IOP Concise Physics | A Morgan & Claypool Publication

Biophysics of the Senses

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Morgan & Claypool Publishers

ISBN 978-1-6817-4111-6 (ebook)
ISBN 978-1-6817-4047-8 (print)
ISBN 978-1-6817-4239-7 (mobi)

DOI 10.1088/978-1-6817-4111-6

Version: 20161201

IOP Concise Physics
ISSN 2053-2571 (online)
ISSN 2054-7307 (print)

A Morgan & Claypool publication as part of IOP Concise Physics
Published by Morgan & Claypool Publishers, 40 Oak Drive, San Rafael, CA, 94903 USA

IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK

Dedicated to my parents: Mr Jerome Presley, and the late Mrs Geneva Presley

Contents

Preface

I distinctly remember as a young girl being very fascinated by numbers and the desire to count money. At the age of two, I was able to count large sums of money and found great enjoyment in doing so. I was also delighted by the question of 'why'. Throughout my entire life, my dad would always fix things around the house. I enjoyed taking things apart and putting them back together—sometimes it would be right and other times I would have to ask my dad for help. As a high school senior, I took a physics class with an amazing teacher, who made the class very exciting and dynamic. Shortly after graduating from high school, my mother passed away and I found myself arriving back to the question of 'why'. It was this detrimental event that inspired my interest in studying the 'why' of the human body—'physics of the human body'. The question of whether there was a career that I could pursue to study the physics of the body arrived in my mind. At the time, I was unsure; however, I just knew that I enjoyed learning physics, was fascinated by how the body worked and was eager to learn more. Upon entering my interdisciplinary program as a freshman, I began to delve into the basic, fundamental principles of physics, biology and chemistry. My knowledge was further strengthened as I matriculated into my biophysics program. It was during graduate school that I knew that I was on the right path to decipher the aspects of 'why'.

I am often asked the question: 'What is the key or trick to physics?' My response is always: 1) pay attention to your units and thoroughly understand the units; 2) clearly understand your concepts to develop a strong foundation and uncover any vital given information if you are trying to solve a word problem; 3) identify the question and determine the appropriate formula(s) to answer the unknown. Yes, the math is there and exists; however, you will not know what math to perform if you do not understand the concepts and the units. Remember that the units are just like your significant other, your siblings, parents, grandparents or children—you LOVE them! You should love your units the same way that you love the people that are near and dear to you. When you love your units, they will love you right back!

The tricks that I suggest to best tackle and understand physics involve the 'senses'. The most common senses associated with the human body are the senses of touch (tactioception), taste (gustaoception), sight (ophthalmoception), smell (olfacoception), and hearing (audioception). However, the human body also has the ability to respond to an array of stimuli such as variations in temperature, imbalance, excitement, pain and fear. Many would refer to these as a 'sixth sense'. On a daily basis, people migrate from place-to-place without stopping to think about the questions of *who, what, when, where, and why—the five 'W's'.* These are the essential 'senses' of biophysics that one must consider. When applying these 'senses', one should always remember that the ideals and laws of physics can never be negated. They follow us everywhere that we go and aid in explaining how the nerve impulses send the signals within the body, leading to the known senses of sight, taste, touch, sound and smell. It is the five W's that provide clarity to the true existence of physics.

In this book, the reader will take a journey to view the body from a physics perspective. Newton’s laws of motion are applied to explain the mechanics of the body, whereas aspects of heat, energy and power elucidate how the body maintains a level of stability. The role of charges and free radicals in exercise and disease are also addressed. This text is written for an undergraduate who may have an interest in medicine, one who may be new to physics, or one who may struggle with understanding why physics is important. Throughout the book, simple algebraic mathematics and the International System (SI) of units are used. Several questions—‘How does physics impact a person’s day-to-day life?’, ‘Why is the body oriented the way that it is and why is it able to function in the manner that it does?’—will be addressed. Above all, this is my love story with physics and how understanding the field has provided a positive impact and improved my overall way of life.

Acknowledgements

First, I would like to thank God for allowing me the opportunity create this piece of work.

I would like to extend my sincerest gratitude to Mrs Janeen Stone Morehead, owner of StoneWorkz Graphic Design & Original Artistry, who created the cover of this book. You are an amazing friend and your work is phenomenal!

I have a plethora of mentors that continuously inspire me and keep me motivated. I am eternally grateful to each of you that have played a role in the knowledge that I have gained. It is true that we as people stand on the shoulders of giants.

To my family and dearest friends, thank you for your love, support and prayers. You all help me stay grounded and focused.

Lastly to my students: Each if you that have ever taken a course with me challenge me to be creative and develop ways to make physics easy. Never stop learning.

Author biography

Tennille D Presley

Tennille D Presley, PhD is a tenured Associate Professor of Physics at Winston Salem State University (WSSU). She obtained her BS degree in Interdisciplinary Physics from North Carolina A & T State University, and acquired her MS and PhD degrees in Biophysics from The Ohio State University. While at The Ohio State University, she became the first African American to graduate from the Biophysics program, received the Young Investigator Award and the Best Advanced Research Award.

Following her PhD, Dr Presley completed her post-doctoral training at Wake Forest University in the Department of Physics and the Translational Science Center. Since joining WSSU in 2010, she has been the recipient of the Research Initiation Program for two years, the Preparing Critical Faculty for the Future Program Grant funded by the National Science Foundation and the Co-Director for the Provost's Scholars Science Immersion Program. Furthermore, she has been a part of the National Institutes of Health Programs to Increase Diversity Among Individuals Engaged (PRIDE) in Health Related Research division of Functional and Applied Genomics of Blood Disorders. Most recently, Dr Presley was Visiting Faculty at Brookhaven National Laboratory and a recipient of the *Buckeyes Under 40* Award. She has published more than a dozen articles in free radical research. Her current research involves investigating the effect of thermodynamics on free radicals and proteins in a state of vascular dysfunction.

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Chapter 1

Units: the essential tools to all understanding

1.1 What are units and why are they important?

Universal **N**umeric **I**mpartial **T**rusty **S**ervants (UNITS)—these are the perfect words that embody the true essence and meaning for ‘a unit’. Units are a measure of the amount of something and are designed to serve you. They are a universal language that can be well-trusted and are necessary to better understand the exact value of things encountered in a person’s day-to-day life. A unit denotes a distinct magnitude for a standard measurement. For example, if you go to the bank and you request ‘100’, chances are that you will be asked ‘one-hundred what’? Alternatively, someone may assume that you mean $100. However, this value could mean 100 pennies, 100 thousand dollars or even 100 shares of stock. It is evident that it is not only important to account for values, but to also specify a unit with the number to provide clarity. Units are the foundation to a true understanding, especially in the realm of physics.

When mentioning dollars or cents, a person automatically knows that those words refer to money. Irrespective of language or dialect, everyone speaks ‘money’. The dollar is the American language for money and the amount can be converted to other types of currency. Similarly when discussing physical concepts, there are specific units that must be understood for maximum comprehension. Units are a person’s saving grace when it comes to calculations in physics. There may be instances where a calculation or word problem may be confusing, but the units can be like ‘tour guides’ and lead you to the right place. They are the perfect navigation tools to solving a particular problem. If a person takes the time to learn their units and be consistent, then life in physics is far easier and more meaningful.

Units are also very important when cooking. If you are baking, it is imperative that the oven is set to the appropriate temperature in degrees Fahrenheit, that you monitor the amount of time for cooking (whether in hours or minutes) and that the ingredients are accurately measured to ensure the best taste. What if you are making a cake and the recipe states that you need a ½ dozen of eggs. Being aware that

doi:10.1088/978-1-6817-4111-6ch1

1 dozen is equivalent to 12 individual eggs, you automatically know that a ½ dozen accounts for 6 eggs. If ½ a cup of sugar is required, you automatically know that this represents 4 ounces of sugar to be measured. You can taste the foods and recognize if the adequate amount of ingredients were added. Having complete knowledge of what these values represent, promotes a more solid foundation of how the world works and functions. Similarly, it is known that a person has a pair of hands which equals ‘two’, three regions of the brain which represents a trio, and four chambers of the heart which is a ‘quad’.

I always use the phrase: ‘If you love your units, they will love you right back!’ How much do you love your family and friends? Unconditionally, right? You should love your units the same way! Often a person may become frustrated with a problem and negate the units involved. However, units are very forgiving and will not be unwavering from their job—their purpose is to ‘serve’ and guide a person in the right direction to the solution. When there is any doubt, it is imperative to know the specific units that directly correspond to individual concepts. In general, the standard system of units used by scientists is the International System (SI).

When considering the aspect of length, the meter is the *standard unit*. It was the first international standard ascertained back in the late 1700s, and was later redefined with respect to the origin of the speed of light. To put this into perspective, one meter is approximately the length from your shoulder to the tip of your index finger, whereas the length of a typical index finger is approximately 2½ inches. Commonly the doorknob on a typical door is nearly one meter above the floor.

Each unit is unique in its own way, providing a clear indication of what concept is being discussed, as outlined in table 1.1. For instance, if someone says that they jogged 5 miles in 40 minutes, this reveals a lot of information, such as the distance that the person traveled (number of miles) and how long or the amount of time (number of minutes) that was necessary for the person to complete the five mile jog. The distance traveled per amount of time would be 0.125 miles/minutes. This defines speed, which we will discuss in a later chapter.

Measuring a value in particular units relies on making the distinction between both accuracy and precision. **Accuracy** is when a measurement is close to the exact value, whereas **precision** is the ‘repeatability’ of a measurement using the same instrument or tool. Let’s say that you are on your way to a birthday dinner, you put

Table 1.1. List of common units.

Concept	*Unit(s)*
distance	*miles (mi), feet (ft), meters (m), yards (yd), inches (in)*
time	*seconds (s), minutes (min), hours (h), days (dy), years (yr)*
mass	*grams (g)*
weight	*pounds (lb), Newtons (N)*
volume	*liters (L), cubic meters (m^3), cubic inches (in^3)*
temperature	*degrees Fahrenheit (°F), degrees Celsius (°C)*

the address in the GPS (global positioning system) and the expected travel time is 15 minutes. As you drive, you arrive to the dinner within 12 minutes. Since you arrived 3 minutes ahead of schedule, the expected travel time was ‘inaccurate’. Likewise, if you are moving into a new home or rearranging a room, it is necessary to measure the room and have the exact dimensions so that you can ensure all of your furniture will fit into the room as desired. One of my favorite sports to watch is basketball. As the coach, your goal is to have all of your players be both accurate and precise. When a player stands at the free throw line, his precision is demonstrated by his ability to shoot the ball the same exact way each and every time. The hope is that his technique will be accurate and that the ball will go into the hoop each time.

Prefixes for units are a common practice, and the primary prefixes within physics are the ‘centi-’, ‘milli-’, ‘kilo-’, ‘micro-’, and the ‘nano-’. Any of these prefixes can be conjoined to a base concept. For example, 100 centimeters is equivalent to 1 meter. Similarly, 1000 grams equates to 1 kilogram. Each prefix provides a shorthand way to account for a particular value. For instance in table 1.2, there is a list of the metric prefixes with the values that each represents, as well as the abbreviation associated with each metric prefix. Numbers are often written in the ‘power of ten’ notation best described as **scientific notation**. Scientific notation is a convenient method for expressing numbers that are considered to be extremely small or large when written

Table 1.2. List of basic prefixes.

Metric prefix	*Abbreviation*	*Value*
Hella	*H*	10^{27}
Yotta	*Y*	10^{24}
Zetta	*Z*	10^{21}
Exa	*E*	10^{18}
peta	*P*	10^{15}
tera	*T*	10^{12}
giga	*G*	10^{9}
mega	*M*	10^{6}
kilo	*k*	10^{3}
hecto	*h*	10^{2}
deka	*da*	10^{1}
deci	*d*	10^{-1}
centi	*c*	10^{-2}
milli	*m*	10^{-3}
micro	*μ*	10^{-6}
nano	*n*	10^{-9}
pico	*p*	10^{-12}
femto	*f*	10^{-15}
atto	*a*	10^{-18}
zepto	*z*	10^{-21}
yocto	*y*	10^{-24}

Table 1.3. List of common measurements.

Concept	*Measurement*
Average length of human hand	*18.1 centimeters*
Length of a football field	*120 yards*
Average human life expectancy	*81 years*
Mass of an electron	9.11×10^{-31} *kilograms*
Mass of a normal, human heart	*300 grams*
Weight of a normal, human brain	*3 pounds*
Total blood volume for 70 kg person	*5.5 liters*
Normal body temperature	*98.6 degrees Fahrenheit*
Average weight of skin in the body	*10 900 grams*

in standard decimal notation. So what exactly does it mean when a value is considered to be 'extremely large or small'? An example is if you have the number 0.0000000345 written in standard notation. This number would be best demonstrated in scientific notation as 3.45×10^{-8}. Now if you want to provide more clarity and specify the number as 3.45×10^{-8} m, it is obvious that this number is a representation of a unit of measure for length. The number could also be written using a prefix from table 1.2 as 34.5 nanometers.

What about the measurements affiliated with your body and bodily organs? Is it necessary to know the amount of space your organs occupy or even the mass they contain? There are nearly 78 organs within the human body, where some occupy more space than others. Table 1.3 includes some measurements that are associated with the body, where the heart and brain are amongst the larger organs in the body. However, the skin is the largest organ of the body, having a mass of ~11 000 grams (depending on the weight of the individual). Measurements are key to aiding in normal maintenance and function of the body. For instance, you need to know what size clothing and shoes you wear in order to obtain the correct sizes. Alternatively, if you are ill, it is important to know what your physiological temperature is and the pharmacist must be knowledgeable in order to prescribe the appropriate dosage of medication.

1.2 Unit conversions

Have you ever been in the department store and paid cash for a purchase? If you give the cashier more money that the purchase costs, the cashier must then determine how much change you are owed. Let's say that you are owed $2.85; however, the cashier recognizes that they are out of dollars when they prepare to give the change back to you. As they look down at the coins in front of them, they remind themselves that four quarters or even ten dimes will equate to one dollar. This is an important lesson for ensuring that the conversion of units is well-defined. The cashier must have a clear understanding of the value of the coins in front of them and how each correlates to the dollar amount of change that is required to be returned to you. The secret to every unit conversion is to know what the conversion factor is for the

Table 1.4. List of some conventional conversion factors.

Distance/length
12 inches = 1 foot
1 mile = 1609 meters
1 mile = 5 280 feet
1 meter = 39.37 inches
1 inch = 2.54 centimeters

Mass/weight
1 kilogram = 9.8 Newtons
1 pound = 4.45 Newtons
1 kilogram = 2.21 pounds

Time
1 year = 365 days
1 day = 24 hours
1 year = 3.156×10^7 seconds
1 hour = 3600 seconds

Volume
1 liter = 1000 cubic centimeters
1 gallon = 4 quarts

concept that is being converted. A **conversion factor** is a ratio which portrays the correlation between two units. Many questions within everyday life can be answered by utilizing the conversion of units.

