td>
</tr>
<tr>
<td>Grey Sole</td>
<td>56 ± 36</td>
</tr>
<tr>
<td>Farmed Salmon</td>
<td>240 ± 108</td>
</tr>
<tr>
<td>Wild Salmon</td>
<td>988 ± 524</td>
</tr>
<tr>
<td>Farmed Trout</td>
<td>388 ± 212</td>
</tr>
<tr>
<td>Tuna</td>
<td>404 ± 440</td>
</tr>
</tbody>
</table>

Like vitamin C, E, and A, international units (IU) are also used for vitamin D.

For vitamin D the conversions are:

1 ug of D3 = 40 IU
1 ug of 25-OH-D = 200 IU²

Thus, since not many foods contain vitamin D, many brands of milk have been fortified with vitamin D2 or D3 (100 IU/8 oz) since
the 1930s\textsuperscript{3}. However, the actual measured amount of vitamin D in many brands of milk is far less than stated on their labels\textsuperscript{4,5}. Part of this problem stems from a lack of a standardized method for measuring vitamin D in the past. Without standardized analysis, there inevitably was a wide range of variation from lab to lab in the reported amount of vitamin D.

Another issue with relying on dairy products to provide vitamin D is the common problem of lactose intolerance. Lactose intolerant individuals don't have lactase, the enzyme needed to break down lactose. Common symptoms of this condition include:

- Abdominal Pain
- Abdominal Bloating
- Gas
- Diarrhea
- Nausea\textsuperscript{6}

Lactose intolerance is a fairly common problem worldwide, as shown in the map below.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure12121.png}
\caption{Lactose intolerance worldwide (red high, green low)}\textsuperscript{7}
\end{figure}

The following table shows the percent of people who are lactose intolerant by race:

Table 12.122 Lactose intolerance rates\textsuperscript{8}

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
Race & Percent of People Lactose Intolerant & Percent of People Lactose Tolerant \\
\hline
African-American & 0.05 & 0.95 \\
Asian & 0.07 & 0.93 \\
Caucasian & 0.06 & 0.94 \\
Hispanic & 0.08 & 0.92 \\
\hline
\end{tabular}
\end{table}
<table>
<thead>
<tr>
<th>Race or ethnicity</th>
<th>% Lactose Intolerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast Asian</td>
<td>98%</td>
</tr>
<tr>
<td>Native Americans</td>
<td>62-100%⁶</td>
</tr>
<tr>
<td>Asian Americans</td>
<td>90%</td>
</tr>
<tr>
<td>Alaskan Eskimo</td>
<td>80%</td>
</tr>
<tr>
<td>African-American Adults</td>
<td>79%</td>
</tr>
<tr>
<td>Mexicans (rural communities)</td>
<td>74%</td>
</tr>
<tr>
<td>North American Jews</td>
<td>69%</td>
</tr>
<tr>
<td>Greek Cypriots</td>
<td>66%</td>
</tr>
<tr>
<td>Cretans</td>
<td>56%</td>
</tr>
<tr>
<td>Mexican American Males</td>
<td>55%</td>
</tr>
<tr>
<td>Indian Adults</td>
<td>50%</td>
</tr>
<tr>
<td>African-American Children</td>
<td>45%</td>
</tr>
<tr>
<td>Indian Children</td>
<td>20%</td>
</tr>
<tr>
<td>Descendants of N. Europeans</td>
<td>5%</td>
</tr>
</tbody>
</table>

Thus, you can see that many people are lactose intolerant. Coincidentally, many of these people have darker pigmented skin, meaning that they have an increased risk of vitamin D deficiency/insufficiency because they require greater sun exposure to synthesize adequate amounts of vitamin D3.

Other foods that are sometimes fortified are breakfast cereals and orange juice. Despite the fact that orange juice doesn’t contain fat, and vitamin D is fat-soluble, vitamin D is quite bioavailable in orange juice¹⁰.

Vitamin D in supplements is found as vitamin D2 or D3. However, based on the recent evidence suggesting that D2 isn’t as beneficial as D3, many are being reformulated to contain D3¹¹.

References & Links


One of the major functions of vitamin D is to assist in maintaining blood calcium concentrations. The other major regulators of blood calcium levels are 2 hormones: parathyroid hormone (PTH) and calcitonin, which are released from the parathyroid glands and thyroid glands, respectively. Bone serves as the calcium depot, or reservoir, if there is a sufficient concentration in the body. In bone, calcium is found in hydroxyapatite crystals on a collagen matrix.

The chemical formula of hydroxyapatite is:
$$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$$

Calcium and phosphorus are either jointly deposited (deposition) or jointly liberated (resorption) from bone hydroxyapatite to maintain/achieve blood calcium concentrations. Osteoblasts are bone cells that are responsible for bone formation or depositing hydroxyapatite. Osteoclasts are the bone cells that are responsible for breaking down or resorption of bone. An easy way to remember the function of these cells is:

Osteoblasts “build” bone
Osteoclasts “chew” bone

Bone resorption is the process of liberating calcium and phosphorus from hydroxyapatite.

Bone deposition is the process of depositing calcium and phosphorus in bone as hydroxyapatite.

**Response to Low Blood Calcium**

The parathyroid senses low blood calcium concentrations and releases PTH. These steps are designed to maintain consistent blood calcium levels, but also affects phosphate (phosphorus) levels. PTH has 3 effects:

1. Increases bone resorption
2. Decreases calcium and increases phosphorus urinary excretion
3. Increases 1,25(OH)2D activation in the kidney\textsuperscript{1,2}

The first effect of PTH is increased bone resorption. Hydroxyapatite must be broken down to release both calcium and phosphate. This effect is illustrated below.

![Figure 12.131 PTH effect 1: increased bone resorption\textsuperscript{3}](image)

The second effect of PTH is decreased calcium excretion in urine. This is a result of increased calcium reabsorption by the kidney before it is excreted in urine. Kidney phosphate reabsorption is decreased, meaning the net effect is less calcium, but more phosphate in urinary excretion, as shown in the figure below.
The 3rd effect of PTH is that it increases 1,25(OH)2D activation in the kidney, by increasing 1alpha-hydroxylase levels. The 1,25(OH)2D then increases calcium and phosphorus absorption in the small intestine to help raise blood calcium levels, as shown below. This mechanism will be discussed in more detail in the vitamin D receptor subsection.
Overall PTH causes more calcium and phosphate to be leached from bone, and absorbed from the intestine, into the blood. Coupled with decreased calcium and increased phosphate urinary excretion, means that blood calcium levels rise without a marked rise in phosphate levels, as depicted in the figure below.
References & Links


In adults, it is rare for blood calcium levels to get too high. However, in infants and young children whose bodies, and thus bones, are not as large, the hormone calcitonin helps to prevent blood calcium levels from getting too high¹.

**Response to High Blood Calcium**

High blood calcium levels are sensed by the thyroid, which releases calcitonin. This response is designed to maintain/achieve normal blood calcium levels, but also affects phosphate (phosphorus) levels. Calcitonin has 3 effects¹,²:

1. Decreases bone resorption, increases bone deposition
2. Increases calcium and phosphorus excretion in urine
3. Decreases 1,25(OH)2D activation in the kidney

The first effect of calcitonin is to inhibit bone resorption, thus promoting the deposition of calcium and phosphorus into bone as hydroxyapatite.

![Calcitonin effect 1: increased bone deposition](image)

The second effect of calcitonin is to increase calcium and phosphorus excretion in urine.
The third effect of calcitonin is to decrease 1alpha-hydroxylase levels, which decreases the activation of 1,25(OH)2D. As a result, the absorption of calcium and phosphorus from the small intestine is decreased, as shown below.
Overall, calcitonin inhibits the 3 actions that PTH uses to increase blood calcium levels. Thus, more calcium and phosphate are deposited into bones and excreted into urine, as shown below. This causes blood calcium levels to decrease.

Figure 12.143 Calcitonin effect 3: decreased 1,25(OH)2D activation
12.144 Response to high blood calcium

References & Links

Vitamin D, along with vitamin A, are unique among the vitamins because they have nuclear receptors. Many steroid hormones have nuclear receptors. The following figure illustrates the action of a nuclear hormone receptor.

In the figure above of the hormone (in this case thyroid hormone), the receptor’s ligand (something that binds to the receptor), enters the nucleus and binds to the thyroid hormone receptor (TR). The TR has paired (formed a dimer) with the retinoid X receptor (RXR) on the hormone response element (HRE) in the promoter of target genes. The HRE for thyroid hormone is the thyroid hormone response element. Target genes are those whose transcription is altered by the hormone binding to its receptor on the response

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Figure 12.151 Nuclear hormone receptors action
element. The mRNA produced then leaves the nucleus where it is translated into protein.

Vitamin A and D have nuclear receptors that act in the same fashion as nuclear hormone receptors. The video below very clearly explains the action of a nuclear hormone receptor. A thorough explanation of the nuclear Vitamin D receptor follows.

Web Link

–Video: Steroid Hormone Receptors (0:42)

1,25(OH)2D is considered to be the active form of vitamin D because it is the form that binds to the vitamin D receptor (VDR). Like the thyroid hormone example above, there is a vitamin D response element (VDRE) in the promoter of specific vitamin D target genes. In the figure below, 25(OH)D, the major circulating form of vitamin D, is usually transported through the blood to the kidney by vitamin D binding protein (DBP). Again, the kidney converts 25(OH)D to 1,25(OH)2D by use of the enzyme 1alpha-hydroxylase. 1,25(OH)2D (bound to DBP) moves from the kidney, or the tissue itself, into the nucleus. It then binds to the vitamin D receptor (VDR), that is dimerized to the RXR on the vitamin D response element of the target gene. Consequently, this then increases transcription of mRNA. The mRNA then moves into the cytoplasm to synthesize specific proteins. This process is shown in the figure below.
It’s through this action that 1,25(OH)2D is able to increase calcium absorption. In this case, the target gene is the calcium-binding protein calbindin. Thus, increased 1,25(OH)2D leads to increased calbindin mRNA. This then leads to increased calbindin protein levels. Calbindin will be discussed in more detail in the calcium section.
References & Links


**Video**

Steroid Hormone Receptor - [http://www.youtube.com/watch?v=Dxyq8GAWbpo](http://www.youtube.com/watch?v=Dxyq8GAWbpo)
Rickets is a vitamin D deficiency in infants and children. A lack of vitamin D leads to decreased bone mineralization, causing the bones to become weak. The bones then bow under pressure, leading to the characteristic bowed legs, as seen below.

![Children suffering from rickets](image1)

*Figure 12.161 Children suffering from rickets*
Another characteristic symptom of rickets is rachitic rosary, or beaded ribs. The beading occurs at the areas where cartilage meets bone on the rib cage, as shown in the link below.³

Web Link

Rachitic Rosary

Osteomalacia is a vitamin D deficiency in adults and results in poor
bone mineralization. The bone becomes soft, resulting in bone pain and an increased risk of fractures\(^3\).

While rickets and osteomalacia are fairly rare in the United States, it is believed that vitamin D insufficiency might be much more widespread. Insufficiency means that the level of intake, or body status, is suboptimal (neither deficient nor optimal). The figure below illustrates this concept.

![Figure 12.163 Illustration of insufficient or suboptimal levels](image)

Suboptimal/insufficient means intake, or status, is higher than deficient, but lower than optimal. Thus, higher intake levels will provide additional benefits. The functions of vitamin D are growing by the day due to increased research discoveries. These functions now include benefits beyond bone health, further supporting the importance of vitamin D. In late 2010, an RDA for vitamin D was established (was an Adequate Intake before). This made it, along
with calcium, the first micronutrients to have their DRIs revised\(^4\). The RDA for vitamin D is 3 times higher than the previous AI. Many believe these are more reasonable levels, while others think that the new RDA is still not high enough. This belief, that many people’s vitamin D intake/status is suboptimal, is challenged by a recent review described in the link below that found that vitamin D did not reduce osteoporosis risk. In addition, a recent meta-analysis (second link) concluded that “there is probably no benefit to expect from vitamin D supplementation in normally healthy people.”