When setting up a unit conversion, there are a few basic steps that should be taken. First, identify the unit that needs to be converted. Next, determine the appropriate conversion factor to use for the preferred unit. Table 1.4 lists common conversion factors that are often useful. To begin to convert, it is easiest to set up the problem like a 'train track', as demonstrated in example 1.1. In the first block or the numerator, place the unit that needs to be converted. The next block should have the desired unit in the numerator and the unit you wish to discard in the bottom block or the denominator. This is necessary so that the unwanted units will 'cancel' out with each other, as any value divided by itself is equivalent to one. You can always confirm that the conversion is accurately set-up if the units properly cancel out.

Example 1.1 A woman decides to take a jog on a trail in the park that is 3 miles long. How many meters does she jog?

Knowing that 1 meter is equal to 1609 m (from table 1.4),

$$(3\ \cancel{\text{miles}})\left(\frac{1609\ \text{meters}}{1\ \cancel{\text{mile}}}\right) = \textbf{4827 meters}$$

**The reason that the conversion factor of 1 609 meters is in the numerator and 1 mile is in the denominator is so that the units of 'miles' can be properly cancelled out, thus leaving only the unit in 'meters'.*

Example 1.2 A football player weighs 175 pounds, but desires to gain 8 more pounds of muscle over the course of the next few months. A) How much weight would this be in Newtons? B) What would be the player's body mass?

If the football player plans to gain 8 more pounds, the player's weight will be:

$$175 \text{ pounds} + 8 \text{ pounds} = 183 \text{ pounds}$$

(A) To convert this weight into Newtons,

$$(183 \ \cancel{\text{pounds}})\left(\frac{4.45 \text{ Newtons}}{1 \ \cancel{\text{pound}}}\right) = \mathbf{814.35 \ Newtons}$$

(B) To determine the amount of mass of the player,

$$(814.35 \ \cancel{\text{Newtons}})\left(\frac{1 \text{ kilogram}}{9.8 \ \cancel{\text{Newtons}}}\right) = \mathbf{83.1 \ kilograms}$$

**Alternatively, the mass could be determined by converting the weight of 183 pounds to kilograms. Since there are 2.21 pounds equal to 1 kilogram, we would divide the 2.21 pounds into the 183 pounds to cancel the units. Thus, the answer would be 82.81 kilograms (~83 kilograms), which is very close to the value that was calculated above'.*

Whether you are taking a road trip and trying to decide how long it will take to arrive at a certain destination or if you have a headache and are trying to figure out how many milligrams of aspirin to take, the measurement of units is critical to understand. The world is driven by units and the corresponding conversion factors. As we deepen our knowledge in future chapters, we will delve into concepts that have units which are derived from basic fundamental units. We will also utilize units to help solve word problems.

Chapter 2

Mechanics of the body

2.1 What is mechanics?

Without even thinking, people awake in the mornings and get out of the bed to go to work, school or wherever desired. Laying in a supine or horizontal position, individuals are able to fold and twist their bodies so that they are able to get out of the bed. Yes, this is a natural process; however, how is this possible? The human body is constantly impacted by movements whether it is from the Universe, galaxy, cells, or internal processes. All of this is due to the unique mechanics of the body. **Mechanics** is defined as movement by way of forces and energy. When one thinks of mechanics, two main branches come to mind: 1) *classical mechanics;* and 2) q*uantum mechanics*. Classical mechanics focuses on macroscopic objects and how forces impact them. However, quantum mechanics deals with the interaction of energy and matter of very small, nanoscopic materials. It is thought to supersede classical mechanics when it comes to subatomic or molecular levels. The relevance of quantum mechanics lies within the uncertainty principle, and the behaviors of electrons, protons, and other objects that are part of the atomic scale. In this chapter, our attention will be on *classical mechanics*, as it relates to the importance of mechanics to the human body. We will further discuss quantum mechanics in later chapters.

There are two main components of *classical* mechanics: 1) *dynamics*—explains why things move the way that they do; and 2) *kinematics*—explains how things move. These concepts date back to Aristotle when he addressed both natural motion and violent motion. These aspects of motion define why objects tend to stay at rest, have a natural position that they strive to achieve, and why objects are impacted by an external force. I always tell students: 'You have a natural tendency to want to stay home and relax or do something fun; yet, you have a forced or imposed motion to come to class to further your knowledge and to fulfill the requirements of your major'. Objects move on the basis of a forced motion or a natural position or state. This is the basis for how the cells in our body move and interact with other cells.

doi:10.1088/978-1-6817-4111-6ch2

Think of how white blood cells rapidly move to protect against injury and infection, or even how insulin binds to receptors on the cell membrane to maintain the appropriate blood sugar levels. Cells move to keep us alive and well! Our bodies are regulated by the impact of mechanics.

2.2 Speed, velocity, and acceleration

Kinematics explain how things move on the basis of three main terms: 1) **speed**—how fast something is moving; 2) **velocity**—how fast and in what direction something is moving; and 3) **acceleration**—the change in velocity with respect to the change in time. When I drive my car to work daily, I pay close attention to how fast the car is traveling so that I do not exceed the speed limit. Speed is a distinct measure of a distance (how far something travels) per time, where the common units are miles per hour (mph). However, when considering the body or physics-based problems, the primary units used are meters per second ($\mathrm{m\ s^{-1}}$). The distinction between the units is based on the fact that within the body, speeds occur on a smaller scale. To convert from miles to meters, one must understand that there are approximately 1609 meters equal to 1 mile (1 mi = 1609 m). When runners compete in a marathon, it is imperative to pay close attention to their speed to monitor or predict how quickly they will complete the race. Speed is a concept that impacts our daily lives, often in instances where we are not always aware or carefully observe.

Commonly, the questions of 'how fast', 'how long', and 'how far' come up in kinematics-based problems. 'How fast' correlates with the amount of speed or velocity. If you ask for 'how long', this indicates a query of the amount of time and inquiring 'how far' denotes the distance or the displacement. **Displacement** is a measure of the location of an object from the original starting point, while **distance** is the amount of ground that is covered or traveled. These questions play a vital role in guiding how to solve a problem and direct which formula(s) should be used to arrive at a particular answer. A formula is a way to show the relationship between various concepts, and often includes an 'equal sign'. For example, the formula for speed is as follows:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

or

$$s = \frac{d}{t}$$

Notice that the variable 's' symbolizes speed, while 'd' implies distance and 't' designates the time. With speed or any other formula, there should only be one 'unknown' variable missing in order to find the actual answer. Example 2.1 provides both the distance and time, thus the speed can be determined.

If we know how fast something is going, why is it important to also know the direction? Direction is an important factor in distinguishing between a vector versus a scalar. A **vector** is a quantity that has both a magnitude and direction, whereas a

scalar denotes magnitude only. Speed is a scalar. If you were taking a road trip and needed to determine an estimated time of arrival, it is essential that not only the speed is taken into account but also the direction of travel is well noted. This is best defined as **velocity** which is a measure of displacement (*how far an object is from its starting point*) per time, or simply put, it is the speed and the direction. This vector quantity can be best identified by:

$$\text{velocity} = \frac{\text{displacement}}{\text{time}}$$

or

$$v = \frac{\Delta x}{\Delta t}$$

In the formula above, 'Δ' is the Greek letter *delta,* which means *'change in'.* When this symbol is present, it suggests that the initial value of a particular concept is subtracted by the final value of the concept ($\Delta = \mathit{final} - \mathit{initial}$). In example 2.1, the velocity is quantified. The initial position is 20 m and the final position is also 20 m. Thus, Δx = final position−initial position = 20 m − 20 m = 0 m. Velocity is also important for how the blood flows within the body related to systemic and pulmonary circulation. We will address blood flow in a latter chapter.

Example 2.1. A student begins walking to her class from her dorm, which is nearly 30 meters away. After walking two-thirds of the way, she realizes that she left her notebook in her dorm room, so she turns around to get her book. If it takes her 5 min to make it back to her dorm, what is the speed of the student? What is her velocity?

Solution: Let's first draw a picture that illustrates what is occurring in this problem. As shown in the figure 2.1, the student begins at her dorm (at 0 meters) and walks ~20 meters, which will represent 'x_1'. She then turns around and walks back to the dorm, which represents 'x_2'. Thus, the total distance traveled is 40 m (20 m + 20 m = 40 m); however, the displacement is zero ($x_2 - x_1$ = 20 m −20 m = 0 m), as she returns back to her original starting point. The time given is 5 min. Using figure 2.1 and the given information, we can determine both the speed and the velocity.

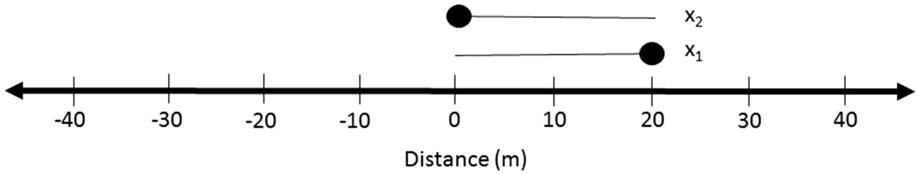

Figure 2.1. The student begins at the dorm (0 m) and returns back to her original position.

To determine the speed,

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$= \left(\frac{40\ \text{m}}{5\ \text{min}}\right)$$

$$\textbf{speed = 8 m min}^{-1}\ \textbf{(or 0.133 m s}^{-1}\textbf{)}$$

**To calculate the answer in ‘ m/s’, simply convert using 1 min = 60 s.*
To determine the velocity,

$$\text{velocity} = \frac{\text{displacement}}{\text{time}}$$
$$= \frac{0\ \text{m}}{5\ \text{min}}$$

$$\textbf{velocity} = 0\ \textbf{m min}^{-1}$$

Acceleration is the rate of change of an object’s velocity and can be clearly elucidated with how an automobile works. If you are driving your car and you want to speed up the car, the gas pedal is pressed. This will result in an increase in the acceleration of the car. To slow the car down, you apply the brakes resulting in deceleration or a decrease in speed. In order to change the direction in which the car is moving requires turning the steering wheel. Based on this example, it reveals that an increase or decrease in speed, as well as altering the direction will ultimately impact an object’s acceleration. Direction affects acceleration, thus making it a vector quantity, as well. If there is no change in velocity, then no acceleration occurs. The rate of change in velocity may be due to variations in speed and/or direction. Acceleration is represented as

$$\text{acceleration} = \frac{\text{velocity}}{\text{time}}$$

or

$$a = \frac{\Delta v}{\Delta t}$$

The units for acceleration are meters per second squared (m s^{-2}). Velocity explains how quickly the position of an object changes, while acceleration tells how quickly the velocity changes. Example 2.2 asks to determine *how fast* the car travels based on a given acceleration and an amount of time. Knowing that this question alludes to calculating the velocity, the formula for acceleration is used.

Example 2.2. A car accelerates down a street at a constant rate of 12.5 m s^{-2} within 2.8 s. How fast is the car traveling in miles per hour?

Figure 2.2. Car accelerating.

Solution: The given information is the acceleration of 12.5 m s^{-2} and the time equal to 2.8 s. Since the question asks 'how fast', this phrase implies that we should determine a speed or velocity. Hence, we will use the following equation:

$$\text{acceleration} = \frac{\text{velocity}}{\text{time}}$$

$$12.5 \text{ m s}^{-2} = \frac{\text{velocity}}{2.8 \text{ s}}$$

In order to determine the velocity, we must cross-multiply. Accordingly,

$$\text{velocity} = (12.5 \text{ m s}^{-2})(2.8 \text{ s})$$

$$\mathbf{velocity = 35 \ m\,s^{-1} (or \ 78.3\,mph)}$$

In order to convert the velocity from m/s to mph, we can first convert meters to miles by using the conversion factor of 1 *mi* = 1 609 *m; we know that there are* 3600 *s* = 1 *h. Thus, the tools gained for converting from chapter* 1 *can be used to determine that* 35 $m\ s^{-1}$ *is equal to* 78.3 *mph.*

Together, the three aspects of kinematics are the foundational formulas for understanding how movement occurs, especially in the body. Next we will address how the views of Sir Isaac Newton have impacted our way of thinking of mechanics.

2.3 Newton's law of motion

Sir Isaac Newton is considered to be one of the most influential scientists of all time, especially when it comes to classical mechanics. Classical mechanics is often referred to as 'Newtonian mechanics'. Newton revealed how every movement in the Universe can be mathematically analyzed. He is well-known for his three laws of motion. Newton's first law of motion is recognized as the *law of inertia.* **Inertia** is the tendency of an object to resist changes in motion and was first defined by Galileo; however, Newton refined this concept and made it his first law. The law of inertia simply states: 'An object at rest will stay at rest and an object in motion will stay in motion unless acted upon by an external force'. When referring to 'force', it is a push or pull, having the unit of a Newton (N). The Newton is equal to the product of a kilogram and meter per second squared ($\text{kg} \cdot \text{m s}^{-2}$). Newton's first law is easily conveyed in a car with a seatbelt. If you approach a stop light and you have to decelerate the car by pushing the brakes, your body will lunge forward if you apply a great amount of force on the brakes. However, it will then return to its original, upright position. The body's desire was to resist the change in motion. Similarly, if you have a box at rest on the floor, the box will remain in that position unless 'something' or 'someone' (some type of force) causes the box to move.

Force is an important component in understanding physics and how things work. A stationary object needs a force to get it moving, while an object in motion needs a force to alter its velocity. There are a number of forces that are commonly influencing an object. They include: applied force, normal force, gravitational force, force of tension, air resistance and frictional force. The best demonstration for showing the forces acting on a specific object is a **free body diagram**. A free body diagram is a visual representation of the forces acting on a particular entity, as shown in figure 2.3. Friction is the opposing force of two items as they slide, and can often be related to the applied force. There are two kinds of friction: static, which typically applies to things that are at rest, and kinetic, where the objects are in motion. Static friction is greater than kinetic. Think of it this way: if you have a heavy box that is sliding across the floor, it is usually easier to keep the box moving than if the box were originally stationary and then you attempt to move it. In general, an upward force exists, best known as the normal force or the support force. It is the force that counterbalances the gravitational force to provide stability. The force of tension is common in the presence of a cable, rope or a string. Within the body, this force is exercised by a muscle on a body part.

Newton's second law is often acknowledged as the most popular of the three laws of motion and addresses the notion of force. Known as the *law of acceleration*, this law states that: 'The sum of all forces or the net force is directly proportional to the

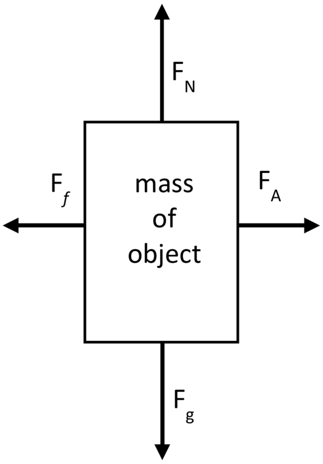

Figure 2.3. Example of a basic free body diagram, where the force of gravity, F_g, the force of friction, F_f, the applied force, F_A, and the normal force, F_N, act on an object containing a particular mass.

acceleration and in the same direction as the net force acting on an object. The acceleration and the mass are inversely proportional to each other'. Newton's second law also means the net force of an object is equal to the rate of change of its linear momentum. Amongst the three laws, this one is represented by an equation:

$$\text{Net Force} = (\text{mass}) \times (\text{acceleration})$$

or

$$\text{Net Force} = \frac{\text{change in momentum}}{\text{change in time}}$$

In shorthand, it is often displayed as: $\Sigma F = ma$ or $\Sigma F = \frac{\Delta p}{\Delta t}$. In each equation, ΣF denotes the net force, m is the mass, a is the acceleration, Δp is the change in momentum and Δt is the change in time. 'Σ' is the Greek letter *sigma* and means the *'sum of'*. **Mass** is a measure of an object's inertia or merely the amount of matter that makes up an object, having units of kilograms (kg). This concept does not change. However, a person or object's **weight** is the product of the mass and the acceleration due to gravity (g) as shown below.

$$\text{weight} = (\text{mass}) \times (\text{acceleration due to gravity})$$

or

$$(w = mg)$$

Earlier in the chapter, the concept of acceleration was introduced. On Earth, the acceleration due to gravity (g) has a constant value of 9.8 m s^{-2}. This value can slightly vary depending on altitude. The gravitational pull on the Moon is nearly one sixth less than the Earth, resulting in an acceleration due to gravity of approximately 1.67 m s^{-2}. Weight is a type of force (gravitational force) and has units of Newtons, like other forces that have been discussed. Especially in the United States, people measure their weight in pounds (lbs). A weight in pounds can be converted to Newtons by using one of the conversion factors that were mentioned in chapter 1. This is observed in example 2.3.

Example 2.3. An 11 pound poodle is lying on the porch. As the mailman approaches the mailbox, the dog runs towards the mailman at 10 mph within 6 s. How much force does the poodle exert to get to the mailman?

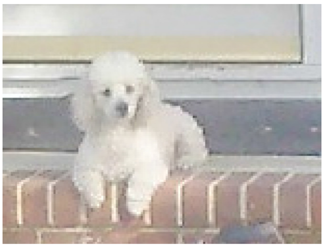

Figure 2.4. Poodle at rest, having an initial velocity of zero.

Solution: The weight of the poodle is 11 pounds ($w = 11$ lbs), the initial velocity of the dog is 0 mph (since the dog is at rest), the final velocity of the dog is 10 mph ($\Delta v = 10$ mph) and the time is 6 s ($t = 6$ s). To determine the amount of force, Newton's second law should be utilized.

Before we can use the formula, we must convert the velocity to m s^{-1}. The conversion factor for miles to meters is 1 mi = 1609 meters and 1 h = 3600 s. Therefore, 10 mph = 4.47 m $\mathrm{s}^{-1} = \Delta v$.

Next, the mass of the poodle should be quantified using the given weight. Let's use the formula for weight after converting the weight from pounds to Newtons. From chapter 1, we learned that 1 pound = 4.45 Newtons. Therefore, the weight is 48.95 Newtons.

$$w = \mathrm{mg}$$

$$48.95\ \mathrm{N} = \mathrm{m}(9.8\ \mathrm{m\ s^{-2}})$$

$$m = 4.99\ \mathrm{kg}$$

Alternatively, the mass of the poodle could have been determined by using 1 kg = 2.21 lbs to obtain 4.99 kg (approximately 5.0 kg).

Based on what we are given, Newton's second law can now be applied to acquire the force:

$$\Sigma F = ma$$

$$\Sigma F = m\frac{\Delta v}{\Delta t}$$

$$\Sigma F = \left(4.99\ \mathrm{kg}\right)\frac{4.47\ \mathrm{m\ s^{-1}}}{6.0\ \mathrm{s}}$$

$$\boldsymbol{\Sigma F = 3.72\ \mathrm{N}}$$

There are scenarios when the force of gravity is the only force acting. An instance where this occurs is when something is in *free* fall—the acceleration is equivalent to the acceleration due to gravity ($a = g$); thus, the acceleration is constant and the speed increases at 10 m s^{-1} for every second of fall. Objects may not only move left-to-right or up-and-down in a straight line, but may move diagonally or in a path that covers two dimensions. First described by Galileo, **projectile motion** is movement in two dimensions where an object travels in an arc near the Earth's surface only under the influence of gravity. The path of the horizontal component is at a constant velocity and the vertical component of motion is at constant acceleration. An illustration of projectile motion is when the quarterback passes the football on the field to the tight end or the receiver. As the ball is tossed into the air at a certain angle, it reaches a peak where the velocity along the vertical axis is zero. The ball continues to move with respect to being pulled downward by gravity.

As a lover of amusement parks, I am always intrigued by the amount of physics involved in the rides. **Circular motion** is a very common concept that exists. It occurs when an object is moving in a circle, and the speed is uniform but the direction of velocity changes. There are two main types of circular motion: centripetal (towards the center of the curve) and centrifugal (away from the center of the curve). A centrifuge is an example of a centrifugal force. It is an instrumentation that is used to separate mixtures such as blood. It spins rapidly to separate blood into its three components—red blood cells, white blood cells/platelets and plasma. Centrifugal force is usually measured in 'g'. A typical rollercoaster exerts 2 g on the people who ride them. The ferris wheel and merry-go round are also popular rides that exhibit circular motion at the amusement park. When the ferris wheel rotates in a vertical circle, gravity as well as other forces that are acting on the body must be taken into consideration. How do you feel at the top of the ferris wheel compared to the bottom of the wheel? How forces act on the body at the top of the ferris wheel differ in comparison to how the forces act at the bottom of the wheel. Similarly, the merry-go round moves in a circle, but horizontally. Newton's second law of motion can address both of these scenarios, where centripetal force can be measured. It is understood that the gravitational and normal forces will act in the same direction towards the center of the circle when at the top of the ferris wheel ($\Sigma F = F_N + F_g$); however, at the bottom, the normal force will point towards the center of the circle and the gravitational force will point downward wheel ($\Sigma F = F_N - F_g$). Centripetal force is derived from Newton's second law and is represented as

$$\text{Net Force} = \frac{(\text{mass})(\text{velocity})^2}{\text{radius}}$$

This formula tells us that centripetal acceleration is equal to $\frac{\text{velocity}^2}{\text{radius}}$.

Newton's third law of motion is the *law of action–reaction*. It states: 'For every action, there is an equal, opposite reaction'. An action–reaction pair acts on two different objects. As a child, did you ever play the game tug-of-war? You were demonstrating Newton's third law of motion and probably did not know it. As you pulled the rope on your team, the opposing team was pulling the rope with an equal yet opposite amount of force. Together with the second law, the law of action–reaction validates a number of the natural processes within the body including how the body moves and is affected by motion. For instance, the second law addresses the change in **momentum**—the product of mass and velocity. The concept of momentum is often correlated with collisions. Let's say that you are walking in the grocery store and a child accidentally hits you with their shopping cart, causing a bruise on your leg. What amount of force does the shopping cart exert on you and you on it? The forces are equal, yet opposite. As the shopping cart pushes against your leg, your leg pushes back on the force. However, the cart's acceleration was greater.

2.4 Bodily movements

Thus far, we have discussed key aspects of mechanics and the basic forces that influence movement. How do these components affect the movement of the body? There are six basic bodily movements that people exhibit: walking/running, squatting, pushing/pulling, bending, lunging, and twisting. Many of these movements are performed without even thinking about it. Our pair of hands, legs and feet allow us to fulfill most of these gestures. The musculoskeletal system is the primary system that impacts the mechanics of the body. There are three types of muscles in the human body: 1) cardiac; 2) skeletal; and 3) smooth. Muscle cells are long, cylindrical cells that can contract when excited by nerve signals, allowing them to move bones. The contraction of muscles creates a force on the bone and regulates bodily movement. Whether bending, squatting or lunging, muscle contraction occurs and force is present.

Skeletal muscles and joints are an intricate system of levers. A lever is a simple machine that lifts heavy objects. It consists of three main parts: 1) fulcrum—the pivotal point; 2) effort—the force applied to the end of the lever; and 3) resistance—the opposing force on the other end of the lever. Within the body, the joints serve as the fulcrum, the force of the muscle is the effort and the body part's weight designates the resistance. Since muscles and joints are a system of levers and the applied force of the muscle onto the bone is rotational, the concept of torque is important. **Torque**—*the measure of how much a force acting on an object causes that object to rotate*—is required for an object to start or stop rotating. Torque must be understood when the body 'twists' and is represented by the following equation:

$$\text{Torque} = (\text{lever arm}) \times (\text{line of force})$$

$$\tau = r_{\perp} \cdot \mathrm{F}$$

τ is the Greek letter 'tau' which denotes the torque in $\mathrm{m} \cdot \mathrm{N}$, $r_{\perp}$ is the perpendicular distance from the axis of rotation to the line of force with units of meters, and F is the applied force with the units of Newtons. Nodding your head, bending your arm or even standing on your tip toes are examples of torque. In each case, the forces acting are dependent on the position of the load from the pivot point.

Walking is a perfect example of when a person is out of balance for brief increments of time. As one foot is placed in front of the other, a force is applied to the ground and the ground exerts a force on us. In addition, the center of gravity extends beyond the foot that remains on the ground. **Center of gravity** is the point in the body where the average position of weight is properly distributed, and the *net* torque due to gravitational forces disappears. When an object is supported at its center of mass, it will remain in static equilibrium. Mechanical equilibrium is achieved when the net force is equal to zero. It represents a scenario where all of the forces are balanced—the amount of force in one direction is equivalent to the forces in the opposing direction. A perfect illustration is when a person is sitting in a chair. If the person does not lift vertically upward out of the chair or fall through the chair downward, then the net forces acting on the person are equal to zero and mechanical equilibrium is achieved. When a person is balanced, this means that the net force is zero and their body is in mechanical equilibrium. The ear is an important organ in the body which regulates equilibrium and balance. It is directly connected to the brain. Thus, the main function of the ear is not only to aid in hearing, but also to provide equilibrium to the body.

There are many factors that affect movement in our daily lives, from various forces to how fast the movement occurs. The way that these aspects are involved is contingent upon the type of motion that occurs, whether it is one-dimensional or two-dimensional. It is important to maintain movement within the body and to also understand the impact of these movements (or lack thereof). So, let’s keep moving!

Chapter 3

How physics generates order in the body?

3.1 Bodily order

The body is a very complicated machine that thousands of individuals study to have a better understanding of how it works to prevent disease and to maintain a normal, functioning life. Despite the many efforts, the body has its own innate processes for regulating a level of normalcy. We know that the body naturally lives and breathes when it is functioning properly. However, have you ever stopped and taken the time to ask how? There are numerous contributing factors that impact the normal day-to-day machinery of the body. **Homeostasis** is the regulation of internal conditions remaining constant and stable. The body's natural goal to maintain normal bodily function is due to homeostasis. This stability is impacted by the senses of sight, touch, taste, smell and hearing. While physics can be centered on each of these five senses; there is a 'sixth sense' that interposes the conventional operations of the body as well. This may be the voice in your head that tells you when something is wrong or that feeling that is in the pit of your stomach when you are on the right track to solving a problem. Either way, this helps to regulate your natural processes. This is the embodiment of physics!

3.2 Work, energy, and power

As demonstrated in chapter 2, force plays an important role in the mechanics of the body. In the presence of force and displacement, work exists. If there is no force, then there is no work. Likewise, zero work transpires in the absence of displacement. Thus, work subsists only if there is motion involved. The unit for work is the Joule, which is a Newton-meter (N·m). Work is defined as

$$\text{Work} = (\text{Force}) \times (\text{displacement}) \cos \theta$$

or

$$W = Fd \cos \theta$$

doi:10.1088/978-1-6817-4111-6ch3

Work may be positive or negative, depending on the direction of the force and motion of the object involved. When the angle between the displacement and the force is less than 90°, then the work is positive. A positive work implies that both the direction of movement and force are the same. Alternatively, negative work is when the direction of movement and force act in opposite directions. An angle greater than 90° also leads to a negative work. When the force and the displacement are perpendicular to each other ($\theta = 90°$), work is equal to zero. If you lift a gallon of milk from the shelf in the refrigerator, you perform work on the milk. However, if you hold the milk in a stationary position, there is no work being done because there is no displacement.

The ability to do work is defined as **energy**. All energy production originates in the cytosol of the cell. The five main forms of energy are chemical, mechanical, nuclear, thermal and electromagnetic. Each of these types have their own distinctiveness in regards to how they aid to regulate or contribute to bodily function. One of the key sources of chemical energy is from food. Mechanical energy is a composite of both **potential energy** (stored energy) and **kinetic energy** (energy due to motion). Potential energy comes in various forms including gravitational and elastic. Gravitational potential energy is with respect to the vertical position of an object, where the acceleration due to gravity must be considered. Elastic potential energy involves situations where energy is stored due to stretch. Think of our muscles and joints that we discussed in the previous chapter. As muscles stretch and move, elastic potential energy occurs. Each of these types can be mathematically quantified using the formulas below:

$$\text{Potential Energy (gravitational)} = mgh$$

$$\text{Potential Energy (elastic)} = \frac{1}{2}kx^2$$

Gravitational potential energy (PE_G) is the product of mass (m), the acceleration due to gravity (g), and the vertical displacement or height (h). Elastic potential energy is directly proportional to the square of the amount of stretch, where k is the spring constant and x is the displacement. The spring constant represents the threshold of stretch. For a woman that has naturally curly hair, the curl in her hair is a perfect example of elastic potential energy. If the hair is stretched, the hair will tend to go back to its original compressed state once it is released. On the other hand, kinetic energy involves motion. The faster an object moves, the greater its kinetic energy will be. As a result, kinetic energy is written

$$\text{Kinetic Energy} = \frac{1}{2}(\text{mass})\,(\text{velocity})^2$$

or

$$KE = \frac{1}{2}mv^2$$

The units of mass are the kilogram (kg) and the units for velocity are in meters per second (m s^{-1}). In a situation where the velocity doubles, the kinetic energy will enhance by a factor of 4.

Energy has the unique ability to be transformed amongst its different forms. This process occurs due to the **conservation of energy**—*energy is neither created nor destroyed, but simply transformed to another form; yet, the total amount of energy remains the same*. Efficiency is the capability of an object to complete a task based on the amount of energy supplied. Ideally, 100% efficiency is desired; yet, the efficiency of a person is nearly 25%. While work and energy have the same units, they are not the same thing. Work is a way to transfer energy. The work–energy principle is where the net work is equal to the change in energy ($W_{\text{net}} = \Delta KE$). This principle is a practical reformulation of Newton's laws of motion. When the net work is negative, the kinetic energy decreases; if the net work is positive, the kinetic energy is augmented.