**Web Link**

Vitamin D Ineffective for Preventing Osteoporosis
Limits of Vitamin D Supplements

Vitamin D from supplements can become toxic. You cannot develop vitamin D toxicity from sun exposure, because the sunlight degrades a precursor of vitamin D3 in the skin\(^5\). Vitamin D toxicity results in hypercalcemia or high blood calcium levels. These become problematic because it can lead to the calcification of soft tissues.

**References & Links**


**Links**

Rachitic Rosary – http://1.bp.blogspot.com/_ZWqgYBROGHw/S9r9rOb8thI/AAAAAAAAAh4/y8uHS9m42MU/s1600/18111.jpg
Vitamin D Ineffective for Preventing Osteoporosis – http://well.blogs.nytimes.com/2013/10/17/vitamin-d-ineffective-for-preventing-osteoporosis/?

676 | 12.16 Vitamin D Deficiency, Toxicity & Insufficiency
Calcium is a macromineral and the most abundant mineral in the body. The reason for calcium's abundance is its distribution in the skeleton, which contains 99% of the calcium in the body.

Subsections:
12.21 Calcium Absorption
12.22 Calcium Bioavailability
12.23 Calcium Functions
12.24 Calcium Deficiency & Toxicity
Calcium Absorption

Calcium is taken up into the enterocyte through Transient Receptor Potential V6 (TRPV6), a calcium channel found on the brush border. Calbindin is the calcium binding protein that facilitates uptake through TRPV6 and transport across the enterocyte. Ca\(^{2+}\)-Mg\(^{2+}\) ATPase functions to pump calcium out of the enterocyte and into circulation and to pump magnesium into the enterocyte, as shown below\(^1\).

![Diagram of Calcium uptake and absorption](image)

*Figure 12.211 Calcium uptake and absorption*

As we have previously discussed, increased 1,25(OH)2D synthesis in the kidney causes increased binding to the vitamin D receptor, which increases calbindin synthesis. Increased calbindin ultimately increases calcium uptake and absorption.
There are a couple of calcium-binding compounds that inhibit its absorption. Therefore, even though some foods are good sources of calcium, the calcium is not very bioavailable. Oxalate, found in high levels in spinach, rhubarb, sweet potatoes, and dried beans, is the most potent inhibitor of calcium absorption\(^2\). Recall that calcium oxalate is one of the compounds that makes up kidney stones. Based on this understanding, it should not be a surprise that formation of this compound inhibits calcium absorption.
Another inhibitor of calcium absorption is phytate. Phytate is found in whole grains and legumes.3
Figure 12.21 Structure of phytate

References & Links


173. 12.22 Calcium Bioavailability

Calcium bioavailability varies greatly from food to food, as shown in the table below. This table gives the serving size, calcium content of that food, and percent absorbed. The calcium content is multiplied by the absorption percentage to calculate the estimated calcium absorbed. Finally, it shows the servings of each food needed to equal the estimated calcium absorbed from 1 serving of milk.

Table 12.221 Bioavailability of calcium from different foods sources\(^{1-3}\)
<table>
<thead>
<tr>
<th>Food</th>
<th>Serving Size (g)</th>
<th>Calcium content (mg)</th>
<th>Absorption (%)</th>
<th>Estimated Calcium Absorbed</th>
<th>Servings needed to equal 240 mL milk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cow’s Milk</td>
<td>240</td>
<td>300</td>
<td>32.1</td>
<td>96.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Almonds, dry roasted</td>
<td>28</td>
<td>80</td>
<td>21.2</td>
<td>17.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Beans, Pinto</td>
<td>86</td>
<td>44.7</td>
<td>26.7</td>
<td>11.9</td>
<td>8.1</td>
</tr>
<tr>
<td>Beans, Red</td>
<td>172</td>
<td>40.5</td>
<td>24.4</td>
<td>9.9</td>
<td>9.7</td>
</tr>
<tr>
<td>Beans, White</td>
<td>110</td>
<td>113</td>
<td>21.8</td>
<td>24.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Bok Choy</td>
<td>85</td>
<td>79</td>
<td>53.8</td>
<td>42.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Broccoli</td>
<td>71</td>
<td>35</td>
<td>61.3</td>
<td>21.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Brussel Sprouts</td>
<td>78</td>
<td>19</td>
<td>63.8</td>
<td>12.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Cabbage, Chinese</td>
<td>85</td>
<td>79</td>
<td>53.8</td>
<td>42.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Cabbage, Green</td>
<td>75</td>
<td>25</td>
<td>64.9</td>
<td>16.2</td>
<td>5.9</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>62</td>
<td>17</td>
<td>68.6</td>
<td>11.7</td>
<td>8.2</td>
</tr>
<tr>
<td>Cheddar Cheese</td>
<td>42</td>
<td>303</td>
<td>32.1</td>
<td>97.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Chinese mustard greens</td>
<td>85</td>
<td>212</td>
<td>40.2</td>
<td>85.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Chinese spinach</td>
<td>85</td>
<td>347</td>
<td>8.36</td>
<td>29</td>
<td>3.3</td>
</tr>
<tr>
<td>Fruit Punch (CCM)</td>
<td>240</td>
<td>300</td>
<td>52</td>
<td>156</td>
<td>0.6</td>
</tr>
<tr>
<td>Kale</td>
<td>85</td>
<td>61</td>
<td>49.3</td>
<td>30.1</td>
<td>3.2</td>
</tr>
<tr>
<td>Kohlrabi</td>
<td>82</td>
<td>20</td>
<td>67.0</td>
<td>13.4</td>
<td>7.2</td>
</tr>
<tr>
<td>Mustard Greens</td>
<td>72</td>
<td>64</td>
<td>57.8</td>
<td>37.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Orange juice (CCM)</td>
<td>240</td>
<td>300</td>
<td>36.3</td>
<td>109</td>
<td>0.8</td>
</tr>
<tr>
<td>Radish</td>
<td>50</td>
<td>14</td>
<td>74.4</td>
<td>10.4</td>
<td>9.2</td>
</tr>
</tbody>
</table>

684  | 12.22 Calcium Bioavailability
<table>
<thead>
<tr>
<th>Food</th>
<th>Calcium</th>
<th>Phosphorus</th>
<th>Oxalate</th>
<th>Excess Calcium (mg)</th>
<th>Excess Phosphorus (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhubarb</td>
<td>120</td>
<td>174</td>
<td>8.54</td>
<td>10.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Rutabaga</td>
<td>85</td>
<td>36</td>
<td>61.4</td>
<td>22.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Sesame seeds, no hulls</td>
<td>28</td>
<td>37</td>
<td>20.8</td>
<td>7.7</td>
<td>12.2</td>
</tr>
<tr>
<td>Soy milk (tricalcium phosphate)</td>
<td>240</td>
<td>300</td>
<td>24.0</td>
<td>72.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Soy milk (calcium carbonate)</td>
<td>240</td>
<td>300</td>
<td>21.1</td>
<td>66.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Spinach</td>
<td>85</td>
<td>115</td>
<td>5.1</td>
<td>5.9</td>
<td>16.3</td>
</tr>
<tr>
<td>Sweet Potatoes</td>
<td>164</td>
<td>44</td>
<td>22.2</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Tofu with Ca</td>
<td>126</td>
<td>258</td>
<td>31.0</td>
<td>80.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Turnip Greens</td>
<td>72</td>
<td>99</td>
<td>51.6</td>
<td>51.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Watercress</td>
<td>17</td>
<td>20</td>
<td>67.0</td>
<td>13.4</td>
<td>7.2</td>
</tr>
<tr>
<td>Yogurt</td>
<td>240</td>
<td>300</td>
<td>32.1</td>
<td>96.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Notice that the foods high in oxalate like spinach, rhubarb, sweet potatoes, and dried beans are poorly absorbed. But there are still a number of calcium sources outside of milk.

The 2 most common forms of calcium found in supplements are calcium carbonate and calcium citrate. As you can see in the figure below, they differ in the amount of elemental calcium they contain. This shows how much of the molecular weight of the compound is calcium.
The higher the percent elemental calcium, the greater the amount of calcium you will receive per given weight of that compound, versus a compound that has a lower elemental calcium percentage. Both carbonate and citrate forms are well absorbed, but individuals with low stomach acid absorb citrate better. Also, carbonate is best absorbed when taken with food, while for citrate it is equally well absorbed when taken alone.

Older research suggested that calcium citrate malate was more bioavailable than other calcium sources. However, a more recent clinical study found no difference in the bioavailability of calcium from calcium citrate malate in orange juice, skim milk, or calcium carbonate supplements. There is some evidence that suggests that even though bioavailability is the same among these different forms, they might not be equally effective in improving bone measures.

**References & Links**

2. Weaver CM, Proulx WR, Heaney R. (1999) Choices for achieving...
adequate dietary calcium with a vegetarian diet. Am J Clin Nutr 70(3 Suppl): 543S-548S.


Calcium in hydroxyapatite is a major component of bones and teeth. There are also a number of non-bone functions of calcium. Calcium is an intracellular signaling molecule. Because of this, intracellular calcium is tightly controlled, primarily stored within organelles.

Non-bone functions include:

**Neurotransmitter release**

Neurotransmitter release is stimulated by the opening of voltage-gated Ca2+ channels. This stimulates the synaptic vesicle to fuse with the axon membrane and release the neurotransmitter into the synapse, as shown below.

![Figure 12.231 Calcium regulates neurotransmitter release](image)

**Muscle contraction**

Calcium is released in muscle cells, where it binds to the protein troponin, changes its shape, and removes the tropomyosin blockade.
of actin active sites so that contraction can occur\textsuperscript{3}. This can be seen in the following animation and figure (same link).

### Web Link

**Muscle contraction**

### Hormone release

Calcium acts as an intracellular messenger for the release of hormones, such as insulin. The link below shows how in the beta cells of the pancreas, the opening of voltage-gated calcium channels stimulates the insulin granules to fuse with the beta cell membrane to release insulin.

### Web Link

**Insulin release**

### Blood Clotting

As will be discussed more in the vitamin K section, calcium binding to activated Gla proteins is important in the blood clotting cascade.

*Figure 12.232 Calcium bind to Gla proteins. Adapted from reference\textsuperscript{4}*

### Enzyme regulation

The binding of calcium to calcium-binding proteins also regulates the action of a number of enzymes\textsuperscript{4}.

### References & Links

12.23 Calcium Functions | 689

Links
12.24 Calcium Deficiency & Toxicity

Because of the large amount of calcium in bones, deficiency is rare. Hypocalcemia (low serum calcium levels in blood) can result in tetany (involuntary muscle contractions). In addition, calcium deficiency in children can lead to rickets, which is a vitamin D deficiency. While not a deficiency, low calcium intake can lead to decreased bone mineral density and the conditions osteopenia and osteoporosis. How these differ from osteomalacia and normal bone is illustrated and described below. There are two different bone components that we will consider to understand what is happening in the bone. Matrix is the scaffolding onto which mineral is deposited. Mineral is at it sounds, the mineral that is deposited on the matrix.
Osteomalacia – Bone mass is normal, but the matrix to mineral ratio is increased, meaning there is less mineral in bone.