Adenosine triphosphate (ATP) also provides energy. ATP is viewed as the molecular unit of 'currency' for energy transfer within the cell. Produced in the mitochondria, ATP is an unstable molecule, making it a 'universal' carrier of energy for the cells. For example, ATP is an energy source for muscle contraction, motility and active transport across the plasma membrane. ATP production is insufficient to sustain human life without the presence of oxygen. One meaningful role of oxygen is with the lungs. The main function of the lungs is to transport oxygen from the atmosphere into the bloodstream and to release carbon dioxide from the bloodstream into the atmosphere.

One afternoon, you decide to take a walk in the park. Before you know it, you have walked nearly three miles and did not feel tired; however, you may feel differently if you were to climb up three miles of stairs, as you are using more power. **Power** is the rate at which work is performed or the ratio of energy transformation with respect to time. This concept can be mathematically determined by using the following equation:

$$\text{Power} = \frac{\text{Work}}{\text{time}}$$

The units for power are the Watt (W) which is equivalent to a Joule per second (J s^{-1}). When a person thinks of power, it is often considered in terms of its relevance to electricity in a home or building. However, this same exact concept is pertinent to the normal operations of the body. If you were to run up a hill, you can measure your power based on your body's weight (the force), the height of the hill (the displacement) and the amount of time that it takes you to walk up the stairs. When walking versus running up the hill, the gravitational potential energy will remain the same; however, the power changes.

3.3 Thermodynamics

Thermodynamics is the study of heat and its effects on temperature, pressure, volume, work, internal energy, and entropy. Have you ever touched something and told yourself: 'Wow that is hot or cold?' If the answer is 'yes', you have questioned the temperature of a substance. **Temperature** is simply a measure of how warm or cold something is. It is also noted as the amount of random kinetic energy of the molecules of a substance. Temperature may be ascertained with a thermometer in degrees Fahrenheit (°F), degrees Celsius (°C), or Kelvin (K). Both degrees Fahrenheit and Celsius directly measure temperature, but Kelvin measures energy. **Heat (Q)** is simply energy in transit from a higher temperature to a lower temperature. It can be quantified by accounting for the product of the mass (m), specific heat (c) and change in temperature (ΔT) of a material.

$$\text{Heat} = (\text{mass})(\text{specific heat})(\text{change in temperature})$$

or

$$Q = mc\Delta T$$

The formula above is only relevant provided that a phase change does not transpire. The units for heat are either Joules or calories. A calorie is the quantity of energy required to raise the temperature of one gram of water by one degree Celsius. Body temperature is controlled when there is equilibrium between the production and the loss of heat ($Q_{\text{lost}} = Q_{\text{gained}}$). Under normal circumstances, the body dissipates heat at a rate of 100 J s^{-1}; this means that it yields nearly the same amount of heat as a 100 W light bulb.

There are three ways in which heat can be transferred: conduction, convection and radiation. Conduction involves the collision of molecules, where these collisions impact momentum and can be elastic or inelastic. A collision where kinetic energy is not conserved is called an inelastic collision. During this process, internal organs and circulating blood are at an elevated temperature. The human body naturally maintains a normal, physiological temperature of ~98.6 °F. If the body's temperature falls below its physiologic state (e.g. below 91 °F), muscle failure or even loss of consciousness may occur. Exceeding this temperature will cause the central nervous system to break down, and ultimately death will occur at ~111 °F. If the temperature of the body declines lower than its surroundings, then conduction and radiation aid in the body gaining heat. Contractions of both the liver and muscles are mainly responsible for generating heat within the body. Alternatively, the skin loses heat if the temperature of the body is greater than its surroundings. 20% of this loss is due to conduction and convection, 50% comes from radiation, and 30% is due to evaporation. **Specific heat** is 'thermal inertia', meaning that it explains the resistance of a material or object to changes in temperature. Water ($c_{\text{water}} = 4.18\ \text{J g}^{-1}\ °\text{C} = 1\ \text{cal g}^{-1}\ °\text{C}$) is known to have a high specific heat. It is an important molecule in the body, as it makes up about 70% of the body's mass. Various organs and tissues within the body resist changes in temperature differently. The lung has a slightly higher specific heat than the skin; yet, the average specific heat of the organs and tissues in the human body is 0.84 kcal kg^{-1} °C. **Latent heat** is when there is a phase change in matter and the temperature remains constant. There are two types: 1) latent heat of vaporization (L_v)—where a liquid changes to a gas; and 2) latent heat of fusion (L_f)—where a solid changes to a liquid. The latent heat of fusion for water is 80 kcal kg^{-1}, while the latent heat of vaporization for water is 540 kcal kg^{-1}. An example of latent heat of vaporization is when water changes from liquid to gas through the lungs, mouth and skin. Due to evaporation, the water molecules in contact with these tissues gain enough kinetic energy to escape the liquid phase and turn into water vapor.

Example 3.1. An elderly woman is walking outside of her home. She slips and breaks her ankle. The ankle results in significant swelling as shown in figure 3.1. In addition to a brace, the woman is instructed to put an ice pack on the ankle. If she places a 57 g ice pack on her ankle and it cools the area from 37 °C to 13 °C, what is the mass of the area where the ice pack is placed (Note: $c_{\text{tissues}} = 0.84$ kcal kg^{-1} °C)?

Solution: We are given the mass of the ice pack ($m_{\text{ice}} = 57$ g $= 0.057$ kg), the change in temperature ($T = 13$ °C − 37 °C = −24 °C), and the average specific heat of tissues is 0.84 kcal kg^{-1} °C. An additional factor that can be added is the L_f for water, 80 kcal kg^{-1} for the ice pack. This problem is an example of the conservation of energy ($Q_{\text{lost}} = Q_{\text{gained}}$). Considering, the two formulas described above for heat will be used: $Q = mc\Delta T$ and $Q = mL$

$$\begin{aligned} Q &= m_{\text{ice}}L_{\text{f}} \\ Q &= (0.057\ \text{kg})(80\ \text{kcal/kg}) \\ Q &= 4.56\ \text{kcal} \end{aligned}$$

Next, we will use Q = $mc\Delta T$ to determine the mass of the area

$$\begin{aligned} -\text{Q} &= mc_{\text{tissues}}\,\Delta T \\ (-\,4.56\ \text{kcal}) &= m\,(0.84\ \text{kcal/kg °C})(-24\ \text{°C}) \\ (-\,4.56\ \text{kcal}) &= m\,(-20.16\ \text{kcal/kg}) \\ \mathbf{0.23}\ \text{kg} &= \boldsymbol{m}\ (\textbf{mass of the area where the ice pack is placed}) \end{aligned}$$

Figure 3.1. Broken, swollen ankle.

The **first law of thermodynamics** is a perfect explanation of how the body converts food into energy, coinciding directly to the conservation of energy. It shows that the change in internal energy equals the difference in the amount of heat added to a system and the work done by the system. The **second law of thermodynamics** states that heat will not spontaneously move, but migrates from a warm to a cold environment. This law can also be addressed on the basis of entropy (a measure of disorder); if a thermodynamic process moves from one equilibrium state to another, then the entropy of the entire system will increase or remain constant.

3.4 Metabolism

The energy that the body uses throughout the day comes from food. **Metabolism** plays an active role in regulating order within the body. It involves the net chemical reactions that take place in the body, digestion and the elimination of wastes. The metabolic processes in the liver, heart, brain and skeletal muscles are the primary sources of heat. Metabolism can be catabolic—'requiring energy' or anabolic—'energy releasing'. During the catabolic state, the body processes food to use for energy; anabolism is when food is used to mend or restore cells. Catabolism is referred to as an oxidation reaction and anabolism is known as a reduction reaction. Cellular respiration is an oxygen-dependent process that is the most proficient catabolic pathway used by organisms to yield energy ($\sim$38 ATP) stored in glucose. ATP transmits chemical energy within cells for metabolism. The basal metabolic rate (BMR) is when the body converts energy into heat while at rest. This rate is slightly lower in females compared to males. If you have a male and female with a similar mass of 70 kg, the BMR for the female will be nearly 60 kcal h^{-1} while the BMR for the male would be 70 kcal h^{-1}. A higher weight results in a larger BMR. Total metabolic rate (TMR) is the overall amount of energy expended by the body to carry out all of its internal and external work. When changes in body temperature occur, the total metabolic rate increases and more energy is burned. Nearly all of the weight in food is comprised of carbohydrates, proteins, fats, and water. Fats have the highest food energy per mass of 8.8 kcal g^{-1}, while carbohydrates and proteins have a food energy per mass of 4.1 kcal g^{-1}. Most foods are composed of water, with fruits and vegetables comprising as much as 95% of water. Our bodies are made up of 70% of water. Water is found in three central locations in the body: within our cells, in between our cells, and in our blood. It is important for proper transport of nutrients, regulating body temperature, hydration and the obliteration of wastes. The threshold for life without water on average is 4 days. Polyuria is relevant to metabolism as it will occur when the body feels as though it has too much fluid and is unable to maintain it; hence, the fluid is released.

Typically, a person uses approximately 2000 calories daily. This is slightly more than the total energy that is necessary to light a 60 W bulb for 30 h. The calories used on food labels are actually kilocalories and are usually indicated by 'Calorie'—1000 calories equals 1 Calorie. For example, a 100 calorie snack contains '100 Calories"; however, to a physicist, the snack contains 100 000 calories. A person's TMR may vary depending on numerous factors including illness, age, pregnancy and depression. In general, children have a greater total metabolic rate in comparison to adults. As people age, the TMR declines. Pregnancy may increase TMR and depression can cause the TMR to decline.

3.5 Pressure

As we walk, what type of pressure and force do we apply to the ground? We learned from Newton’s 3rd law that as we exert a force on the ground, the ground responds with an equal and opposing force. Yet, we know that pressure also has a direct effect on overall stability and equilibrium. Pressure is a ratio of the amount of applied force to a given area. For example, the middle ear and the throat are connected by the Eustachian tube, which helps to equilibrate the pressure between the body and the atmosphere. At a higher pressure, it is not unusual for a person to appear to be senseless, experiencing a disturbing feeling in their ears. It is thought that if you massage the balls of your feet, it will help to drain the inner and middle ear, reducing blockage of the Eustachian tubes. Moreover, the body has ‘pressure points’ that align with energy pathways. Pressure points can relate to points of pain that coincide with the muscles and tendons, or reflex points that involve involuntary movements. There are over 300 pressure points that are known to help regulate function within the body. Acupuncture and reflexology are two fields that have become popular that focus on the pressure points to improve overall functional health.

IOP Concise Physics

Biophysics of the Senses

Tennille D Presley

Chapter 4

Electrical properties of the body

4.1 Atoms and electricity

We have discussed how the body has the capacity to bend and move. Now it is important to address the inner workings of the body and how internal processes occur. All of our bodily activities are controlled by electrical signals that migrate through our bodies. These signals allow us the ability to detect movement, pain, heat, thirst and hunger, as well as how to react to these sensations. Best described as **bioelectricity**, this type of electricity impacts cell-to-cell communication and proper biological functioning for regular survival. Bioelectricity is an electric current that is produced by living tissues. Your cells are able to generate charges that 'leap' from one cell to the other, until arriving at their desired location.

The body is merely one large machine full of circuitry and electricity. Since practically 70% of the body is made up of water, it is considered to be a good conductor of electricity on average. This is due to the ions (i.e. Na^+, K^+, Cl^-) that are contained within the water. Deionized water will not conduct an electric current because it is a covalent compound, which shares electrons. An ion is something that has the ability to gain or lose an electron. Ions are important when thinking of disease as they impact the flow of charge throughout the body to maintain its functionality. For instance, the kidneys help to remove excess ions from the blood by excretion via urine and osmotic pressure regulation. In general, negative ions fortify the body's immune system and augment metabolism, whereas positive ions have the opposite effect.

At rest, your cells have an influx of potassium ions inside the cells compared to sodium ions; more sodium ions are outside the cells. Because of this natural imbalance of potassium and sodium ions inside and outside of the cell, a negative resting state exists. Potassium ions are negative, while sodium ions are positive. When the body desires to send a message, the membrane gate opens and the sodium and potassium ions begin to migrate. This leads to changes in charge between the inside and outside of the cell, and an electrical impulse is triggered. An impulse is the

doi:10.1088/978-1-6817-4111-6ch4

product of force and time. Also recognized as the 'total change in momentum', impulse is most common when dealing with forces that function during a brief time interval.

Generating electricity within the body gives cells the opportunity to communicate and perform fundamental biological functions that are required for life. Cells that are not robustly transferring messages are thought to be negatively charged. The cells produce electrical charges through electrolytes (e.g. sodium and potassium). Electrolytes are solutions of ionic substances and have the capability to conduct electricity. Simply put, electrolytes are developed from ions. Many foods that have a high acidity such as lemons, potatoes, carrots and pickles, act as electrolytes and conduct electricity.

Atoms regulate electricity and are defined as the building blocks of matter. They are the smallest particle of an element and are composed of positive (protons), negative (electrons), and neutral (neutrons) charges. The basic structure of the atom is visualized as the protons and neutrons (known as nucleons) which are more massive and concentrated within the nucleus of the atom, and the electrons are assumed to circle the nucleus. Our bodies consist of mainly four atoms: carbon, hydrogen, nitrogen and oxygen. Oxygen is predominant equaling around 65%, followed by carbon (18%), hydrogen (10%), and nitrogen (3%). The majority of the atoms within the body are hydrogen; yet, oxygen makes up most of the mass. The electrons control the chemical behavior of the atom, whereas the neutrons affect the structural stability of the nucleus. The protons and electrons have a 'marriage' that exists, where they are naturally attracted to each other—'*like charges repel and unlike charges attract*'. An atom is normally neutrally charged, having an equal number of protons and electrons. The magnitude of charge for both a proton and electron is the same, $q = 1.602 \times 10^{-19}$ Coulombs (C); since the electron has a negative charge, this value is -1.602×10^{-19} C. Coulomb is the unit for charge. Harnessing the electrical charge of the Earth via grounding has been known to have a positive effect on health such as reducing inflammation, relieving pain and improving sleep. It has been suggested that the easiest way to stay 'grounded' is to walk outdoors barefooted on grass or sand. Grounding dissipates electricity.

4.2 Electric force, electric field, and electric potential

Protons and electrons are just like males and females—in general, males and females like to come together to create a relationship, whether friendship or romantic. Positive and negative charges are similar. Although opposite, they attract and develop stability with each other. When the charges are stationary, there is a force that exists between these charges called an electrostatic force. This force is best represented by Coulomb's law, which states: '*The product of two charges is directly proportional to the electrostatic force and this force varies as the inverse square of the distance between the two charges*'. Thus, Coulomb's law is:

$$F = k\frac{q_1 q_2}{d^2}$$

where F is the force in Newtons, k permittivity of free space equal to $8.99 \times 10^9\ \mathrm{N \cdot m^2\ C^{-2}}$, q_1 and q_2 are the charges measured in Coulombs, and d is the distance in meters. The double strands of deoxyribonucleic acid (DNA) consist of positive and negative charges, causing these strands to be attracted by electrostatic forces. The detection of the electric field is by the force that it exerts on other electric charges. It is a vector quantity that is defined as the force on a stationary charge divided by the charge and is denoted by

$$E = \frac{F}{q}$$

The SI units for electric field can be measured as Newtons/Coulomb (N/C) or Volts/meter (V/m). In the presence of a positive charge, the charge feels a force in the direction of the electric field; however, a negative charge in an electric field experiences a force in the direction opposite to the field. Exhibiting the ability to detect electric field is electroreception. Several aquatic animals, including fish, dolphins, and sharks are capable of sensing changes in the electric field in their surrounding environment. However, when it comes to humans, work is required to move an electric charge the same way that it is needed to lift a box vertically from the ground. Electric potential is merely the potential energy per charge.

Electric field and electric potential are directly proportional to each other. Therefore, a hasty change in voltage implies that there is the presence of a strong electric field. Electric field can be demonstrated by the following formula with respect to electric potential:

$$E = \frac{V}{d}$$

4.3 Current, voltage, and power

Ohm's law demonstrates the relationship between electric potential (voltage), current, and resistance ($V = IR$). Voltage is the capacity to drive an electric current across a resistance. At a fixed resistance, voltage and current are directly proportional to each other. The standard voltage in a home in the United States is 120 V, whereas it is significantly higher in other parts of the world such as Europe and Asia. The standard voltage in those continents is 240 V. Current (I) is a ratio of the amount of charge that flows past a point and the amount of time it takes the charge to flow. It is expressed as

$$\mathrm{I} = \frac{Q}{t}$$

The unit for current is Coulombs per second which is equivalent to an ampere (A) or amp for short. The pressure points that were discussed in chapter 3 send electrical currents throughout the body to improve health. The majority of people can feel a current as low as 1 milliampere (mA). At higher currents between 10–20 mA, muscle contraction occurs. At 50 mA of current, a person feels pain. Currents that exceed this level can result in fibrillation of the heart. When there is an electric field in a conductor, charges move and electric current is created.

Resistance restricts the flow of current in an electronic circuit, and has units of the Ohm (Ω). The rate of resistance depends on the type of material that the resistor is made up of, the area and the length. Resistance is represented as

$$R = \rho \frac{L}{A}$$

ρ is the resistivity—a property of the material that is dependent on temperature and purity. Resistance is directly proportional to length and inversely proportional to area and diameter.

Within the body, the skin (specifically the epidermis) is a poor conductor of electricity, thus implying that it has a high resistance. The skin is where most of the body's resistance exists. The resistance of the skin can range from 1000 to 100 000 Ω. This large variability depends on the skin's moisture, a person's gender and how healthy the skin may be. Dry skin can be somewhat insulating, whereas wet or blistered skin has a lower resistance. In the presence of moisture, there is less resistance and greater current. The electrical resistance varies from person to person. Yet, there are distinguishing factors between men and women. In general, men are typically more massive and have thicker arms and legs than women. As a result, men have a lower resistance. Internal resistance in the body can vary between 300 to 1000 Ω. The route that electricity takes through the body is also important. If it enters the left hand and exits out of the right foot, then it will be considerably higher than if it goes in and out of neighboring fingers. Resistance values ranging between 500 to 1500 Ω are customary for hand-to-hand, hand-to-foot, and foot-to-foot.

Alternating current (AC) is when the current frequently changes direction, while direct current (DC) is a consistent flow of current in one direction. AC is most common of the two, with respect to its utilization in buildings, homes, the body, and practical daily life. Each of their effects can impact the body in different ways. Both alternating current (AC) and direct current (DC) can be fatal; however, the path in which the current travels through the body is a major factor. DC will create a single, continuous contraction of muscles, whereas AC will generate a series of contractions (*depending on the frequency*). If current travels across the body, and through the heart, lethal effects can result and possibly death.

Power was discussed in chapter 3 as the rate of energy transformation. As this concept relates to electrical activity, **power** is the product of current and voltage ($P = IV$), and still has the units of Watts. If we correlate Ohm's law, two additional formulas for power can be resolved:

$$\text{Power} = (\text{Current})^2(\text{Resistance})$$

$$\text{Power} = \frac{\text{Voltage}^2}{\text{Resistance}}$$

While $P = IV$ can be useful for any electrical device, the two equations above can only be used if a resistance is present. There is a direct correlation with how power is viewed with respect to energy compared to electricity. For instance, the electric companies measure more the energy that a home uses and not the power. In a household circuit, a fuse or circuit breaker opens when there is an overload of current. The body has a similar pattern, where a human body can produce between 10–100 millivolts. A large voltage simply means that there is a high potential for current to rapidly flow through the body. If you are taking a shower or are in the pool, I suspect that you avoid using your cell phone or any other electrical device. As people, we have a higher conductivity when wet, increasing the likelihood of electric shock or electrocution. Electric shock disturbs the normal operations of the body. An extreme shock such as lightning can result in electrocution and of course the body's resistance is drastically depleted. A person's body chemistry can also have a substantial effect on electric current.

The dominant ions within the body were discussed, and each ion has an ion channel. An ion channel is responsible for regulating the flow of ions across the cell membrane. The electrical properties of biological tissues and cells can be studied via electrophysiology. This method entails measurements of voltage change or electric current from single ion channel proteins to large organs. Patch clamping is a common technique to study a single channel or the entire electrical activity of a cell. With patch clamping, a glass micropipette is filled with an electrolyte solution and the tip of the micropipette is attached to the cell membrane.

4.4 Magnetism

While electric charges can generate an electric field when stationary, magnetic fields require 'movement' whether it is a result of charges that are migrating or current in wires. These ions move when subjected to an electric field. When moving, these charges have the capability to interact with magnetism. A magnetic force is exerted on a charge that moves in a magnetic field. This force can be denoted by:

$$F = qvB \sin \theta$$

As demonstrated by the formula, the magnetic force is also influenced by the velocity of the charge and by the magnetic field (B), having units of Tesla (T). Theta (θ) is the angle between the velocity and the magnetic field. A changing electric field can cause a change in the magnetic field and a changing magnetic field can lead to a change in the electric field. This is best explained as electromagnetism, as electricity and magnetism have a direct effect on each other. The interaction of electric and magnetic fields is a perpendicular relationship with each other. It is possible to detect the direction that someone is facing based on the Earth's magnetic field, known as magnetoception. The Earth has a magnetic field of 5.0×10^{-5} T. While this sense is not common amongst humans, it is observed in birds and bees.

The human body generates an electromagnetic field, causing the forces of electricity and magnetism to coexist. The electrical portion consists of a low frequency, DC electric field. When these forces are present, electrical energy also exists. This electromagnetic energy is impacted by the natural electromagnetism of the Earth. Although the Earth's electromagnetic environment is typically unobtrusive, it may become disturbed by an environment that may be electromagnetically charged. The overlap of electricity and magnetism within the biological system can also be studied via electrophysiology.

We currently live in an era where technology significantly impacts our lives. Have you ever questioned how is it that when you touch your smartphone or tablet, the screen recognizes your touch? Your finger has a different dielectric constant compared to the air. It changes the electric field and the mutual capacitance of the wires. When you place your finger near the screen, it senses the capacitance between the electrode or wire and your body. This is possible due to small capacitor grids that team up so that one direction of wires carries current and the other senses the capacitance between them. This is a direct correlation of the bioelectricity in the body and how you transfer charges from your body to the screen.

4.5 Capacitance

A capacitor is a set of conducting plates with charges of equal magnitude, but opposite signs. Capacitance is a measure of a capacitor's ability to store electric potential energy or charge. This storage of energy is equivalent to the work done to charge the capacitor, and occurs by disassociating positive and negative charges. The charges from one plate are transferred to the other plate, as commonly modeled by a battery that is conjoined to a capacitor. Capacitance is represented by the ratio of charge to voltage and can be determined by the formula

$$\text{Capacitance} = \frac{\text{Charge}}{\text{Voltage}}$$

The units for capacitance is a Coulomb per Volt, which is a Farad (F). Similar to any other electrically conductive material, the human body can store electric charge if properly insulated. The capacitance for the human body in a normal surrounding is around 10–105 picofarads (pF). While humans are larger than many electronic devices, this capacitance is small compared to electronic standards and people usually are well-spaced from other conductive objects. The attire that you wear will impact your capacitance. Direct contact with a conductor reduces a person's capacitance whereas an insulating material will enhance the capacitance. A person's posture also influences their capacitance.

Dielectrics are simply insulating materials. The dielectric constant for human tissue ranges between 30 to 80. Tissues from the lungs have a lower dielectric constant than liver and muscle tissues. In a typical electrical circuit, a battery (or source of power) is present with a positive charge at one end and a negative charge at the other end. When you connect the battery within a complete circuit, there usually exists some type of grounding, which prevents too much current from flowing through the circuit. The purpose of a battery is to generate a difference in potential and trigger the movement of charges. In order for current to flow, a complete circuit must be present. However with the human body, charges on either side of the cell membrane are created through passive processes such as simple diffusion, migration through protein channels in the membrane, or active-energy dependent processes involving ATP:

$$\text{Capacitance} = K \in_0 \frac{A}{d}$$

K denotes the dielectric constant. This value varies depending on the particular material that is present. ϵ_0 is a permittivity constant equivalent to $8.85 \times 10^{-12}\ \mathrm{C}^2\ \mathrm{N}^{-1} \cdot \mathrm{m}^2$; A represents the area and relies on the shape of an object and d is the displacement. Capacitance is dependent on physical characteristics, and not the charge or voltage.

It is appropriate to consider the energy stored in a capacitor as being deposited in the electric field between the plates of the capacitor. When there is a lot of energy accumulated in a large capacitor, it can be detrimental and cause a burn or electric shock if you come into contact with the capacitor. Capacitors can carry charge even if the power source is deactivated. Thus, be extremely careful in the presence of circuits. Electric potential energy stored in a capacitor is

$$\text{Potential energy} = 1/2\mathrm{QV} = 1/2\mathrm{CV}^2 = 1/2\frac{Q^2}{C}$$

When positioned in contact with a piece of metal, the epidermis will function as a capacitor. The tissue directly beneath the epidermis and the metal act as the conductive plates of a capacitor; the dry surface of the epidermis can act as the dielectric. Static shock has low amounts of energy stored and is not harmful. A high frequency electric current or AC is far more dangerous than a DC. Both AC and DC can be fatal; however, it takes more milliamperes of DC than AC at the same voltage to have the same effect. If electric shock occurs via AC, the body's overall resistance is significantly lowered; however, electric shock by a DC source will not have as great an effect. For instance, an electrical shock of 1 mA of AC at 60 hertz would be equivalent to 4 mA of DC. The probability of severe shock enhances with a greater amount of voltage. A voltage exceeding 450 V causes dielectric breakdown of the skin. Electric shock that results in death is considered as electrocution.

Think about a solar-powered watch. If you place the watch in the Sun to let it charge and then place it on your arm, the body's electrical activity will interact with the normal workings of the watch to keep the watch functioning to tell time. There are also watches that are fueled by the conversion of kinetic energy from the body to electrical energy. Furthermore, research exploring the body as a 'human battery' is ongoing. For example, Panasonic has developed a method for human blood to be used to 'power' electrical devices. The intent is that this could aid with nanodevices that may be implanted in the body. From minute changes in temperature to harnessing kinetic energy, the body can be useful for low powered electronic devices of 100 microwatts.

Reflect on how you feel at the end of a very long day. If you are anything like me, you feel exhausted at the end of the day. The goal is usually to have dinner, relax and rejuvenate for the next day. Your body is a natural capacitor in the fact that food and sleep aid in providing the body with the right amount of energy so that it can 'recharge' and be prepared for the next day. All-in-all, there are so many useful ways that the electricity from the body is important.

Chapter 5

Free radicals

5.1 What is a free radical?

If you ruled the world, what would you do or what would you be? You can ask yourself the question of what would you do; however, the answer to what you would be is a free radical. A **free radical** is a chemically reactive atom, molecule or ion that has an unpaired electron. Free radicals are thought to have 'dangling' covalent bonds, and in a sense rule the world because they are everywhere. Free radicals usually arise during metabolism, but can also be generated by cigarette smoke, pollution and radiation. It is impossible to consider an environment lacking these radicals. When there are more free radicals, there are more positively charged ions. If there are more free radicals in the blood, cellular metabolism is reduced and less efficient. As a result, the cells are weakened and the body is more prone to sickness and aging. This may also initiate failure to the body's immune system. When you are sick, you have a higher amount of free radicals. Think about how you feel. In most cases, you feel depleted of energy. This lets you know that the free radicals are heavily present. Free radicals are 'robbers' of energy. They wait for the most opportune time, then they take over and impact our daily lives (figure 5.1).

Free radical damage exists within our bodies and our surrounding environment. This damage transpires when an unpaired electron seeks another electron that is paired to a molecule. The unpaired electron normally approaches a weak bond and 'steals' the electron, causing the 'attacked' molecule to become a radical; thus, a chain reaction and disruption of a living cell occurs. Stress or any type of imbalance instigate the prevalence of free radicals. Diet, exercise, disease, and aging also influence radicals. The free radical theory of aging states: '*Organisms age because cells accumulate free radical damage over time*'. Damage from free radicals within the cells is associated with a number of diseases including cancer, diabetes, Alzheimer's diease, cardiovascular disease, and stroke. However, we cannot survive without free radicals, as they are also involved in vital processes within the body to regulate homeostasis. For instance, free radicals aid in abolishing bacteria.

doi:10.1088/978-1-6817-4111-6ch5

Figure 5.1. Free radicals are 'thieves'. They steal energy, leaving the body with disorder.

Table 5.1. List of common free radicals and their half-lives.

Reactive species	Half-life
Hydrogen peroxide	*minutes*
Nitric oxide	*seconds*
Peroxynitrite	*milliseconds*
Superoxide anion	*microseconds*
Hydroxyl radical	*nanoseconds*

5.2 Types of free radicals

The most problematic free radicals within biological systems are the oxygen radicals. Since oxygen has two unpaired electrons in its outer shell (in separate orbitals), it has a high probability of generating radicals. Known as reactive oxygen species (ROS), these oxygen-centered radicals include the hydroxyl radical, superoxide and hydrogen peroxide as shown in table 5.1. They are constructed from normal oxygen metabolism, and impact homeostasis and cell signaling. ROS are involved in various enzymatic reactions, and are also reduced along the electron transport chain. Although during oxidative stress, ROS may markedly increase. This effect can be triggered by overexposure to heat, ionizing radiation, abnormal concentrations of oxygen or physical exhaustion. A perfect example of an overproduction of oxygen radicals is with white blood cells. These cells tend to produce oxygen radicals to kill invading pathogens. Ionizing radiation is a common producer of ROS within biological systems, and is most detrimental in highly oxygenated tissues. Long-term consequences of ionizing radiation is DNA damage. Numerous daily activities have also been shown to enhance the production of ROS inclusive of exposure to sunlight, cigarette smoke, and air pollution. Sun exposure has been shown to encourage oxidative destruction of the skin, augment the probability of skin cancer and induce wrinkling of the skin.