Osteopenia – Bone mass is decreased, but the matrix to mineral ratio is not altered from normal bone. This condition is intermediate in between normal and osteoporosis.

Osteoporosis – Bone mass is further decreased from osteopenia, but the matrix to mineral ratio is not altered from normal bone.

The National Osteoporosis Foundation estimates that “about 54 million Americans have osteoporosis and low bone mass, placing them at increased risk for osteoporosis. Studies suggest that approximately one in two women and up to one in four men age 50 and older will break a bone due to osteoporosis.” To prevent
osteoporosis it is important to build peak bone mass, 90% of which is built in females by age 18 and age 20 in males, but can continue to increase until age 30. After that time, bone mass starts to decrease. For women after menopause, bone mass decreases dramatically because of the decrease in estrogen production, as shown in the link below\textsuperscript{5}.

\textbf{Web Link}

\textbf{Bone Mass}

Combining the decrease after menopause along with the fact that women have lower bone mass to begin with, helps further explain why osteoporosis is more common in females. A measure of bone status is bone mineral density. As the name indicates, bone mineral density is a measure of the amount of mineral in bone. Dual energy X-ray absorptiometry (DEXA) accurately measures bone mineral density using a small amount of radiation. A DEXA is shown in the figure below.
A person lies down on the table and the arm of the machine moves slowly over them.

From the scan, a bone mineral density t-score is generated. As shown below, normal bone mineral density has a t-score of greater
than -1, low bone mass is from -1 to -2.5, and osteoporosis is a t-score of less that -2.5 as illustrated in the figure in the link below.

**Web Link**

**Bone Mineral Density T-Scores**

There are other methods of measuring bone mineral density, such as peripheral DEXA and ultrasound. These typically are done on the wrist or heel, but are not as accurate because that one area might not reflect the bone mineral density in other parts of the body.

Calcium toxicity is rare, occurring in those with hyperparathyroidism or high calcium supplementation levels. Like vitamin D, toxicity can lead to calcification of soft tissues. In addition, a very high intake of calcium can lead to kidney stone formation.

**References & Links**

3. Sambrook, P. Bone structure and function in normal and disease states [link]
4. [http://nof.org/articles/7](http://nof.org/articles/7)

**Link**

Bone Mineral Density T-Scores – [Image]
We have already talked about how blood phosphate levels are regulated in the body by PTH, calcitonin, and 1,25(OH)2D. Animal products are rich sources of phosphate. Plant products contain phosphorus, but some is in the form of phytic acid (phytate). In grains, over 80% of the phosphorus is phytate. This structure is shown below.

![Figure 12.31 Structure of phytic acid](image)

The bioavailability of phosphorus from phytate is poor (~50%) because we lack the enzyme phytase. Nevertheless, ~50-70% of phosphorus is estimated to be absorbed from our diet. Another source of phosphorus is phosphoric acid that is used to acidify colas. Colas are caramel-colored, carbonated soft drinks that contain caffeine, such as Coca-Cola, Pepsi, etc. Epidemiological studies have found that soft drink consumption is associated with decreased bone mineral densities, particularly in females. It has been hypothesized that phosphoric acid plays some role in this effect, but there is limited evidence to support this belief.

Most phosphorus is excreted in the urine.
Phosphorus deficiency is rare, but can hinder bone and teeth development. Other symptoms include muscle weakness, rickets, and bone pain. Toxicity is also rare, but it causes low blood calcium concentrations and tetany.

Subsection:

12.31 Phosphorus Functions

References & Links

Phosphorus has a number of functions in the body.

Phosphate is a component of hydroxyapatite in bones and teeth, as described earlier.

Non-bone functions include:

**Phosphorylation**

Phosphates are used to activate and deactivate a number of proteins. In addition, compounds are also frequently phosphorylated, like the monosaccharides shown below.

![Diagram of monosaccharide uptake into hepatocyte](image)

**Phospholipids**

Phosphates are a component of phospholipids, as shown below.
DNA/RNA

DNA/RNA have a phosphate backbone as shown below.
ATP

The major energy currency, ATP, stores energy in its phosphate bonds.
Secondary Messengers

The intracellular secondary messengers cyclic AMP (cAMP) and inositol triphosphate (IP3) both contain phosphate. The action of these secondary messengers can be seen in the links below.

Web Links

cAMP
IP3

Other functions of phosphate include:
  Acid/Base Balance
  Intracellular Anion

References & Links
Links

cAMP – http://courses.washington.edu/conj/gprotein/cyclicamp.htm
Fluoride is a nonessential mineral. It is not required by the body and it is not widely found in the food supply. The majority of what we consume comes from fluoridated water. Other good non-dietary sources are fluoridated toothpaste and dental rinses\(^1\). Absorption of fluoride is near 100% for both dietary and non-dietary forms and it is rapidly excreted in the urine\(^2\).

Fluoride alters the mineralization of bones and teeth. It does this by replacing hydroxyl (OH) ions in hydroxyapatite (Ca\(_{10}\)(PO\(_4\))\(_6\)(OH)\(_2\)\(^\)\), forming fluorohydroxyapatite. Fluorohydroxyapatite is more resistant to acid degradation than hydroxyapatite, leading to fewer cavities\(^2\).

Since it is a nonessential mineral, there is no fluoride deficiency. However, fluoride can be quite toxic. Acute toxicity symptoms from large intakes of fluoride include\(^1\):
- Nausea
- Vomiting
- Diarrhea
- Convulsions

Chronic toxicity results in an irreversible condition known as fluorosis, characterized by the mottling and pitting of teeth as shown below.

![Fluorosis before Treatment](image1) ![After Treatment(Porcelain Laminate Veneers)](image2)

*Figure 12.41 Fluorosis*
As you can see from the figure below, fluorosis is more prevalent in the United States than most people would probably believe.
Figure 12.43 Fluorosis prevalence by age in the United States

A comparison of the prevalence of fluorosis in US children, ages 12-15, indicates an increase from the late 1980s to the early 2000s\textsuperscript{5}. 

NOTES: Dental fluorosis is defined as having very mild, mild, moderate, or severe forms and is based on Dean’s Fluorosis Index. Error bars represent 95% confidence intervals.

There is debate as to whether water should be fluoridated. The following links are examples of just how conflicted the U.S. is. The first is a New York Times article on this topic. There is also an article about Portland’s decision to begin fluoridating its water in 2014. The third article is about a bill introduced by a Kansas lawmaker concerned about the effects of water fluoridation. Salina, Kansas, which is home to one of Kansas State University’s campuses, voted last November to not rescind its policy of fluoridating its water, as described in the fourth link.

Web Links

Fluoridation Debate, Redux
Portland Approves Fluoridation by ‘14
Dentists speak out as fluoride bill nears hearing

References & Links

Links

Dentists speak out as fluoride bill nears hearing – http://ksn.com/2014/02/10/dentists-speak-out-as-fluoride-bill-nears-hearing/
There are 3 forms of vitamin K. Phylloquinone (K1), the plant form of vitamin K, is the primary dietary form of vitamin K. Its structure is shown below.

![Structure of phylloquinone (K1)](image)

*Figure 12.51 Structure of phylloquinone (K1), the 3 outside of the brackets indicates that the structural unit inside the brackets is repeated 3 times*

Green leafy vegetables, broccoli, Brussels sprouts, and asparagus are foods that are good sources of phylloquinone.

Another form of vitamin K, menaquinone (K2), is synthesized by bacteria in the colon. Menaquinone comprises ~10% of absorbed vitamin K every day and can also be found in small amounts in animal products. Its structure is shown below.
Figure 12.52 Structure of menaquinone (K2). Menaquinones have side chains of varying length.

In the structure above, if it was menaquinone-8, there would be 7 \((8-1)\) repeating units of the structure inside the brackets above.

The synthetic form of vitamin K is menadione (K3), whose structure is shown below.
A tail, similar to the one found in menaquinone, has to be added to menadione for it to be biologically active.

Vitamin K is absorbed like other fat-soluble substances. Approximately 80% of phylloquinone and menaquinone are incorporated into chylomicrons and stored primarily in the liver. Once metabolized, vitamin K is primarily excreted via bile in the feces, with a lesser amount excreted in urine.

Subsections:
12.51 Vitamin K Functions
12.52 Vitamin K Deficiency & Toxicity

References & Links
12.51 Vitamin K Functions

Vitamin K is a cofactor for carboxylation reactions that add a CO2 to the amino acid, glutamic acid (glutamate), in certain proteins. The structure of glutamic acid is shown below.

![Structure of glutamic acid](image)

The enzyme, gamma-glutamyl carboxylase, uses a vitamin K cofactor to convert glutamic acid to gamma-carboxyglutamic acid (Gla). Gla proteins are those that contain glutamic acid(s) that have been converted to gamma-carboxyglutamic acid(s). The formation of Gla proteins allows the 2 positive charges of calcium to bind between the 2 negative charges on the carboxylic acid groups (COO-) in the Gla. The binding of calcium activates these proteins\(^2\).
Gla proteins are important in blood clotting. Blood clotting occurs through a cascade of events, as shown in the following 2 videos. The animation below gives an overview of blood clotting, the video is a fun depiction of the blood clotting cascade.

**Web Links**

Hemostasis Animation

Video: The Clotting Cascade (1:20)

Within the blood clotting cascade, there a number of potential Gla proteins, as shown in the figure below.
If these proteins within the blood clotting cascade are not activated to Gla, the cascade does not proceed as normal, leading to impaired blood clotting. After being used as a cofactor by gamma-glutamyl carboxylase to produce a Gla protein, vitamin K becomes vitamin K epoxide. Vitamin K epoxide needs to be converted back to vitamin K to serve as a cofactor again. Warfarin (Coumadin) and dicumarol are a couple of blood thinning drugs that inhibit this regeneration of vitamin K. This reduces the amount of Gla in the blood clotting proteins, thus reducing the clotting response. The structure of warfarin and dicumarol are shown below.

Figure 12.513 Blood clotting cascade with potential Gla proteins circled

12.51 Vitamin K Functions | 715
Figure 12.514 Structure of warfarin

Figure 12.515 Structure of dicumarol

The following coumadin rap song video gives further information on warfarin.
Vitamin K may also be important for bone health. There are 3 Gla proteins found in bone: osteocalcin, matrix Gla protein (MGP), and protein S6. Osteocalcin is a major bone protein, constituting 15–20% of all non-collagen proteins in bone. However, overall, the function of these 3 proteins in bone is not known. Some research suggests that higher vitamin K status or intake decreases bone loss, but it is still not clear whether vitamin K truly is important for bone health.

References & Links

Videos
The Clotting Cascade - https://www.youtube.com/watch?v=NJm4DE-tVuY&feature=related
Coumadin Rap Song - http://www.youtube.com/watch?v=Mfk05IFFW48&feature=watch_response
Vitamin K deficiency is rare, but can occur in newborn infants. They are at higher risk, because there is poor transfer of vitamin K across the placental barrier, their gastrointestinal tracts do not contain vitamin K producing bacteria, and breast milk is generally low in vitamin K\(^1\). As a result, it is recommended (and widely practiced) that all infants receive a vitamin K injection within 6 hours of birth\(^2\).

Prolonged antibiotic treatment (which kills bacteria in the gastrointestinal tract) and lipid absorption problems can also lead to vitamin K deficiency\(^3\). Vitamin K deficient individuals have an increased risk of bleeding or hemorrhage. Remember that high levels of vitamin E intake can also interfere with vitamin K's blood clotting function. It is believed that a vitamin E metabolite, with similar structure to the vitamin K quinones, antagonizes the action of vitamin K.

Phylloquinone and menaquinone have no reported toxicities. However, menadione can cause liver damage\(^1\).

References & Links


There are 3 forms of vitamin A (retinol, retinal, and retinoic acid) that collectively are known as retinoids. Retinol is the alcohol (OH) form, retinal is the aldehyde (COH) form, and retinoic acid is the carboxylic acid (COOH) form, as shown in the figure below (areas of difference are indicated by red).

Among these different retinoids, retinol and retinal are fairly interchangeable. Either form is readily converted to the other. However, only retinal is used to form retinoic acid, and this is a one-way reaction. Thus, once retinoic acid is formed it can't be converted back to retinal, as shown in the figure below.
There are 2 primary dietary sources of vitamin A:

- Retinyl/retinol esters (Animal Products)
- Provitamin A Carotenoids (Plants)

Preformed vitamin A means that the compound is a retinoid. Preformed vitamin A is only found in animal products (carrots are not a good source of preformed vitamin A). Most retinol in animal products is esterified or has a fatty acid added to form retinyl esters (aka retinol esters). The most common retinyl ester is retinyl palmitate (retinol + the fatty acid palmitate) whose structure is shown below.
Provitamin A is a compound that can be converted to vitamin A in the body, but currently isn't in vitamin A form. The next section will talk about carotenoids, some of which are provitamin A compounds.

International units are also used for vitamin A, such that:
1 IU = 0.3 ug retinol or 0.6 ug beta-carotene

Subsections:
12.61 Carotenoids
12.62 Vitamin A Uptake, Absorption, Transport & Storage
12.63 Vitamin A Nuclear Receptors
12.64 Vitamin A Functions
12.65 Vitamin A Deficiency & Toxicity

References & Links
Carotenoids are 40-carbon compounds that are found throughout nature. Animals do not produce carotenoids, thus any found in animals came from consumed plants or microorganisms. There are more than 600 natural carotenoids. However, the 6 main ones found in the diet and in the body are:

- Beta-carotene
- Alpha-carotene
- Beta-cryptoxanthin
- Lutein
- Zeaxanthin
- Lycopene

Many carotenoids are pigments, meaning they are colored. The table below gives the color of some of these carotenoids, as well as some food sources.

Table 12.61 Carotenoids’ color and food sources

<table>
<thead>
<tr>
<th>Carotenoid</th>
<th>Color</th>
<th>Food Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta-carotene</td>
<td>Orange</td>
<td>Carrots, Sweet Potatoes, Leafy Greens</td>
</tr>
<tr>
<td>Lycopene</td>
<td>Red</td>
<td>Tomatoes, Watermelon, Pink Grapefruit</td>
</tr>
<tr>
<td>Lutein/Zeaxanthin</td>
<td>Yellow</td>
<td>Kale, Corn, Egg Yolks, Spinach</td>
</tr>
</tbody>
</table>

Carotenoids can be further classified as provitamin A or non-provitamin A. Provitamin A carotenoids are those that can be cleaved to form retinal, while the non-provitamin A carotenoids cannot. The structure and classification of the 6 major carotenoids are shown below.
After provitamin A carotenoids are taken up into the enterocyte, some are cleaved to form retinal. In the case of symmetrical beta-carotene, it is cleaved in the center to form 2 retinal molecules as shown below.

Alpha-carotene and beta-cryptoxanthin are asymmetrical, thus they can be used to form only 1 retinal.
To help account for the fact that retinol can be made from carotenoids, the DRI committee made retinol activity equivalents (RAE) that take into account the bioavailability and bioconversion of the provitamin A carotenoids.

1 ug RAE

= 1 ug of retinol
= 2 ug of supplemental beta-carotene
= 12 ug of dietary beta-carotene
= 24 ug of alpha-carotene or beta-cryptoxanthin

References & Links


The uptake, absorption, transport, and storage of vitamin A and carotenoids are summarized in the figure below.

Esters are removed by esterases so that free retinol can be taken up into the enterocyte. Preformed vitamin A is highly bioavailable (70-90%) if consumed with some fat\(^2\). Carotenoids have a much lower bioavailability, which varies based on the carotenoid and matrix it is in when consumed. Once provitamin A carotenoids are taken up into the enterocytes, they are: (1) cleaved to retinal and then converted to retinol or (2) absorbed intact and incorporated into chylomicrons.
Retinol in the enterocyte is esterified, forming retinyl esters. The retinyl esters are packaged into chylomicrons (CM) and enter the lymph system. Once the chylomicrons reach circulation, triglycerides are cleaved off to form chylomicron remnants (CM Rem). These are taken up by hepatocytes, where the retinyl esters are de-esterified to form retinol.

The liver is the major storage site of vitamin A. For storage, the retinol will be transported from the hepatocytes to the stellate cells and converted back to retinyl esters, the storage form of vitamin A. If vitamin A is needed to be released into circulation, retinol will combine with retinol binding protein (RBP). Retinol + RBP are then bound to a large transport protein, transthyretin (TTR). It is believed that retinol + RBP would be filtered out by the kidney and excreted in urine if it was not bound to TTR\(^1\).

After it is further metabolized, 60% of vitamin A is excreted in the urine, 40% in feces\(^2\).

**References & Links**


Vitamin A, like vitamin D, has a nuclear receptor. Vitamin A technically has two nuclear receptors, the retinoic acid receptors (RARs) and retinoid X receptors (RXRs). Vitamin A, like polyunsaturated fatty acids, can be found in trans and cis forms, depending on the conformation of its double bonds. The ligand for RARs is all-trans-retinoic acid, and the ligand for RXRs is 9-cis retinoic acid.

As shown in the figure below, all-trans retinol is brought to the cell by RBP and TTR. All-trans retinol is converted to all-trans-retinal, and then to all-trans-retinoic acid. RAR and RXR are paired, or dimerized, on the retinoic acid response element (RARE) in the promoter region of target genes. The binding of all-trans retinoic acid causes the transcription and ultimately the translation of target proteins. This is why all-trans-retinoic acid is the active form of vitamin A because it is the ligand for RARs, leading to many of the biologic effects attributed to vitamin A.
No References
Vitamin A has a number of important functions in the body.

**Vision**

The retina is the inner back lining of the eye that takes visual images and turns them into nerve signals that are sent to the brain to form the images that we “see”, as shown in the following link.

[Web Link – Retina](#)

Inside the retina are the photoreceptor cells, rods and cones. Cones are responsible for color vision, while rods are important for seeing black and white. Within the rods, 11-cis retinal combines with the protein, opsin, to form rhodopsin. When light strikes rhodopsin, the compound splits into opsin and all-trans retinal. This sends a signal to your brain for us to “see”. This process is illustrated in the figure below.
Most all-trans retinal is converted back to 11-cis retinal through a series of steps so it can continue to be used to form rhodopsin. However, this recycling is not 100% efficient. Vitamin A stores, or continued intake, is required to provide the 11-cis retinal needed to continue to form rhodopsin. Normally, our eyes adapt to darkness by increasing the amount of rhodopsin available so we can see under reduced light conditions \(^1\). If a person does not have enough
rhodopsin he/she will become night blind, meaning his/her eyes do not adjust, or adjust very slowly, preventing he/she from seeing under limited light conditions. The picture below is an example of what night blindness looks like.

![Figure 12.642 The left is normal vision, the right is what someone with night blindness would see.](image)

**Cell Differentiation**

Vitamin A, in particular retinoic acid, is important for cell differentiation, or the ability of stem cells to develop into specialized cells.
Other functions that vitamin A is important for include:

- Growth and development
- Reproduction
- Immune function

**References & Links**

Links
Retina – http://webvision.umh.es/webvision/imageswv/Sagschem.jpeg
Vitamin A deficiency is rare in North America, but is a huge problem in developing countries. In many developing countries, they do not have a stable dietary source of retinoids or provitamin A carotenoids. The figure below gives you an idea of countries where vitamin A deficiency is a problem.

Often the earliest symptom of vitamin A deficiency is night blindness, due to the insufficient production of rhodopsin. The reason that this is the earliest symptom, is that circulating vitamin A levels are homeostatically-controlled, meaning that they do not change until after vitamin A stores are exhausted. This means that blood, serum, plasma measurements are going to appear normal until all stores are exhausted. As a result, sensitively assessing someone as vitamin A deficient can be challenging. There are further changes to the eye that occur during vitamin A deficiency, collectively referred to as xerophthalmia, which are shown in the link below.
Ultimately the person can become blind. Vitamin A deficiency is the leading cause of blindness in some parts of the world\textsuperscript{2}.

Another symptom of vitamin A deficiency is hyperkeratosis. In this condition, cells overproduce the protein keratin, causing the skin to become rough and irritated, as shown in the link below\textsuperscript{2}.

One way to counter vitamin A deficiency in developing countries is for staple crops, like rice and corn, to contain beta-carotene. In the case of rice, Golden Rice was genetically modified to produce beta-carotene. A second generation of golden rice, known as Golden Rice 2, has now been developed. However, politics and regulations have prevented it from being used. This is described in the first link. The second link shows some of the opposition to Golden Rice. The third is a nice figure that details the progress towards Golden Rice being used.

There are also corn varieties that have been bred to produce high amounts of beta-carotene, as described in the link below.

Vitamin A can be very toxic and can cause serious symptoms, such as blurred vision, liver abnormalities, skin disorders, and joint
pain\(^2,3\). In addition, research has suggested that people who consume high levels of vitamin A are more prone to bone fractures\(^2\). Toxic levels of vitamin A are also teratogenic, which means they could cause birth defects.

This is important to keep in mind because a vitamin A derivative isotretinoin is the active ingredient in the oral acne medication, Accutane. Accutane is effective, as you can see in the video below.

**Web Link**

– Video: Accutane (1:10)

However, due to the number of adverse events reported from its consumption, Accutane was recalled from the US market in 2009\(^4\). Isotretinoin medications though are still commonly prescribed.

Retin-A is a topical product of all-trans-retinoic acid. Women of childbearing age need to exercise caution when using these products due to the risk of birth defects, should they become pregnant\(^3\). People should not consume huge doses of vitamin A expecting to get the same effects seen from these 2 medications\(^5\).

It is important to note that you cannot develop vitamin A toxicity from consuming too much beta-carotene or other provitamin A carotenoids. Instead, a nontoxic condition known as carotenodermia occurs when large amounts of beta-carotene are consumed, where the accumulation of the carotenoid in the fat below the skin causes the skin to look orange, as shown in the link below.

**Web Link**

– Carotenodermia

**References & Links**


**Links**
The eye signs of vitamin A deficiency – http://www.cehjournal.org/article/the-eye-signs-of-vitamin-a-deficiency/
Hyperkeratosis – http://api.ning.com/files/pKcbIy8a8fSwvjlw-NqcoyW-h1U9xsjxM86*Pg7xe7WAS91frtrQFThTH2oDWcMvbUJ9Mlutd3B9tXk8hjbfmXkeZyJs-7Mi/follicularhyperkeratosis1.jpg
Golden Rice – http://www.goldenrice.org/
Carotenodermia – http://4.bp.blogspot.com/__7hHVSyD26Y/R8xxsFbRc0I/AAAAARAAAAs/I73IzYHNE5k/s1600-h/carotenodermia.jpg

**Video**
Accutane – https://www.youtube.com/watch?v=r93K-w2saPA
There are 2 major dietary forms of iron: heme iron and non-heme iron. Heme iron is only found in foods of animal origin, within hemoglobin and myoglobin. The structure of heme iron is shown below.

![Structure of heme iron](image)

Approximately 40% of iron in meat, fish, and poultry is heme-iron, and the other 60% is non-heme iron. Non-heme iron is the mineral alone, in either its oxidized or reduced form. The 2 forms of iron are:

- Ferric (Fe$^{3+}$, oxidized)
- Ferrous (Fe$^{2+}$, reduced)

It is estimated that 25% of heme iron and 17% of non-heme iron are absorbed. Approximately 85-90% of the iron we consume is non-heme iron.