Singlet oxygen ($^1O_2$) is an excited form of oxygen, and is another oxygen-derived radical. With $^1O_2$, one of the unpaired electrons hops to a superior orbital after energy absorption. While singlet oxygen is a prooxidant, the main ROS are superoxide, hydrogen peroxide and the hydroxyl radical. Also known as hyperoxide, superoxide (O_2^-) is generated when oxygen is reduced by a single electron; molecular oxygen gains an electron. Superoxide has a molecular weight of 32 g mol^{-1}, is paramagnetic and occurs widely in nature. A great source of superoxide is NADPH oxidase. It becomes activated by inflammation and vasoactive factors. O_2^- may also be produced during the oxidation of hemoglobin to methemoglobin. An increase in superoxide is believed to enhance the aging process. Superoxide and hydroxyl are generally associated with cytotoxicity.

Hydrogen peroxide (H_2O_2) is a strong oxidizer that is naturally produced by oxidative metabolism. It is the most significant ROS in cell cycle regulation, and important for the immune system. H_2O_2 is most recognized as a common solution found in a person's medicine cabinet. H_2O_2 is commonly used to disinfect wounds, whiten teeth, treat acne, and for hair bleaching. Hydrogen peroxide expedites wound healing. Through catalysis, hydrogen peroxide can be rapidly transformed into hydroxyl radicals. Hydrogen peroxide is also recognized for its detrimental effects. For instance, a person with asthma has higher levels of hydrogen peroxide in their lungs, leading to unsuitable amounts of white blood cells.

The hydroxyl ($OH^\cdot$) radical is recognized for its popular characteristics of extreme toxicity and reactivity. $OH^\cdot$ can lead to the formation of hydrogen and oxygen. It usually attacks everything that it collides with, especially phospholipids in cell membranes and proteins. Unlike superoxide, the hydroxyl radical cannot be eradicated by an enzymatic reaction.

Another category of reactive species are the reactive nitrogen species (RNS). Nitric oxide is considered as an RNS. Discovered as the endothelium-derived relaxation factor (EDRF), nitric oxide ($NO^\cdot$) or nitrogen monoxide is a stable radical that is naturally produced in the body. In the blood, NO has a very short half-life of just a few seconds. It is present in the body both endogeneously and exogeneously. At low amounts, NO production is protective against ischemic damage in organs such as the liver. Nitric oxide is best known for its vasodilation. It is also commonly recognized to inhibit platelet aggregation, protects against vascular dysfunction, and exhibits properties of a neurotransmitter. $NO^\cdot$ aids in processing nerve signals as they cross synapses. Out of the 20 amino acids that comprise proteins, L-arginine is the only one that makes substantial amounts of NO. A limited amount of NO contributes to endothelial dysfunction. The gut is a key site for high concentrations of NO.

NO is an efficient intracellular messenger because of its ability to diffuse through most cells and tissues, causing very little disturbance. NO impacts many diseases, especially those that affect the vasculature. This signaling molecule initiates homeostatic functions including cell-to-cell communication, wound healing, pain reduction, cell proliferation, and the immune response. The effect of nitric oxide on neurotransmission happens by cyclic guanosine monophosphate (cGMP) allowing the phosphorylation of ion channels. Adequate levels of oxygen and glucose are carried to the nerve cells, improving the production of ATP. NO also increases cGMP, and uses its vasodilating properties to reduce pressure on nerves; this results in a decreased level of pain. Inhaled NO has been a useful treatment for pulmonary hypertension.

$NO^\cdot$ can be studied from both an endogenous and exogenous perspective. Endogenously, nitric oxide synthase (NOS) is an enzyme that creates $NO\cdot$ from L-arginine. There are three isoforms of NOS: NOS1 (neuronal NOS, nNOS); NOS2 (inducible NOS, iNOS); and NOS3 (endothelial NOS, eNOS). nNOS aids in transmitting information between the nerves and the brain. iNOS is named for its need to become activated when an abnormality (i.e. injury, disease, etc) exists. Extremely high concentrations of NO (100–1000 times the normal amount) are produced by iNOS. This isoform has been observed in the brains of individuals with multiple sclerosis.

Amongst the three isoforms, eNOS is important in supporting normal activity in the blood vessels. eNOS is found in the inner lining of blood vessels (the endothelium) and enhances the growth of new blood vessels (called angiogenesis). The activation of eNOS happens by the stretching and relaxation of the blood vessel wall in response to each heartbeat. eNOS is also known to play a role in affecting cellular respiration and can associate with various proteins, such as heat shock proteins (Hsps). Hsps are proteins that are present in all cells at every biological level and aid in cardioprotection. Specifically, eNOS can conjoin to Hsp90 to enhance NO production, inhibit the generation of superoxide and regulate vascular tone. NO generated from eNOS preserves the diameter of the blood vessels to maintain adequate blood flow throughout the body.

Exogenously, nitrite (NO_2^-) and nitrate (NO_3^-) contribute to the availability of NO. Nitrate is reduced to nitrite, which is then reduced to NO. Low concentrations of NO_2^- in tissues range between 1–20 μM, whereas nanomolar concentrations of 100–200 nM exist in the blood. NO_2^- therapeutics has grown over the years, where it helps to improve blood pressure and the presence of NO, specifically in conditions of low availability of NO. Two primary sources of nitrate and nitrite are by the endogenous L-arginine-NO pathway and through the diet. Most NO_2^- comes from the oxidation of 'NOS-generated NO'. A reaction of NO with oxyhemoglobin produces nitrate, while oxidation of NO forms nitrite. During hypoxia, NO produced by NOS is limited, but the nitrate–nitrite-NO pathway is amplified. Beet juice and green, leafy vegetables such as spinach are also a great sources of nitrates.

Melanin is unique in the fact that it is not chemically reactive like other radicals. It is normally found in high concentrations in individuals of African descent. Melanin has 'superconducting' capabilities as it can conduct electricity and also has insulating properties. It will not allow electrical current to pass through its structure. Melanin is also protective of cells against oxygen toxicity, and aids with tissue repair and skin regeneration. It is present in the nervous system, the blood, brain and a number of foods.

5.3 Interrelationships of radicals

Knowing that free radicals are highly reactive, it only makes sense that they have the ability to react with each other. Yet, what happens and how do these processes occur? Recent reports have shown that one of the main causes of heart failure is the

NO/ONOO$^-$ cycle. Nitric oxide and superoxide generally have an inversely proportional relationship with each other, where the concentration of one radical increases, the other will decrease. There are exceptions to this where increases in NO in contracting skeletal muscle of aged mice does not result in a decline in superoxide. When superoxide and nitric oxide coexist, they chemically react to form peroxynitrite (ONOO$^-$) and cause NO toxicity. This reaction causes NO toxicity, and may compete with the dismutation of superoxide and hydrogen peroxide. ONOO$^-$ can be damaging to both DNA and proteins with cells. It can lead to lipid peroxidation and inactivation of enzymes. Peroxynitrite is also capable of forming the hydroxyl radical and nitrogen dioxide. Lipid peroxidation is a common example, which is initiated when a free radical removes a hydrogen atom from a polysaturated fatty acid.

An oxidation–reduction (redox) reaction is when electrons are moved from one atom to another. Oxidation is when there is a loss of electrons by an atom and reduction is when the atom gains electrons. Thus, any reaction that has oxidation must also have reduction—occurrence of a redox reaction. The ‘redox’ properties of iron is a source of free radicals in biological systems. A reversible redox reaction also exists with nitrite and nitric oxide. This interplay impacts brain function, the gut and the digestive system.

5.4 Antioxidants

As a child, I distinctly remember my parents and grandparents saying to eat my vegetables. It was not until I became an adult that I realized that the reason was for combating free radicals by way of antioxidants. An antioxidant is a stable molecule that has the ability to donate an electron to neutralize the free radical—they scavenge free radicals. Antioxidants are reducing agents that inhibit oxidative damage to biological systems—they neutralize free radicals. A balance between free radicals and antioxidants is essential for normal physiological stability and function. Most antioxidants are either derived from the diet or enzymes within the body. β-carotene, vitamin C (ascorbic acid), and vitamin E (α-tocopherol) are from the diet. Vitamins C and E can also be used topically to reverse damage from the Sun. Vitamin E is a fat soluble vitamin that is present in whole grains, nuts and vegetable and fish oils.

Vitamin C or ascorbic acid is a water soluble vitamin that is found in citrus fruits, broccoli, cabbage, green peppers, kiwi and strawberries. It is essential for tissue collagen production and protective against plaque formation in the arteries. Although vitamin A is not an antioxidant, its precursor, beta-carotene is. Beta carotene is present in milk, carrots, yams, peaches, spinach and egg yolk. Green tea is an excellent source of catechins, known to augment the immune system and cardiac health. In general, most people do not naturally obtain the necessary amount of antioxidants daily. Specifically with vitamins C and E, the American diet is low in the recommended amounts. On average, an adult should consume approximately 15 milligrams of vitamin E per day.

In the absence of catalase, toxicity from H_2O_2 transpires. As previously discussed, free radical chain reaction may occur. Due to the high toxicity and reactivity of superoxide, it is imperative that all organisms in the presence of oxygen have a protective enzyme to neutralize superoxide. Superoxide dismutase (SOD) is capable of rapidly counterbalancing the detrimental effect of superoxide, into hydrogen peroxide and oxygen. This class of enzymes comes in three forms: SOD1, which is located in the cytoplasm; SOD2, located in the mitochondria; and SOD3, found extracellularly. SOD1 and SOD3 contain copper and zinc, while SOD2 has manganese in its reactive center. Glutathione is the only antioxidant capable of destroying the hydroxyl radical.

5.5 Ways to measure free radicals

Due to the short half-lives of most radicals, scientists and researchers have developed unique ways to detect the presence of these radicals in biological tissues and samples. The most common approach for measuring free radicals is to utilize **electron paramagnetic resonance** (EPR). This is a technique that measures energy absorption due to the transition of an atomic particle between energy levels. During EPR, there is a fixed frequency in the presence of an electromagnetic field. The unpaired electrons interact with a magnetic field. Free radicals in cellular samples, intact tissues, organs and whole animals can be measured. Since EPR has a fixed frequency, the type of EPR machine will vary depending on the type of sample that is used for measurement.

EPR can be spectroscopic or via imaging, where a specific paramagnetic probe is necessary for detecting nitric oxide, superoxide and the hydroxyl radical. Because each of these radicals are ‘short-lived’, a spin trap is necessary for EPR measurements. When a spin trap interacts with one of these radicals, it forms a covalent bond to ‘stabilize’ the radical so that it can be detected by EPR. A metastable radical is created with a half-life of 1–15 min. Examples of spin traps include 5,5-dimethyl-1-pyrroline-N-oxide (DMPO), which detects superoxide, and N-methyl-D-glucamine dithiocarbamate iron (FeMGD), which measures nitric oxide. In some studies, the desire to match the temperature condition of the EPR experiment to the actual environment (i.e. free radical formation in biological tissues) exists. To measure cellular activity, room temperature EPR measurements can be performed; however, low-temperature EPR is for reactions that take place in the body rapidly. For example, the reaction of hemoglobin and nitrite within whole blood must be measured at a low temperature.

Other techniques exist that can measure the concentration of free radicals in biological samples and tissues. The ENO-20 is a high performance liquid chromatography (HPLC)-based technique that measures both nitrite and nitrate. It is a highly sensitive technique that can perform measurements as quickly as five minutes, with a microliter volume of sample. The superoxide dismutase (SOD) assay uses tetrazolium salt to detect superoxide in plasma, tissues and cells. It can detect all three types of SOD (Cu/Zn, Mn and FeSOD). Fluorescent probes are also commercially available to measure radicals. 5-Diaminofluorescein diacetate (DAF-2DA) is commonly used to detect the presence of nitric oxide, while dichlorofluorescin diacetate (DCFDA) measures ROS. NO can also be measured with a Clark electrode. This electrode is a specific electrochemical sensor that causes NO to diffuse through a gas-permeable membrane and a thin film of electrolyte. Oxidation occurs on the electrode, generating a current directly proportional to the concentration of NO on the outside of the membrane.

Whether it is paint peeling on our homes, pollutants in the environment, or reactions within the body, free radicals impart themselves into our lives. The key is to have a thorough understanding of the benefits and dangers of all radicals, and counterbalance the harmful effects with antioxidants. Yet, remember that too much or too little of anything can have detrimental effects—everything in moderation.

Chapter 6

Cardiac conductivity

6.1 Machinery of the heart and blood flow

The heart is the dominant organ within the body's circulatory system that is responsible for pumping blood throughout the body. It exhibits perfect machinery to keep the body functioning in the way that it needs to continue to survive, by contracting at regular intervals to squeeze blood into the blood vessels. It contracts and relaxes due to the flow of electrical activity. This electrical conduction system creates impulses along specialized pathways, having a distinct sequence for contraction. The electrical activity of the heart also relies on electrolytes to properly function. The heart consists of four chambers: the upper chambers—right atrium and left atrium; the lower chambers—left ventricle and right ventricle. The atria and ventricles are electrically separated from each other by connective tissue, which acts like an insulator. The main controller of the normal heart rhythms is the sinoatrial (SA) node, which is located in the right atrium. The SA node produces impulses that stimulate the cardiac muscle or the myocardium, causing contraction of the myocardium. The atrioventricular (AV) node in cardiac electrical activity attenuates the conduction of electrical impulses from the atria, and may function as a 'backup' to the SA node. This well-organized process allows blood to be pumped throughout the body.

Systemic circulation involves oxygenated blood being carried away from the heart to the body, and returning deoxygenated blood back to the heart. The right chambers of the heart contain deoxygenated blood and the left chambers house the oxygenated blood as shown in figure 6.1. The deoxygenated blood is pumped into the lungs for reoxygenation; the left chambers receive the oxygenated blood from the lungs and the blood is pumped throughout the body to provide nourishment for the tissues and organs within the body. Hemoglobin is a protein molecule in the blood (specifically the red blood cells) that transports oxygen from the lungs to the body's tissues, and returns carbon dioxide from the tissues to the lungs. It releases oxygen and provides energy to aid in metabolism. Negative ions generate

doi:10.1088/978-1-6817-4111-6ch6

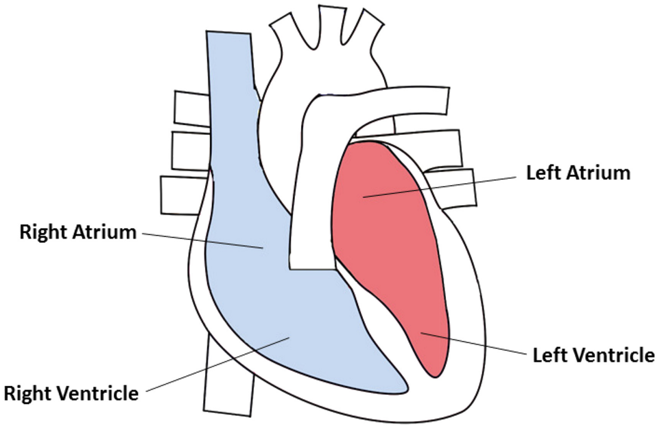

Figure 6.1. Model of the heart. The heart consists of four chambers: the right atrium, left atrium, right ventricle, and the left ventricle. The right chambers of the heart house the deoxygenated blood (shown in blue); the left chambers of the heart contain the oxygenated blood (shown in red).

a rise in the affinity for hemoglobin, causing the partial pressure of oxygen to augment and the partial carbon dioxide pressure to decline. Due to the fact that blood is forced out with a greater resistance from the left ventricle, it is thicker than the right ventricle. However as a whole, very little effort is needed to fill the ventricles, because gravity plays a role. The atria contract before the ventricles. Blood exits the left ventricle and migrates to the aorta, the largest artery in the body. Blood flows through the aorta at a velocity of 30 cm s^{-1}. It travels through various arteries, capillaries and veins and re-enters the heart via the right atrium.