In addition to getting iron from food sources, if food is cooked in
cast iron cookware, a small amount of iron can be transferred to the food. The story below is an iron fish that is being used in Cambodia to increase iron intake in an area with prevalent iron deficiency. However, they found that the iron fish was not effective in reducing anemia\textsuperscript{4}.

**Web Link**

Canadian's lucky iron fish saves lives in Cambodia

Many breakfast cereals are fortified with reduced iron, which looks like iron filings, as the following video shows.

**Web Link**

Video: Iron for breakfast (1:02)

While the iron bioavailability of this reduced iron is low, some is absorbed\textsuperscript{5}.

**Supplements**

Most iron supplements use ferrous (Fe\textsuperscript{2+}) iron, because this form is better absorbed, as discussed in the next section. The figure below shows the percent of elemental iron in different supplements. This is the percentage of elemental iron that is in each compound.

*Figure 12.72 Elemental iron in different iron supplements*3
Vitamin C does not increase absorption of ferrous supplements because they are already in reduced form, as discussed in the following subsection\(^2\). Iron chelates are marketed as being better absorbed than other forms of iron supplements, but this has not been proven\(^6\). It is recommended that supplements are not taken with meals, because they are better absorbed when not consumed with food\(^2\).

Subsections:
12.71 Iron Uptake & Absorption
12.72 Iron Transport & Storage
12.73 Iron Functions
12.74 Iron Deficiency & Toxicity

**References & Links**

**Link**

**Video**
Iron for breakfast – https://www.youtube.com/watch?v=pRK15XSqtAw
There are 2 transporters for iron, one for heme iron and one for non-heme iron. The non-heme transporter is the divalent mineral transporter 1 (DMT1), which transports Fe$^{2+}$ into the enterocyte. Heme iron is taken up through heme carrier protein 1 (HCP-1), and then metabolized to Fe$^{2+}$. Fe$^{2+}$ may be used by enzymes and other proteins or stored in the enterocyte bound to ferritin, the iron storage protein. To reach circulation, iron is transported through ferroportin$^{1,2}$. This process is summarized in the figure below.

Since only the reduced form of non-heme iron (Fe$^{2+}$) is taken up, Fe$^{3+}$ must be reduced. There is a reductase enzyme on the brush border, duodenal cytochrome b (Dcytb), that catalyzes the reduction of Fe$^{3+}$ to Fe$^{2+}$, as shown below. Vitamin C enhances non-heme iron absorption because it is required by Dcytb for this.
reaction. Thus, if dietary non-heme iron is consumed with vitamin C, more non-heme iron will be reduced to Fe2+ and taken up into the enterocyte through DMT1.

**Figure 12.7.12 Reduction of non-heme iron by Dcytb**

In addition to vitamin C, there is an unidentified factor in muscle that enhances non-heme iron absorption if consumed at the same meal3. This unidentified factor is referred to as meat protein factor (MPF). The table shows how MPF can increase non-heme iron absorption.
Table 12.711 Non-heme iron absorption from chicken or beef muscle fraction

<table>
<thead>
<tr>
<th>Mean Fe Absorption (％ of Dose)</th>
<th>Egg Albumin</th>
<th>Whole Muscle</th>
<th>Whole Muscle Protein</th>
<th>Heme-Free Muscle Protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken</td>
<td>8.41</td>
<td>16.43</td>
<td>26.98</td>
<td>36.81</td>
</tr>
<tr>
<td>Beef</td>
<td>11.21</td>
<td>31.52</td>
<td>44.15</td>
<td>38.29</td>
</tr>
</tbody>
</table>

Albumin is a protein, so the egg albumin represents a non-meat protein standard for comparison. You can see that absorption is much higher with whole muscle. When only consuming muscle protein, there is a slight increase from muscle itself, and when they look at heme-free muscle iron, absorption is still higher than egg albumin.

Inhibitors of non-heme iron absorption typically chelate, or bind, the iron to prevent absorption. Phytates (phytic acid), which also inhibit calcium absorption, chelate non-heme iron decreasing its absorption.

![Figure 12.713 Structure of phytic acid](image)

Other compounds that inhibit absorption are:
Polyphenols (coffee, tea)\textsuperscript{1}

\begin{center}
\includegraphics[width=0.5\textwidth]{figure12.714.png}
\end{center}

\textit{Figure 12.714 Structure of gallic acid, a polyphenol}\textsuperscript{3}

Oxalate (spinach, rhubarb, sweet potatoes, and dried beans)\textsuperscript{2}
Calcium is also believed to inhibit iron uptake.

**References & Links**


Transferrin is the major iron transport protein (transports iron through blood). Fe3+ is the form of iron that binds to transferrin, so the Fe2+ transported through ferroportin must be oxidized to Fe3+. There are 2 copper-containing proteins that catalyze this oxidation of Fe2+: hephaestin and ceruloplasmin. Hephaestin is found in the membrane of enterocytes, while ceruloplasmin is the major copper transport protein in blood. Hephaestin is the primary protein that performs this function in a coupled manner (need to occur together) with transport through ferroportin. This means that the Fe2+ needs to be oxidized to be transported through ferroportin. Evidence suggests that ceruloplasmin is involved in oxidizing Fe2+ when iron status is low\(^1\). Once oxidized, Fe3+ binds to transferrin and is transported to a tissue cell that contains a transferrin receptor. Transferrin binds to the transferrin receptor and is endocytosed, as shown below\(^2\).

---

Figure 12.721 Transport and uptake of iron
Once inside cells, the iron can be used for cellular purposes (cofactor for enzyme etc.) or it can be stored in the iron storage proteins ferritin or hemosiderin. Ferritin is the primary iron storage protein, but at higher concentrations, iron is also stored in hemosiderin\(^2\).

**Figure 12.72** Fates of iron within cells

There are 3 major compartments of iron in the body\(^3\):

1. Functional Iron
2. Storage Iron
3. Transport Iron

Functional iron consists of iron performing some function. There are 3 functional iron subcompartments.

1. Hemoglobin
2. Myoglobin
3. Iron-containing enzymes

The functions of these subcompartments are discussed in the next section.

Iron Stores consist of:

1. Ferritin
2. Hemosiderin
The liver is the primary storage site in the body, with the spleen and bone marrow being the other major storage sites.

Circulating iron is found in transferrin$^3$.

The following table shows how much iron is distributed among the different compartments.

Table 12.721 Iron Distribution in adults (mg Fe/kg body weight)$^3$

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional iron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemoglobin</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>Myoglobin</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Fe-containing enzymes</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>Storage iron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferritin and hemosiderin</td>
<td>~11</td>
<td>~6</td>
</tr>
<tr>
<td>Transport iron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transferrin</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Hopefully you notice that the majority of iron is in the functional iron compartment. The figure below further reinforces this point, showing that most iron is found in red blood cells (hemoglobin) and tissues (myoglobin).

![Iron distribution in different compartments](image)

Figure 12.723 Iron distribution in different compartments$^4$
Also notice how small oral intake and excretion are compared to the amount found in the different compartments in the body. As a result, iron recycling is really important, because red blood cells only live for 120 days. Red blood cells are broken down in the liver, spleen, and bone marrow and the iron can be used for the same purposes as described earlier: cellular use, storage, or transported to another tissue on transferrin\textsuperscript{2}. Most of this iron will be used for heme and ultimately red blood cell synthesis. The figure below summarizes the potential uses of iron recycled from red blood cells.

Iron is unique among minerals in that our body has limited excretion ability. Thus, absorption is controlled by the hormone hepcidin. The liver has an iron sensor so when iron levels get high, this sensor signals for the release of hepcidin. Hepcidin causes degradation of ferroportin. Thus, the iron is not able to be transported into circulation\textsuperscript{5}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{iron_recycling.png}
\caption{Iron recycling from red blood cells}
\end{figure}
The iron is now trapped in the enterocyte, which is eventually sloughed off and excreted in feces. Thus, iron absorption is decreased through the action of hepcidin.

References & Links
1. Yehuda S, Mostofsky DI (2010) Iron Deficiency and Overload:


As we talked about in the previous subsection, there are 3 primary functional iron subcompartments.

1. Hemoglobin
2. Myoglobin
3. Iron-containing enzymes

Hemoglobin contains heme that is responsible for red blood cells' red color. Hemoglobin carries oxygen to tissues. The function of hemoglobin can be seen in the link below.

**Web Link**

– [Hemoglobin](#)

Myoglobin is similar to hemoglobin in that it can bind oxygen. However, instead of being found in blood, it is found in muscle. The color of meat products is a result of the state that myoglobin is in, as shown in the link below.

**Web Link**

– [Myoglobin & Meat Color](#)

There are a number of enzymes that use iron as a cofactor. We've already talked about two in this class.

Iron is a cofactor for the antioxidant enzyme, catalase, that converts hydrogen peroxide to water, as shown below.
Iron is also a cofactor for proline and lysyl hydroxylases that are important in collagen cross-linking. This will be discussed further in the vitamin C section. The function of these enzymes is shown below.
Figure 12.732 Importance of ascorbic acid and iron to proline and lysyl hydroxylases.

Heme iron is also found in cytochromes, like cytochrome c in the electron transport chain as shown below.¹

Figure 12.733 Cytochrome c in the electron transport chain contains iron.²
References & Links


Links


192. 12.74 Iron Deficiency & Toxicity

The levels of iron in the different compartments is illustrated by the figure below. The red above the table is meant to represent the amount of iron in the different compartments. In early negative iron balance stage, iron stores are slightly depleted. Once the stores are almost completely exhausted, this state is referred to as iron depletion. In iron deficiency, stores are completely exhausted and the circulating and functional iron levels are also depleted. In iron anemia, the circulating and functional iron levels are further depleted from iron-deficiency.

Figure 12.74.1 Measures of iron status

1 Great measure, but invasive

2 Small amount are released from liver, bone, and spleen – proportional to body stores

3 Also referred to as total iron-binding capacity

The most common measures of iron status are hemoglobin concentrations and hematocrit (described below) levels. A decreased amount of either measure indicates iron deficiency, but
these two measures are among the last to indicate that iron status is depressed. This is because, as you can see in the figure above, circulating iron (plasma iron) levels are not altered until you reach iron deficiency. Thus, other measures are likely better choices.\(^1\)

The hematocrit, as illustrated in the figure below, is a measure of the proportion of red blood cells (erythrocytes) as compared to all other components of blood. The components are separated by a centrifuge. The red blood cells remain at the bottom of the tube. They can be quantified by measuring the packed cell volume (PCV) relative to the total whole blood volume.
One of the best measures of iron status is bone marrow iron, but this is an invasive measure, and is therefore not commonly used. Plasma ferritin, the iron storage protein, is also found in lower amounts in the blood (plasma) and is a good indicator of iron stores. Thus, it is a sensitive measure to determine if someone is in negative iron balance or iron depleted. It is not as useful of a measure beyond this stage because the iron stores have been exhausted for the most part. Transferrin iron binding capacity (aka total iron binding capacity), as it sounds, is a measure of how much iron transferrin
can bind. An increase in transferrin iron binding capacity indicates deficiency (>400 indicates deficiency). But the best measure for deficiency or anemia is either percent serum transferrin saturation or plasma iron. A lower % saturation means that less of the transferrin are saturated or carrying the maximum amount of iron that they can handle. Plasma iron is easily understood as the amount of iron within the plasma.