Responsible for pumping blood to the body, the heart is impacted by pressure. Pressure is the amount of force per unit area. This concept is also recognized as the product of the density of an object, the acceleration due to gravity (9.8 m s^{-2} on earth), and the height of the object. Density is mass per volume. Pressure can be determined using the following formulas:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$\text{Pressure} = (\text{density}) \times (\text{acceleration due to gravity}) \times (\text{height})$$

The density of whole blood is 1.05×10^3 kg m^{-3}. Whole blood represents about 7% of the body's weight. Blood pressure (also known as arterial blood pressure) is the pressure that circulating blood applies to the walls of the blood vessels. Systolic blood pressure (the top number) is the amount of pressure that the blood exerts on the vessels while the heart is beating; diastolic blood pressure (the bottom number) is the pressure in the vessels in between heartbeats. Blood pressure is read as the systolic pressure over the diastolic pressure. A normal blood pressure at a relaxed state is 120/80 millimeters of mercury (mmHg).

Most blood flow is laminar, meaning that the flow is considered to be smooth. Specifically, this behavior is observed with the speed of the blood in small arteries and capillaries. pH regulates the blood at 7.4, and the overall blood flow of an adult at rest is 5000 milliliters per minute (ml min^{-1}). Flow rate in a cylindrical tube such as a blood vessel is contingent on the pressure difference, the dimensions of the tube and the viscosity of the fluid. **Viscosity** is an internal friction between neighboring layers of fluid as the layers migrate past one another. It is due to electrical, cohesive forces between molecules. Thus, the amount of thickness is addressed and a difference in pressure between the ends of a level tube is required for steady flow. When a fluid is viscous, energy is required and friction between molecules occurs. A liquid is typically incompressible, whereas its volume will not change; however, gases are amongst the fluids that are compressible. For a known fluid, the required force is proportional to the area of the fluid and the speed, and inversely proportional to the distance that separates the walls/tubes. This is shown in the formula below:

$$F = \eta A \frac{v}{l}$$

F is the amount of force in Newtons, η is the coefficient of viscosity and is dependent on temperature and the type of fluid, A is the area, v is the velocity and l is the distance or amount of separation between the two layers. The more viscous a fluid, the more force is required for it to move. Whole blood at 37 °C has a coefficient of viscosity of $\sim 4 \times 10^{-3}$ Pa·s, whereas blood plasma's coefficient of viscosity is 1.5×10^{-3} Pa·s. Thus, force and viscosity are directly proportional to each other.

Ohm's law ($V = IR$) was discussed in chapter 4 and can be correlated with respect to blood flow. Just as a higher current implies less resistance, more blood flow suggests a lower resistance. Blood flow is determined by a pressure difference and an inhibition of flow (or resistance) through the vessel. Since viscosity functions similarly to friction, a variance in pressure is needed for continuous blood flow. The pressure difference forces blood to be pushed through the blood vessels. Blood flow can be quantified based on Poiseuille's law:

$$\mathrm{Q} = \frac{\pi R^4 (P_1 - P_2)}{8\eta L}$$

Q is the rate of blood flow, η is the coefficient of viscosity, R is the radius of the blood vessel, L is the length of the vessel, and $P_1 - P_2$ is the pressure difference. This formula demonstrates that the diameter of the blood vessel plays a tremendous role in regulating the rate of blood flow through a vessel.

A person's posture can also impact the cardiac function. In a reclined position, the heart and the brain are leveled and there is less restriction on the heart's ability to pump the blood. A perfect example of this would be the adjustable beds that allow a person to elevate both their head and feet to their desired position. Yet, the outcome varies when a person is stationary, sitting or standing. In a static position, there is an increased 'load' and blood flow is impeded. If a person was required to be on 'bed rest' due to some condition, they may develop bed sores or simply have very poor circulation due to the lack of movement. When a person is sitting or standing, centrifugal force can press down on the heart and obstruct blood flow from the heart to the brain. In general, people with high blood pressure are able to tolerate greater amounts of centrifugal force because their heart works at a higher rate than someone that has a lower blood pressure. Also, shorter people tend to have a greater tolerance for gravitational force because the distance between the heart and brain is less compared to a person who is taller. When there is a delay in blood delivery to the brain, a person may blackout or simply become unconscious. A loss of consciousness typically leads to fainting and the person ends up in a prone position. This allows a more convenient way for the heart to deliver blood to the brain.

6.2 Membrane potential

Electric potentials are present across the membranes of most cells. The membrane functions as an insulator. Discrepancies between the electrical potential of the interior and exterior of a biological cell is the membrane potential. The exterior membrane potential ranges from −40 to −80 millivolts (mV). The membrane potential has two primary functions: 1) to authorize a cell to operate as a battery, providing power for a variety of molecular processes in the membrane; 2) to transport signals in electrically excited cells. Variations in ion concentrations across a selectively permeable membrane can produce a membrane potential.

Chloride, potassium and sodium ions are the key ions concerning the development of membrane potentials. Potassium regulates heartbeat and reduces blood pressure. It is essential in conducting electrical impulses to tell muscles to move. Low amounts of calcium can result in irregular heartbeat. Heart cell rhythm is dependent on the opening and closing of ion channels. When cardiac cells beat, sodium channels open, allowing an expedient flow of sodium ions into the cells as quickly as 2 milliseconds. Following this depolarization of the membrane, a release of potassium ions to the outside of the cell results within 0.5 s—the cell membrane repolarizes.

The heart has the unique ability to ‘spontaneously depolarize’, lacking the requirement of an external stimuli to create a positive increase in voltage across the cell’s membrane. This instinctive depolarization is called autorhythmicity. Autorhythmicity happens because the heart’s membrane has a lower permeability to potassium; yet, passive transfer of calcium ions takes place. Cardiac cells are distinctive in the fact that they are the only cells within the body that are able to contract without being stimulated by the nervous system. When the cell is not being stimulated, a resting membrane potential exists. The standard resting membrane potential in the ventricular myocardium ranges between −85 to 95 millivolts (mV).

6.3 Electrocardiogram and echocardiogram

The electrocardiogram or ECG uses electrodes to study the electrical activity of the heart, while the echocardiogram measures the sound waves of the heart. ECG monitors the position and size of the chambers in the heart, as well as the beats of the heart and the presence of any damage. If a person takes any type of medication for their heart or has an implanted device, the ECG can detect their existence. If you

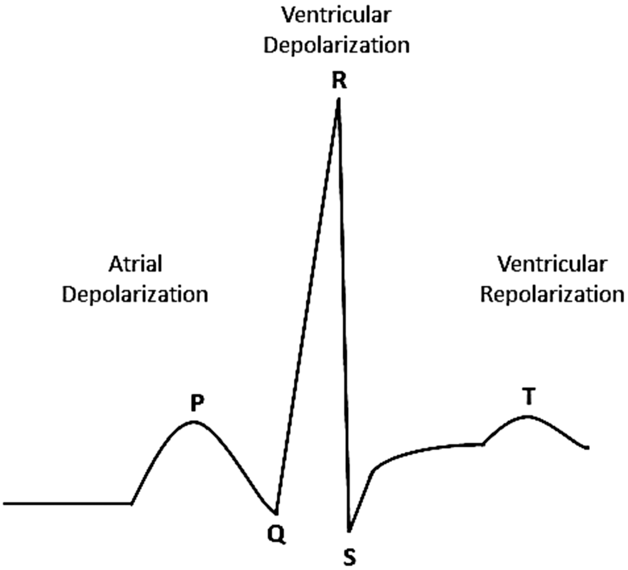

Figure 6.2. Electrocardiogram (ECG). During a normal ECG, the P wave is when the atria depolarize, the QRS complex is when the ventricles depolarize, and the T wave is the repolarization of the ventricles.

have ever made a reference and have heard of the ‘lub-dub’, this is the sound that the heart makes as it contracts and relaxes. Since the ECG assesses the heart rate and rhythm at the time of measurements, it is possible that this technique will miss an intermittent cardiac abnormality. The tracing for an ECG includes a P, QRS, and T wave as shown in figure 6.2. These tracings can provide information about the heart in regards to the heart rate and rhythm, how electrical impulses spread across the heart, thickening of the heart muscle or whether there may be the presence of coronary artery disease. The P wave exemplifies when the atria depolarize, lasting nearly 80 milliseconds (ms). The atria contract and pump blood into the ventricles. Following, the ventricles depolarize, generating the QRS wave within 80–100 ms. The amplitude of the QRS wave is significantly larger than the P wave because the ventricles have a larger muscle mass than the atria. The T wave represents when the ventricles recover. While the ECG is efficient at measuring the heart’s electrical behavior, it is not an accurate technique to gauge the pumping ability of the heart.

An echocardiogram (echo) is a non-invasive technique that utilizes sound waves to generate detailed pictures of the heart. The echo provides an indication of the pumping ability of the heart, and is most commonly used to diagnose and manage heart diseases. It measures the size and shape of the heart, as well as the internal structure of the heart and the velocity of the blood. The echocardiogram can be used to identify the location of tissue damage. The stress echocardiogram can aid in identifying if a person has heart-related chest pains. Both normal and abnormal blood flow through the heart can be measured with the echo, utilizing pulsed or continuous wave Doppler ultrasound. A major advantage of the echo is that there are no known risk factors or side effects associated with this measurement.

6.4 Cardiac abnormalities

In the event that the SA node misfires, an extra heartbeat or palpitation may arise. An arrhythmia is simply an abnormal rhythm of the heart, affecting the electrical activity of the heart. A palpitation may happen along with an arrhythmia; yet, palpitations can occur without being accompanied by an arrhythmia. For instance, if you feel your heart 'pounding', it may simply mean that you consumed too much caffeine or that you are stressed; this will accelerate your heartbeat. When the resting heartbeat is less than 60 beats per minute (bpm), it is called bradycardia; tachycardia is a heartbeat faster than 100 bpm.

If current travels across the chest from hand-to-hand and passes through the heart, fibrillation can occur. Fibrillation is when the heart muscles independently move in a chaotic fashion, as opposed to in a normal, organized manner. This will of course impact the heart's ability to properly pump blood, resulting in cardiac arrest and brain damage. Both AC and DC can initiate fibrillation; it takes 300–500 mA for DC, and 30 mA (with a frequency of 60 hertz) for AC. A much lower current of 1 mA can lead to fibrillation if the current travels directly to the heart. Fibrillation can be deadly if not treated with defibrillation, because circulation is disrupted. A heart defibrillator is a charged capacitor with a high voltage of a few thousand volts. In the case of a heart attack, irregular heartbeats occur and a defibrillator may be useful. A momentary jolt of charge from the defibrillator will 'shock' the heart, allowing the cells to recharge and instigate regular beating. The defibrillator has paddles that distribute current over the chest and discharge voltage very quickly through the heart.

There are various types of cardiac arrhythmias that affect the atria and ventricles including atrial fibrillation and ventricular fibrillation. Atrial fibrillation (AF) is the most common of all arrhythmias, where the heartbeat can range between 350 and 500 bpm. AF may result from high blood pressure or excessive alcohol consumption, and typically accompanies another existing medical abnormality. While the electrical impulses associated with AF transpire at a very rapid pace, heartbeats are uncommon. The AV node slows down the conduction velocity and protects the ventricles. Conversely, ventricular fibrillation (VF) can be fatal. With this arrhythmia, erratic electrical impulses occur and the ventricles 'quiver' instead of pumping blood. The blood pressure significantly declines, there is no blood supply to the vital organs and the person collapses within seconds. A heart attack is the most common source of VF. Although, VF may happen if the heart muscle has insufficient amounts of oxygen or if there are disturbances in electrolytes. VF is considered to be a form of cardiac arrest. In the event that a person does not recover within 2–3 min of this arrhythmia, death is highly probable.

Heart failure is when the heart loses the ability to fill and empty—there is insufficient blood flow. Defective pumping may cause fluid retention in the lungs and shortness of breath—known as congestive heart failure. The primary source of heart failure is coronary artery disease (CAD). CAD is the narrowing of the arteries. The resting coronary blood flow for a person is approximately 225 ml min^{-1}. During CAD, the rate of blood flow is depleted. CAD is also a major cause of myocardial infarction or heart attacks. This is due to the fact that the heart continuously has the desire to contract. Unfortunately, the heart does not get a full contraction, adequate volumes of blood do not reach the body and oxygen deprivation occurs. During a heart attack, irreversible death of the heart muscle develops if blood flow is not restored within 20–40 min. The muscle continuously dies for hours at a time and is replaced by scar tissue.

IOP Concise Physics

Biophysics of the Senses

Tennille D Presley

Chapter 7

The human mind

7.1 What is a neuron?

The human mind is often related to the organ that makes up nearly 2% of the body's weight, the brain; however, the human mind is influenced by other organs in the body in addition to the brain. Have you ever wondered why when you smell food, you desire it or if you see something on television, you want to go and buy it? When the mind is impassable, it is similar to a closed circuit where the flow continues and there is no entry way without completely disrupting the normal flow. The mind is best represented by Newton's third law of motion which states: '*For every action, there is an equal–opposite reaction*'. When you exercise the brain, the brain will react and become stronger.

A neuron is a large nerve cell that receives and transfers information from one part of the brain to the other. It entails a cell body and two types of extensions. These extensions are axons and dendrites; the axons normally transmit signals away from the cell body, whereas the dendrites transport signals toward the cell body. Axons have a smooth surface and there is only one axon per cell. These long nerve processes end at synapses. On the other hand, dendrites are smaller, more abundant than axons, and have many synapses to receive messages from surrounding neurons. Dendrites typically have more branches and have a rough surface. Axons and dendrites are bundled to comprise nerves. Nerves transport signals between the brain, spinal cord, and other parts of the body through nerve impulses. These nerves function for thinking, muscle movement, and to relay information to and from the senses. The cell body entails the cell membrane, the nucleus of the cell, and controls the rate at which the electric signals travel through the neurons.