Iron deficiency is the most common deficiency worldwide, estimated to affect 1.6 billion people. In the US, it is less common, but an estimated 10% of toddlers and women of childbearing age are deficient. Iron deficiency often results in a microcytic (small cell), hypochromic (low color) anemia, that is a result of decreased hemoglobin production. With decreased hemoglobin, the red blood cells cannot carry as much oxygen. Decreased oxygen leads to slower metabolism. Thus, a person with this anemia feels fatigued, weak, apathetic, and can experience headaches. Other side effects include decreased immune function and delayed cognitive development in children.

Those who are particularly at risk are:

Women of childbearing age – because of losses due to menstruation
Pregnant women – because of increased blood volume
Vegetarians – because they do not consume heme iron sources
Infants – because they have low iron stores that can quickly be depleted

To give you a better understanding of these risks, it is helpful to look at how much higher the RDAs are for women of reproductive age and pregnant women compared to men.

Women of reproductive age 18 mg/day
Pregnancy 27 mg/day
Men 8 mg/day

To put this in perspective, 3 oz of beef contains ~3 mg of iron. Thus, it can be a challenge for some women to meet the requirement. The RDA committee estimates the iron requirements to be 80% and 70% higher for vegans and endurance athletes,
respectively. The increased requirement for endurance athletes is based on loss due to “foot strike hemolysis”, or the increased rupture of red blood cells due to the striking of the foot on hard surfaces\(^3\).

Iron toxicity is rare in adults, but can occur in children who consume too many supplements containing iron. Symptoms of this acute toxicity include nausea, vomiting, and diarrhea\(^7\).

50 out of 10,000 newborns in the United States are born with the genetic condition, hemochromatosis. In this condition, there is a mutation in a protein in the enterocyte that prevents the normal decrease of intestinal iron absorption. Without this protein these individuals cannot decrease iron absorption. Since the body cannot excrete iron, it accumulates in tissues, and ultimately can result in organ failure\(^1\).

**References & Links**

193. 12.8 Zinc

Many animal products are good sources of zinc and are estimated to account for 70% of the zinc North Americans’ consume\(^1\). An estimated 15-40% of consumed zinc is absorbed\(^2\). Zinc is taken up into the enterocyte through the Zir-and Irt-like protein 4 (ZIP4). Once inside the enterocyte, zinc can:

1. Bind to the zinc storage protein thionein. Once thionein has bound a mineral (or a metal) it is known as metallothionein.
2. Be used for functional purposes.
3. Bind to the cysteine-rich intestinal protein (CRIP) where it is shuttled to a zinc transporter (ZnT). After moving through the basolateral membrane, zinc primarily binds to the circulating protein albumin\(^3\).

These functions are represented in the figure below.

![Figure 12.81 Fates of zinc once it is taken up into the enterocyte](image_url)

The zinc attached to albumin is transported to the liver through the portal vein. There is not a major storage site of zinc, but there
are pools of zinc in the liver, bone, pancreas, and kidney. Zinc is primarily excreted in feces.

There are some similarities between zinc and iron absorption. Increased zinc consumption results in increased thionein synthesis in the enterocyte. As a result, more zinc is bound to thionein (forming metallothionein) and not used for functional uses or transported into circulation, as represented by the thick and thin arrows in the figure below.

The enterocytes are then sloughed off preventing the bound zinc from being absorbed.
Enterocytes are sloughed off and excreted in feces.

There are a number of inhibitors of zinc absorption:
Phytate (phytic acid), which inhibits calcium and iron absorption, also binds to and inhibits zinc absorption.  

Polyphenols (coffee, tea)
Figure 12.85 Structure of the polyphenol gallic acid

Oxalate (spinach, rhubarb, sweet potatoes, and dried beans)
Non-heme iron also inhibits zinc absorption.
   In supplements, zinc is found as\textsuperscript{3,7}:
   Zinc oxide – 80% zinc
   Zinc chloride – 23% zinc
   Zinc sulfate – 23% zinc
   Zinc gluconate – 14.3% zinc
   Zinc oxide is the least bioavailable form, but since it is 80% zinc, it is commonly used in supplements\textsuperscript{7}.

Subsections:
12.81 Zinc Functions
12.82 Zinc Deficiency & Toxicity

References & Links


Zinc is a cofactor for up to 300 enzymes in the body\(^1\). Enzymes that use zinc as a cofactor are known as metalloenzymes.

Zinc is a cofactor for the antioxidant enzyme superoxide dismutase that converts superoxide to hydrogen peroxide, as shown below.

**Figure 12.811 Superoxide dismutase uses zinc as a cofactor**

Alcohol dehydrogenase uses 4 zinscs per enzyme. Its role in ethanol metabolism is shown below\(^2\).
Delta-aminolevulinic acid dehydratase (ALA dehydrogenase), which is involved in heme synthesis, uses 8 zincs/enzyme to form porphobilinogen, as shown below:

**Figure 12.813 ALA dehydrogenase requires zinc in the heme synthesis pathway**

**Figure 12.812 Ethanol metabolism**

**MEOS – Microsomal Ethanol Oxidizing System**

Figure 12.812 Ethanol metabolism
The enzyme that cleaves the extra glutamates from folate so that it can be taken up into the enterocyte is a metalloenzyme. The cleavage of folate is shown in the figure below.

![Figure 12.814 The absorption of folate and folic acid](image)

Other notable metalloenzymes include DNA and RNA polymerase. Zinc is also important for the formation of zinc fingers in proteins. Zinc fingers help proteins bind to DNA.
Zinc is also important for growth, immune function, and reproduction\(^2\).

A recent Cochrane review concluded that when taken within 24 hours of the onset of symptoms, that zinc lozenges or syrup results in a significant decrease in the duration and severity of common cold symptoms\(^7\). Thus, commonly used zinc lozenges may be an effective way to combat the common cold. However, large amounts of zinc consumption can be problematic for copper and ultimately iron levels in the body, as described in the copper section.

**References & Links**

As can be seen on the bottom map in the link below, the risk of zinc deficiency is low in North America, but there are other places in the world where it is much more common.

At particular risk are children, pregnant women, elderly and the poor. Symptoms of zinc deficiency include:

- Growth inhibition
- Delayed sexual maturation
- Dermatitis
- Hair loss
- Impaired immune function
- Skeletal abnormalities

In the link below you can see a picture of an infant with dermatitis caused by zinc deficiency.
Another cause of zinc deficiency is mutation of ZIP4 that results in the condition acrodermatitis enteropathica. Without ZIP4, zinc cannot be taken up efficiently into the enterocyte. This condition is managed by administering very high levels of zinc, some of which is absorbed through other mechanisms\(^3\).

Zinc toxicity is not common, but an acute toxicity results in:\(^2\):
- Nausea
- Vomiting
- Intestinal cramps
- Diarrhea

Chronic toxicity can result in copper deficiency, as will be discussed in the copper section\(^3\).

**References & Links**


**Links**


12.9 Copper

Like iron, copper is found in 2 forms:

1. Cupric (Cu2+), oxidized
2. Cuprous (Cu1+), reduced

Cu1+ is the form that is primarily absorbed, thus Cu2+ is reduced to Cu1+ in the lumen. It is believed that, like iron, enzymatic reduction of Cu2+ is stimulated by ascorbate. The exact transporter that takes up the copper into the enterocyte is not known. It may be DMT1 that takes up non-heme iron. Once inside the enterocyte, Cu1+ can:

1. Bind to thionein to form metallothionein. While zinc is a better stimulator of thionein levels, copper is actually a more avid binder to this protein.
2. Be used for functional uses discussed in the next subsection.
3. Transported across the cell by an unknown carrier and then exported by ATP7A, an ATPase transporter.

Like zinc, copper is transported through the portal vein to the liver bound to albumin, as shown below. Albumin has a high affinity for Cu2+, so Cu1+ is oxidized before transported to albumin through ATP7A, as illustrated below.
Like zinc, there is not much storage of copper in the body. The liver is the primary site of storage, where copper is taken up through an unknown transporter. If it is going to be stored, it will bind with thionein to form metallothionein. Copper to be sent out to the body is transferred to the copper transport protein ceruloplasmin, which can bind 6 coppers/protein as shown below.  

Figure 12.91 Copper absorption

Figure 12.92 Copper in the hepatocyte
Legumes, whole grains, nuts, shellfish, and seeds are good sources of copper\(^2\). It is estimated that over 50% of copper consumed is absorbed\(^1\). Copper is primarily excreted in the feces.

There are several different forms of copper used in supplements:

- Copper sulfate (25% copper)
- Cupric chloride (47% copper)
- Cupric acetate (35% copper)
- Copper carbonate (57% copper)
- Cupric oxide (80% copper)

All of these forms of copper are bioavailable, except cupric oxide. Assays have shown that it is not absorbed at all. Nevertheless, some supplements still use this form of copper\(^1,3\).

Subsections:
- 12.91 Copper Functions
- 12.92 Copper Deficiency & Toxicity
- 12.93 How High Zinc Intake Can Lead to Iron & Copper Deficiencies

References & Links


197. 12.91 Copper Functions

Copper has a number of functions that are described and shown below.

Two copper-containing proteins, ceruloplasmin and hephaestin, oxidize Fe2+ to Fe3+. Fe3+ is the form that binds to transferrin, as shown below.

![Figure 12.911 Transport and uptake of iron](image)

Because copper is needed for this function, it is important for iron absorption.

Copper is also a cofactor for superoxide dismutase, which converts superoxide to hydrogen peroxide, as shown below.
Superoxide dismutase uses zinc as a cofactor. Copper is also needed for hormone synthesis. For example, it is a cofactor for dopamine beta-hydroxylase, which converts dopamine to norepinephrine, as shown below.¹
Figure 12.913 Dopamine beta-hydroxylase requires copper

Hopefully the following example looks vaguely familiar because we talked about this pathway in the vitamin C functions subsection. Ascorbic acid reduces Cu2+ back to Cu1+ so that this enzyme can continue to function, as shown below. This is analogous to how ascorbic acid reduces Fe3+ back to Fe2+ so proline and lysyl hydroxylases can continue to function.
Cytochrome c oxidase (complex IV) in the electron transport chain is a copper-containing enzyme that reduces oxygen to form water, as shown below.

Figure 12.915 Cytochrome c oxidase (complex IV)
Lysyl oxidase, an enzyme that is important for cross-linking between structural proteins (collagen and elastin), requires copper as a cofactor¹.

**References & Links**

Copper deficiency is rare in humans, but results in the following symptoms\textsuperscript{1,2}:
- Hypochromic anemia
- Decreased white blood cell counts leading to decreased immune function
- Bone abnormalities
- Copper deficiency can result in a secondary iron deficiency, since Fe\textsuperscript{2+} cannot be oxidized to Fe\textsuperscript{3+} to bind to transferrin. This can cause the hypochromic anemia that occurs in iron deficiency.
- Menke's disease is a genetic disorder that results in copper deficiency. It is believed that individuals with this disease have a mutation in ATP\textsubscript{7A} that prevents copper from leaving the enterocyte, thus preventing absorption\textsuperscript{1}.

Copper toxicity is also rare in humans, but acute toxicity results in the following symptoms\textsuperscript{1,2}:
- Nausea, vomiting, diarrhea, abdominal pain
- Chronic symptoms include\textsuperscript{1,2}:
  - Brain, liver, and kidney damage
  - Neurological damage
- Wilson's disease is a genetic disorder where a mutation in ATP\textsubscript{7B} prevents copper excretion, resulting in copper toxicity. One notable symptom is that individuals with this disease have golden to greenish-brown Kayser-Fleischer rings around the edges of the cornea, as shown in the link below\textsuperscript{1,2}.

**Web Link**

Kayser-Fleischer ring

**References & Links**

782 | 12.92 Copper Deficiency & Toxicity


Link
12.93 How High Zinc Intake Can Lead to Copper & Iron Deficiencies

As you learned previously, thionein is the storage protein for zinc, but it more avidly binds copper. When it binds a mineral, it becomes metallothionein. High zinc intake results in increased thionein synthesis in the enterocyte. Thus, when an individual is consuming high zinc levels, the enterocyte will have high levels of thionein as shown below.

The high levels of thionein will bind any copper that is taken up into the enterocyte (as metallothionein), “trapping” the copper in the enterocyte and preventing it from being absorbed into circulation, as shown below.

Figure 12.931 Zinc increases thionein production
Figure 12.932 Copper taken up into the enterocyte is bound to thionein forming metallothionein.

The enterocytes containing the “trapped” copper move up the crypt and are sloughed off and excreted in feces. The copper consumed essentially is lost from the body through this process.

Figure 12.933 Enterocytes are sloughed off and excreted in feces

Without adequate copper being transported to the liver, no
ceruloplasmin is produced and released into circulation. The lack of copper further influences iron transport by decreasing ceruloplasmin in circulation and hephaestin (another copper-containing protein) on the membrane of the enterocyte. These 2 proteins normally convert Fe2+ to Fe3+ so that iron can bind to transferrin.

Without hephaestin and ceruloplasmin, Fe3+ is not formed from Fe2+. As a result Fe2+ is “trapped” in the enterocyte because it can’t bind to transferrin as shown below.

Figure 12.93 Lack of copper means that hephaestin and ceruloplasmin aren’t available to oxidize Fe2+ to Fe3+
The enterocytes containing the “trapped” iron move up the crypt and are also sloughed off and excreted in feces. The iron consumed essentially is lost from the body through this process.

In summary, high zinc intake increases thionein production, which traps all copper; the lack of copper decreases circulating
ceruloplasmin and hephaestin, which causes all iron to be trapped as well. This example illustrates the interconnectedness of zinc, copper, and iron.

No References
In this chapter, electrolytes will be explained before learning more about the 4 electrolyte micronutrients. Then, hypertension will be discussed, along with the impact of these micronutrients on the condition.

Subsections:
13.1 Electrolytes
13.2 Sodium
13.3 Chloride
13.4 Potassium
13.5 Magnesium
13.6 Hypertension, Salt-Sensitivity & the DASH Diet
Electrolytes are compounds that separate into ions (molecules with a charge) in water. Electrolytes can be separated into 2 classes:
  
  Cations: ions that have a positive charge
  Anions: ions that have a negative charge
  
The following table summarizes the major intracellular and extracellular electrolytes by giving their milliequivalents (mEq)/L. Milliequivalents are a measure of charge. Thus, a higher value means that the cation or anion is accounting for more charge.

<table>
<thead>
<tr>
<th>Intracellular</th>
<th>Extracellular</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cations</strong></td>
<td><strong>Anions</strong></td>
</tr>
<tr>
<td>Potassium (K+) 150</td>
<td>Phosphate (PO4−) 104</td>
</tr>
<tr>
<td>Magnesium (Mg2+) 40</td>
<td>Proteins 57</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following figure graphically shows the major intracellular and extracellular cations (green) and anions (red).
Electrolytes and proteins are important in fluid balance. Your body is 60% water by weight. Two-thirds of this water is intracellular, or within cells. One-third of the water is extracellular, or outside of cells. One-fourth of the extracellular fluid is plasma, while the other 3/4 is interstitial (between cells) fluid. Thus, when considering total body water, around 66% is intracellular fluid, 25% is interstitial fluid, and 8% is plasma\textsuperscript{3,4}.

Fluid distribution between the different compartments are shown below.
References & Links


202. 13.2 Sodium

Salt (NaCl) contributes almost all the sodium that we consume. 75-85% of the salt we consume is from processed foods, 10% is naturally in foods, and added salt contributes 10-15% of total salt intake\(^1\).

95-100% of consumed sodium is absorbed\(^2\). Sodium is taken up into the enterocyte through multiple mechanisms before being pumped out of the enterocyte by sodium-potassium (Na\(^+/K^+\)) ATPase. Sodium-potassium ATPase is an active carrier transporter that pumps 3 sodium ions out of the cell and 2 potassium ions into the cell, as shown below.

Sodium is the major cation in extracellular fluid. Sodium has 3 main functions\(^1\):

1. Fluid balance
2. Aids in monosaccharide and amino acid absorption
3. Muscle contraction and nerve transmission (not discussed further below)

**Fluid balance**
The body regulates sodium and fluid levels through a series of processes as shown below. A decrease in plasma volume and blood pressure signals the kidney to release the enzyme renin. Renin activates angiotensin that is converted to angiotensin II. Angiotensin II signals the adrenal glands to secrete the hormone aldosterone. Aldosterone increases sodium reabsorption in the kidney, thus decreasing sodium excretion. These actions cause plasma sodium concentrations to increase, which is detected by the hypothalamus. The hypothalamus stimulates the pituitary gland to release antidiuretic hormone (ADH) that causes the kidneys to reabsorb water, decreasing water excretion. The net result is an increase in blood volume and blood pressure\(^1\).

2. **Aids in monosaccharide and amino acid absorption**

Glucose and galactose are taken up into the enterocyte by sodium-glucose cotransporter 1 (SGLT1), which requires sodium to be transported along with glucose or galactose.
Amino acids are taken up and transported into circulation through a variety of amino acid transporters. Some of these transporters are sodium–dependent (require sodium to transport amino acids).
Sodium deficiency is rare, and is normally due to excessive sweating. Sweat loss must reach 2-3% of body weight before sodium losses are a concern\textsuperscript{1,2}. This situation can occur in marathon runners and ultra-marathon runners who sweat for many hours straight (without proper liquid intake). Low blood sodium levels (hyponatremia) can result in\textsuperscript{1}:

- Headache
- Nausea
- Vomiting
- Fatigue
- Muscle Cramps

Sodium is not toxic, but higher sodium intake increases the risk of developing high blood pressure. High sodium intake also increases calcium excretion, but studies haven't found an increased risk of osteoporosis. High sodium intake may also increase the risk of developing kidney stones (by increasing calcium excretion), because calcium oxalate is the most common form of kidney stone\textsuperscript{1}.

**References & Links**

Sodium’s partner in salt, chloride, is the major extracellular anion. Almost all of the chloride we consume is from salt, and almost all chloride is absorbed. It is excreted in urine like sodium.

Chloride has the following functions:\textsuperscript{1}:
1. Aids in nerve impulses
2. Component of HCl
3. Released by white blood cells to kill foreign substances
4. Helps maintain acid-base balance

Chloride deficiency is rare, but can occur because of severe diarrhea or vomiting. Other symptoms of this deficiency include\textsuperscript{1,2}:

- Weakness
- Diarrhea and vomiting
- Lethargy

Chloride is not toxic, but since it is a part of salt, it is recommended that we restrict our intake to avoid potential increases in blood pressure.

References & Links
Potassium is the major intracellular cation. Good sources of potassium include beans, potatoes (with skin), milk products, orange juice, tomato juice, and bananas. Potassium, like sodium and chloride, is well absorbed. Greater than 85% of consumed potassium is absorbed. Potassium is primarily excreted in urine (~90%).

Potassium is important for:
1. Fluid Balance
2. Nerve transmission and muscle contraction

Increased potassium intake results in decreased calcium excretion. This is the opposite effect of increased sodium intake, which increases calcium excretion.

Potassium deficiency is rare but can be fatal. Symptoms include:
- Weakness
- Fatigue
- Constipation
- Irregular heartbeat (can be fatal)

Deficiency can occur in individuals that are on diuretics, drugs that increase urine production, and individuals with eating disorders.

Toxicity is also extremely rare, only occurring if there is a problem with kidney function. Symptoms of toxicity are irregular heartbeat and even cardiac arrest.

**References & Links**
Magnesium is an electrolyte, but that is not considered its major function in the body. Green leafy vegetables, beans, nuts, seeds, and whole grains are good sources of magnesium. 40-60% of consumed magnesium is absorbed at normal levels of intake. Magnesium is excreted primarily in urine.

55-60% of magnesium in the body is found in bone. Some (30%) of this bone magnesium is believed to be exchangeable, or can be used to maintain blood concentrations, similar to how calcium in bones can be used to maintain blood concentrations.

Magnesium helps to stabilize ATP and nucleotides by binding to phosphate groups. Magnesium plays a role in over 300 enzymes in the body. Here is a list of some of the physiological processes that magnesium participates in:

- Glycolysis
- TCA cycle
- Fatty acid oxidation (beta-oxidation)
- DNA and RNA transcription
- Nucleotide synthesis
- Muscle contraction

Magnesium deficiency is rare, but can be caused by prolonged diarrhea or vomiting. Symptoms include:

- Irregular heartbeat
- Muscle spasms
- Disorientation
- Seizures
- Nausea
- Vomiting

Magnesium toxicity is also rare but can occur from excessive use of antacids or laxatives. Symptoms include:

- Diarrhea
- Nausea
Flushing
Double vision
Slurred speech
Weakness
Paralysis

Magnesium supplements differ in percent of magnesium in the different forms, as shown below.

The bioavailability of magnesium oxide is significantly lower than magnesium chloride, magnesium lactate, and magnesium aspartate. The latter 3 are equally bioavailable⁴.

References & Links

Figure 13.51 Percent magnesium in oral supplements
Approximately 27% of American adults have hypertension (high blood pressure), which increases their risk of developing cardiovascular disease\(^1\). Salt and/or sodium intake is believed to be a major causative factor in the development of hypertension. However, it is now known that not everyone is salt-sensitive. Salt-sensitive means that a person's blood pressure increases with increased salt intake and decreases with decreased salt intake. Approximately 25% of normotensive (normal blood pressure) individuals and 50% of hypertensive individuals are salt-sensitive\(^2\). Most others are salt-insensitive, and in a small portion of individuals, low salt consumption actually increases blood pressure\(^1\). Unfortunately, there isn't a clinical method to determine whether a person is salt-sensitive. There are some known characteristics that increase the likelihood of an individual being salt-sensitive. They are\(^1\):

- Elderly
- Female
- African-American
- Hypertensive
- Diabetic
- Chronic Kidney Disease

There is some evidence now suggesting that there may be negative effects in some people who restrict their sodium intakes to the levels recommended by some organizations. The second link describes a couple of studies that had conflicting outcomes as it relates to the importance of salt reduction in decreasing blood pressure and cardiovascular disease. The third link is to a study
that found that higher potassium consumption, not lower sodium consumption, was associated with decreased blood pressure in adolescent teenage girls.

Web Link

Report Questions Reducing Salt Intake Too Dramatically 
For Teenagers, Potassium May Matter More Than Salt

To combat hypertension, the Dietary Approaches to Stop Hypertension (DASH) diet was developed. This diet emphasizes:
- fruits, vegetables, fat-free/low-fat milk and milk products, whole grain products, fish, poultry, nuts
- It limits:
  - red meat, sweets, added sugars, sugar-containing beverages
As a result the diet is high in:
- potassium, magnesium, calcium, protein, fiber

The daily goals for the DASH diet are shown below:

**Daily Nutrient Goals Used in the DASH Studies**
(for a 2,100 Calorie Eating Plan)

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fat</td>
<td>27% of calories</td>
</tr>
<tr>
<td>Saturated fat</td>
<td>6% of calories</td>
</tr>
<tr>
<td>Protein</td>
<td>18% of calories</td>
</tr>
<tr>
<td>Carbohydrate</td>
<td>55% of calories</td>
</tr>
<tr>
<td>Cholesterol</td>
<td>150 mg</td>
</tr>
<tr>
<td>Sodium</td>
<td>2,300 mg*</td>
</tr>
<tr>
<td>Potassium</td>
<td>4,700 mg</td>
</tr>
<tr>
<td>Calcium</td>
<td>1,250 mg</td>
</tr>
<tr>
<td>Magnesium</td>
<td>500 mg</td>
</tr>
<tr>
<td>Fiber</td>
<td>30 g</td>
</tr>
</tbody>
</table>

* 1,500 mg sodium was a lower goal tested and found to be even better for lowering blood pressure. It was particularly effective for middle-aged and older individuals, African Americans, and those who already had high blood pressure.

Figure 13.61 DASH daily nutrient goals
To get an idea of what types of foods and how much would be consumed in the diet, an eating plan is shown below.

**Box 4**

**DASH Eating Plan—Number of Daily Servings for Other Calorie Levels**

<table>
<thead>
<tr>
<th>Food Groups</th>
<th>Servings/Day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,600 calories/day</td>
</tr>
<tr>
<td>Grains*</td>
<td>6</td>
</tr>
<tr>
<td>Vegetables</td>
<td>3–4</td>
</tr>
<tr>
<td>Fruits</td>
<td>4</td>
</tr>
<tr>
<td>Fat-free or low-fat milk and milk products</td>
<td>2–3</td>
</tr>
<tr>
<td>Lean meats, poultry, and fish</td>
<td>3–6</td>
</tr>
<tr>
<td>Nuts, seeds, and legumes</td>
<td>3/week</td>
</tr>
<tr>
<td>Fats and oils</td>
<td>2</td>
</tr>
<tr>
<td>Sweets and added sugars</td>
<td>0</td>
</tr>
</tbody>
</table>

* Whole grains are recommended for most grain servings as a good source of fiber and nutrients.

Figure 13.62 DASH eating plan

The DASH diet has been shown to be remarkably effective in decreasing blood pressure in those with hypertension. Nevertheless, most people with hypertension aren’t following the DASH diet. In fact, evidence from the National Health and Nutrition
Examination Survey found that significantly fewer hypertensive individuals were following the DASH diet in 1999-2004 than during 1988-1994, as shown in the table below.  

Table 13.61 Percent of hypertensive subjects in NHANES trial meeting the DASH goals

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DASH Accordance</td>
<td>29.3 ± 1.5</td>
<td>21.7 ± 1.3</td>
<td>-7.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total Fat</td>
<td>42.9 ± 1.8</td>
<td>35.9 ± 2.0</td>
<td>-7.0</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated Fat</td>
<td>20.6 ± 1.2</td>
<td>20.4 ± 1.4</td>
<td>-0.2</td>
<td>0.94</td>
</tr>
<tr>
<td>Protein</td>
<td>43.7 ± 2.0</td>
<td>47.7 ± 1.9</td>
<td>4.0</td>
<td>0.73</td>
</tr>
<tr>
<td>Cholesterol</td>
<td>26.4 ± 2.2</td>
<td>24.3 ± 1.6</td>
<td>-2.1</td>
<td>0.44</td>
</tr>
<tr>
<td>Fiber</td>
<td>20.2 ± 1.5</td>
<td>12.3 ± 0.9</td>
<td>-7.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Magnesium</td>
<td>14.2 ± 1.3</td>
<td>6.4 ± 0.8</td>
<td>-7.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Calcium</td>
<td>19.0 ± 1.6</td>
<td>17.6 ± 2.0</td>
<td>-1.4</td>
<td>0.58</td>
</tr>
<tr>
<td>Potassium</td>
<td>12.7 ± 0.9</td>
<td>11.7 ± 0.9</td>
<td>-1.0</td>
<td>0.46</td>
</tr>
<tr>
<td>Sodium</td>
<td>17.8 ± 1.5</td>
<td>14.6 ± 1.3</td>
<td>-3.2</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The main components that contributed to the decrease in DASH diet accordance were total fat, fiber, and magnesium, as indicated by their high negative absolute changes.

References & Links

**Links**


Throughout the documents found in this “Syllabus” folder, you'll find syllabus-like information (Overview, Course Reading and Materials, Course Schedule, etc.). You should read these documents in order and feel free to ask any questions you might have along the way by clicking on the “Ask a Question” discussion found in the left hand side bar. However, this area is not for just for asking questions. I encourage you to respond to any questions posted to help each other out along the way. After reading through the Course Information documents, you should have a clear understanding of my expectations of you in this course. You may want to print out some of the documents, if you are more comfortable reading or keeping the course information off-line.

After you have read through the Syllabus documents, return to the main Learning Modules screen, this area contains all the content and areas for interaction in this course. The Learning Modules contain the all content, reading assignments, and learning activities for this course. The Learning Module section is where you “attend class” on a weekly basis. Rely on the Course Schedule found in this course information section, and the left hand side bar, to plan your participation, work, and to find out when all course learning activities/assignments will begin, end, or are due. If you have any technical questions or problems, please contact the SLN HelpDesk.

Important notice: If something in the course seems odd, or if you are not clear what you are expected to do, let me know.
## Official course description

This course is designed to provide students with an overview of the six classifications of nutrients and their role in the body. Students should exit this course with a better understanding of the basic concepts underlying diet and nutrition throughout the life span. Students should also be prepared to implement the nutrition concepts learned into their daily life. Food safety, technology, and world food problems are also discussed in this course.

**Credits:** 3

**Course prerequisites:** None

This course is fully online. This course is divided into six scheduled modules, a course syllabus, an ice breaking module, and a course survey section. Each scheduled module may include readings, discussion, quizzes, and written assignments.

Module 1: Nutrition Basics & Macronutrient Structures
Module 2: Macronutrient Digestion, Uptake, Absorption, and Transport; and Common Digestive Problems
Module 3: Macronutrient Metabolism and Integration
Module 4: Micronutrient Overview, Antioxidants, and Macronutrient Metabolism to Micronutrients
Module 5: One-Carbon Metabolism Micronutrients; Blood, Bones, and Teeth Micronutrients; Electrolytes and DRIs
Module 6: Term Research Project
Objectives:
1. Enable students to understand the methods scientists use to explore nutritional phenomenon, including observation, hypothesis development, measurement and data collection, experimentation, evaluation of evidence and the use of mathematical analysis.
2. Provide students with the ability to understand the role of the six classifications of essential nutrients and the role they play in the body.
3. Analyze and evaluate current issues in the nutrition field.
210. Textbook

**Required Course Materials**

The standard text for this course is: https://courses.lumenlearning.com/suny-herkimer-nutritionflex/

   Human Nutrition

   The text is an open source textbook.

**Required Software**

In this course you will be using conventional productivity software, such as word processor and graphic presentation tool. Microsoft Word and PowerPoint would be appropriate, or similar programs that can convert files to the RTF or PDF format. In addition, you may require certain Internet plug-ins for using articles, simulations, or videos inserted in some documents of this course. These are:

1. Adobe Reader
2. Macromedia Flash Player
3. Macromedia Shockwave Player

   Click to download and install these plug-ins.

**Additional Resources**

Each module of the course contains many links to Internet resources that are relevant to the specific content. In addition, students can benefit from the HCCC Library.
The course is divided into Learning Modules. In each module there are several graded learning activities, including a written assignment, a written assignment discussion, 2 or more textbook chapter discussions, and a 2-part learning audit. In addition there is a term paper module to be completed throughout the course. These various learning activities are detailed below.

**Written Assignments and Related Discussions:**
Each module includes a written assignment and a written assignment discussion activity. In each module, there is a written assignment folder – the dropbox is in that folder, as is the written assignment discussion forum. In addition to leading the discussion on your own assignment, you must also participate in the discussions of other students.

**Student-led Discussions:**
In every module you will find two or more Student-led Discussions. This is the way we cover the content of the textbook. For each chapter you must ask an original “critical thinking” question about some topic in the chapter. Other students will respond to your question, and you will then reply back to those students. In addition you leading your own discussion thread, you are required to answer some of the questions posed by other students, and they are required to reply to your answers. You are encouraged to keep up these “virtual discussions” as long as they are productive. The idea here is for each student to lead one discussion with the other students about some important and/or controversial issue introduced in each chapter, and participate in a few others. A large percentage of your final grade is determined by your participation in these discussions. I will grade these discussions, but I will not be a participant. If the discussion you are leading gets off track, it is your responsibility to refocus it. You are responsible for maintaining the quality of the discussion threads you lead. Every
posting to a discussion should add something substantive to that discussion.

**Knowledge Audits:**
In each module your appreciation for and understanding of the important content issues and concepts will be assessed two ways:

**Module Exams:**
There is an objective exam on the textbook chapters for each module. Although you may use your textbook, the exams have a time limit.

**Module Recaps:**
You are asked to write a brief overview of the most important things that you have learned in each module.

**Term Paper:**
You are required to complete a three part term paper as part of this course.

**Extra Credit / Make-up Work / Incomplete Grades**

1. The major requirement in this course is to discuss, with other students, the contents of each chapter in the text. There is no substitute for this requirement, and I do not permit “extra credit” or “alternative credit” assignments.
2. Also, there is no way to “go back” after a module has ended and “make-up” missed discussion activity, because there are no other students left to learn from your posts and discuss the content with you.
3. Finally, an incomplete in the course is not appropriate, as there is no way to complete the course once it has ended and all of the other students are gone.
212. Evaluation

Final course evaluation

I will use both qualitative and quantitative evaluation in all courses and learning activities. The qualitative evaluation is represented by my comments to your assignments and discussions. The quantitative evaluation is represented through grades that follow the conventional letter system, and they are based on specific criteria for the course and each learning activity in the course. This page summarizes what you need to know about both the qualitative and quantitative evaluations in this course. You may want to print it for future reference.

Final course evaluation

Final course evaluation will be based on the following percentage weight of each type of Learning Activity:

<table>
<thead>
<tr>
<th>Written Assignments</th>
<th>24%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter Discussions</td>
<td>24%</td>
</tr>
<tr>
<td>Module Recaps</td>
<td>10%</td>
</tr>
<tr>
<td>Module Exams</td>
<td>15%</td>
</tr>
<tr>
<td>Term Paper</td>
<td>27%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
</tr>
</tbody>
</table>

90–100 = A- or A
80 – 89 = B-, B or B+
70 – 79 = C-, C or C+
60 – 69 = D-, D or D+
59 and under = F
My Grades

This course has special features that allows you to see your progress at every moment. Access is through My Grades in the left hand side bar of this course.
This is a regular college course. I expect the same commitment to time and quality as I do in the classroom. The big difference is that Internet study is student centered rather than teacher centered. This means that you are responsible for your own learning and success. If you are highly motivated and produce high quality work – you will be successful. However, if you logon sporadically, participate minimally, or submit poor work – you will not. Online higher education is aimed at independent learners. If you require the structure of a classroom, this method will not suit you.

I expect the successful student will spend an average of about **15-18 hours per module** on this course. Although that may seem like a lot – remember this: A traditional classroom-based course requires 45 hours of “seat time” plus 2-3 hours outside of class for each hour in class. It adds up to around 150 total hours.

**Do you have a plan if you have a technical problem?** If your computer crashes, or if your Internet connection fails – these events do not excuse you from your course responsibilities. You can access this online course from any computer that has an Internet connection. I suggest that you make a plan now for events such as these. If you ever have a technical problem connecting to your course, submitting work to your course, or any other course-related issue, call the SLN Student Helpdesk at (800) 875-6269. If the problem is with the SLN system, you will be granted a time extension for submitting assignments affected by the problem. However, if you do not report the problem to SLN, no time extension will be granted.