The brain houses nearly 100 billion neurons, and the central nervous system (CNS) contains roughly the same amount. There are different types of neurons. Neurons are considered as motor neurons or sensory neurons. Motor neurons are responsible for conveying information from the CNS to glands, muscles, and organs throughout the body. For instance if you are ready to leave your home, your motor

doi:10.1088/978-1-6817-4111-6ch7

neurons tell you to move your legs, to walk to the door, and turn the doorknob to exit. On the other hand, sensory neurons receive information from external stimuli or internal organs and transfer that information to the CNS. They are motivated by temperature, pain, light, and sound, where these interactions are communicated to the brain. If you are outdoors and it is 20 °F, your sensory neurons will send the message to your CNS to let you know that you feel cold. Interneurons are the communicators between the motor and sensory neurons, and represent more than 99% of the neurons in the body. They 'bridge' the neuronal communication between the brain and the spinal cord. Changes in electrical properties trigger the transport of information along the axons and dendrites. When the terminal end of an axon receives an electrical signal, neurotransmitters are released to connect with other neurons and cells.

When functioning properly, ions migrate across the cell membrane of a neuron. Through this process, energy is transferred and a membrane potential is generated. There are instances where 4000 new neurons are created every second. These neurons eventually form networks, and become involved in the communication between the brain and the rest of the body. When a stimulus is applied, the ions move perpendicularly to the axon. This causes a change in the electric potential instigating the movement of ions through the membrane. This differs from the electrical current in wire, as its path is along the same direction as the wire.

7.2 Nerve impulses

As defined in an earlier chapter, an impulse represents the product of a force and time. When thinking of a nerve, an electrical signal travels along an axon known as a **nerve impulse**. A nerve impulse is a wave of electrical activity that travels between nerve cells. Chemical processes create electric energy in the nerve cells, and energy fields result around the body. Billions of nerve impulses of the same size migrate throughout the brain and the CNS. The frequency of the impulses regulate the intensity of each nerve signal. An electrical difference between the surrounding and the inside of the axon exists, similar to a battery. Once the nerve is activated, a change in voltage occurs across the wall of the axon and ions flow in and out of the neuron. The speed for a nerve impulse can vary depending on the type of neuron. The fastest nerve impulses can travel as rapidly as 250 miles per hour. There are nearly a billion nerve impulses in the body that regularly produce magnetic fields. An axon must be properly insulated for an impulse to migrate swiftly. Myelin is a fatty substance that provides insulation to the axon. While this utilizes a lot of energy, there are instances where a neuron may need to transfer information immediately. For example, if you are placing a dish in a hot oven and accidentally touch the oven rack, it is critical that your brain quickly receives the message that you are burning your hand and to remove your hand instantly. Alternatively, myelin may begin to degrade such as with multiple sclerosis. In multiple sclerosis, the nerves are unable to effectively carry electrical signals between the brain and the body.

There is a higher concentration of potassium ions inside the cells and sodium ions outside of the cell. Because of this, there is a tendency for the ions to diffuse from a higher concentration to a lower concentration. The potassium ions will tend to move outside of the cell and the inside of the cell becomes more electrically negative. The resting membrane potential is −70 mV. The presence of the membrane potential causes an electric force to act on the ions. Nerve signals rapidly spread along the nerve membrane by action potentials. The gray matter of the brain is responsible for collecting and conducting nerve impulses.

Electroencephalography (EEG) is used to record the ionic current flowing through the neurons. It measures the voltage changes in the electrical activity along the scalp, and the electrodes detect the electric field generated by moving charges in the connections between the neurons (synapses) in the brain. However, it is not useful for diagnosis of a headache. The brain does not have pain receptors; however, there are regions of the head and neck that do. Thus it is called a ‘headache’ and not an aching brain.

7.3 Quantum mechanics

We have explored the aspect of mechanics, but mainly focused on classical mechanics in chapter 2 and touched the surface of quantum mechanics in chapter 4; however, this aspect of physics plays a major role in the human mind. Do you ever stop to think about the things that exist, but are so small that you cannot see them with the naked eye? Quantum mechanics is an aspect of physics that studies the ‘very small’, addressing the world of atoms and light. Quantum mechanics is also important for understanding higher brain functions such as the generation of voluntary movements, and it is believed that there is a correlation between consciousness and quantum theory.

Our sense of sight is a series of events between the eye, the brain and the outside world. In general, a person rapidly moves their eyes in a coordinated fashion that activates billions of neurons in the brain. The retina in the eye has a sensitivity to small numbers of photons, which are particles of light. The photon can then interact with the quantum state of the retinal cell. Light energy is detected by the eye, and information about intensity, color and shape is transmitted to the brain. The light is converted into electrical signals and the brain interprets those signals into images. This impacts perception, which is the process by which the brain interprets and organizes sensory information. How do you feel when you listen to your favorite song or you hear something that is inspirational? Your senses allow you to pick up this sound and your sensory neurons utilize your networks to cause you to feel ‘positive energy’.

Consciousness is the state of being self-aware and having sensory experiences. It has been speculated that quantum fluctuations inside of microtubules create consciousness. Microtubules contain units of tubulin that is made up of regions where electrons spin closely to each other (though not touching), and ultimately affect each other—quantum entanglement. When conscious awareness goes below the absolute threshold, subliminal stimulation occurs. An example of this is subliminal advertising. Subliminal advertising is a hidden agenda that triggers electrical signals in your brain creating a desire and want for something that you did not ordinarily want. There is now evidence that invisible, subliminal images subconsciously attract the brain's attention. The brain can be affected by images that you are not even conscious of seeing.

7.4 Cognition and neurological disorders

Cognition is simply the thinking processes of the brain related to attention, memory, evaluation, reasoning and problem solving. Cognitive dysfunctions may cause a person to become forgetful or lose some of the normal mobility that a person naturally has. These dysfunctions may be induced by chemical activity, electrical activity or other forms of external factors. For instance, a lack of magnesium can lead to poor memory function, and a shortage of phosphate may result in mental confusion and problems with speech. Similarly, excessive levels of calcium can contribute to depression and confusion. Sleep is a way to restore the body's energy and restore memory.

Other aspects of neurological abnormalities also exist. Think of a concussion or a tremor. A concussion is the most common traumatic brain injury and occurs when a certain amount of force is applied to the skull; it leads to modifications in the normal function of the brain. A tremor is an involuntary movement of muscle contraction and relaxation. It can imply stress or overconsumption of caffeine; in some instances, it is an indicator of a neurological disorder such as traumatic brain injury, stroke or multiple sclerosis. Multiple sclerosis is an inflammatory process that is characterized by the destruction of the myelin sheaths (the protective, insulating outer coverings of the nerves) within the CNS. Symptoms of this disorder include muscle stiffness, double vision, mental confusion, and loss of memory (in severe cases).

As the brain ages, it is more prone to diseases such as dementia or Alzheimer's. Dementia is a progressive decrease in a person's intellectual ability, where the brain's ability to think, reason, and remember is significantly affected. Damage to the brain typically occurs for some time before there are any visible signs of this disease. Dementia is characterized by impaired judgement, memory loss, and drastic changes in personality. Alzheimer's disease is the most common form of dementia and is when the brain ages prematurely. A common finding of this disease is that neurons are lost where cognitive information and memory processing occurs. This disorder can lead to depression, short-term memory loss, a lack of effective communication, and urinary incontinence.

Electrical current can cause neuropathy. Electrical injury can result in neurocognitive dysfunction, potentially altering a person's memory, concentration, attention span and speed of mental processing. If the current travels through the head, loss of consciousness typically happens. Victims of electrical shock have exhibited functional differences in neural activation during spatial working memory and implicit learning ocular tasks.

7.5 Networks and regulatory control

In our current era, we are amongst many venues of social media from Facebook to Twitter to Instagram, just to name a few. These popular mechanisms have developed a way for people to connect and reconnect. As a person connects with another, it is possible to see other people that each of them are connected with. Networks are established, which is very similar to how the networks in the body exists. The web is a perfect analogy of the body because it has a plethora of networks that exists to provide function and communication. The brain is the central conduit for regulating all of the networks of the body. It is through these networks that we move, breath, smell, feel, see and hear. Without the brain, none of the networks in the body will work.

Within the suprachiasmatic nucleus (SCN) of the brain, a master circadian clock exists that aids in directing the body to sleep at night and to be awake during the day. Containing nearly 20 000 nerve cells, the SCN contributes to regulating temperature and hormone levels in the body. Circadian rhythms are naturally produced, but they are affected by environmental factors such as light and darkness from the eyes to the SCN. This internal clock helps the body to 'harmonize' with a 24 h day. Additional time cues such as meal and exercise schedules can affect the timing of the clock. As a person ages, circadian rhythms may change. Disorders in the circadian rhythm can result in insomnia, depression, bipolar disorder and impaired work performance. Circadian rhythms can be impacted by melatonin, which is created by the pineal gland in the brain. A benefit to the circadian clock is that the timing of a medical treatment in coordination with the body's clock can potentially decrease drug toxicity while enhancing efficacy.

Electroconvulsive therapy (ECT) is a technique that involves an intentional seizure being triggered by electric currents that are transmitted through the brain. ECT triggers modifications in brain chemistry, and is often successful when other treatments are not. It is used to treat severe depression, severe mania or even aggression in people with dementia. Although ECT is typically safe, some of the side effects of this treatment are confusion, memory loss, nausea, headaches, and vomiting. Yet, these detriments are usually short-lived.

The brain and the nervous system generate magnetic fields. Has another person ever made you feel more energized and excited, or completely drained? This is in part due to the fact that a person's electromagnetic field can influence their surroundings. In general, your senses inform your brain about variations in your surroundings. Thus, the feeling of your shoes on your feet, the sound of your fish aquarium, the sound of the computer or refrigerator humming, may often go unnoticed. Alternatively, your brain allows you to focus on things that really capture your attention and interest such as gazing into the eyes of your significant other, watching your favorite television show or being engaged in class. The brain 'illuminates' the things that are of great importance. Even before a person pays close attention to something of interest, the irrelevant, background 'noise' is filtered out. Most of the sensory neurons are unipolar, where the receptor region is housed in the peripheral nervous system to control the sense of touch, pain or temperature. Bipolar neurons are less common, but are localized in the eye, ear and nose.

As a whole, the body is full of networks that power the human mind, where the brain is the 'master regulator'. These networks work together to regulate control throughout the body, utilizing each of our senses.

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Biophysics of the Senses

Tennille D Presley

Chapter 8

Physics of nutrition, exercise, and disease

8.1 Physics of a healthy diet—sense of taste

Taste buds are 'chemoreceptors' located on the upper portion of the tongue that have the ability to detect taste. This sense involves chemical signals in foods and electrical signals within the body. The electrical signals migrate to the brain via the nervous system, informing the brain of the sense of taste. Taste buds make direct contact with the chemicals in order for us to taste; however, indirect contact with chemicals occurs for us to smell. The taste buds influence the human mind. An adult has between 3000 to 10 000 taste buds, and this value degrades with age. There are five distinct tastes: 1) salty, 2) bitter, 3) sweet, 4) sour, and 5) spicy. Each taste bud typically responds to only one of the 'distinct tastes' when there is a low concentration of a substance; however at high concentrations, most taste buds will be stimulated by practically all of the tastes. Foods that are high in calories are usually salty, sweet or savory. Acidic foods ($pH < 7$) are typically sour or bitter. The average person uses roughly 2000 calories each day in food. The accumulation of a radical can often shift a substance from sweet to bitter. Acidic foods tend to taste sour, whereas basic foods have a bitter taste. An acidic fluid that exhibits benefits of health is apple cider vinegar. It has been shown to attenuate blood pressure, augment weight loss, and combat disease.

One of the major facets of 'dieting' is to count the calories. In chapter 3, the concept of the calorie was introduced and we identified that 1 calorie = 1 kilocalorie. As we read food labels and identified the amount of 'calories', the reality is that these are actually 'kilocalories'. For example, the popular '100 calorie' snacks are really 100 000 calorie snacks. When we eat, the body turns the food into energy. The major sources of energy in foods are carbohydrates, proteins and fats. One gram of carbohydrates is equivalent to 4 calories, 1 gram of protein is equal to 4 calories and 1 gram of fat contains 9 calories. The amount of energy that is gained from a food can be quantified by multiplying each one of these constants by the amount (in grams) of fats, carbohydrates and proteins that are contained in the food that will be

doi:10.1088/978-1-6817-4111-6CH008

consumed. Having a grasp of these calculations aids in properly reading and understanding food labels. Starvation or a low-restrictive diet can cause a 20–30% decline in a person's basal metabolic rate. In chapter 4, the components of an atom were discussed. In a situation where there are the same number of protons but a different number of neutrons, an isotope exists. Stable isotopes can be used for examining the flow of nutrients through the body. The standard isotopes are calcium, iron, magnesium and zinc. When your body craves certain foods, it is often implying that the body is deficient in what it is craving.

Since water lacks calories, it is an easy way to manage daily caloric intake and maintain a healthy diet. It should be the main source of hydration and a major contributor to managing daily weight gain. As we age, the body composition of water becomes depleted. For instance, a newborn's body is comprised of nearly 75% of water; however, the body of an elderly person is made up of 50% water. If the body contains more fat, it contains less water. Yet, having more muscle means more water. In addition, the fundamental organs of the body have different amounts of water. The brain, heart, liver and kidneys are mainly water, comprising between 65–85%, whereas the bones are made up of approximately 30% water.

We produce more free radicals when consuming fatty foods. To reverse this effect, dietary nitrates have been shown to be advantageous. Vegetable consumption accounts for 80% of dietary nitrates. These vegetables include spinach, celery, carrots, and beets. Dietary nitrates account for half of the steady state concentration of nitric oxide, and aid in reducing blood pressure, improving intestinal health, and exercise performance. Specifically, beet juice contains high levels of nitrates and has been shown to enhance the exercise capacity of younger and older adults, as well as individuals with chronic obstructive pulmonary disease (COPD). Nuts have similar effects to dietary nitrates as they are a great source of antioxidants, specifically vitamin E; they protect against cognitive decline. Likewise, blueberries and avocados promote healthy blood flow and inhibit oxidative stress.

The foods that a person consumes can be compared to a running capacitor versus a starting capacitor. A starting capacitor will help with starting a motor and then it is no longer a part of the circuit. However, a running capacitor has to be a part of the circuit at all times. In the body, the heart and the brain are the running capacitors because both play vital roles in regulating control in the body. However, an energy drink or foods can act as starting capacitors to get the body going, and then the body can function. It is possible to see a decline in capacitance from weight loss. The body can survive without food for nearly three weeks on average, but water is necessary at least every three to four days.

8.2 Exercise

It is no secret that regular physical activity is important for both mental and physical health. It is believed that high intensity interval training allows your metabolic rate to be active throughout the day, while cardio training is only within that particular instance. The concept of work 'conservation' is key with exercising. We know that work is defined as a product of work and displacement. The aspect of simple machines expands the concept of work by denoting that *the amount of work into a system is equivalent to the amount of work out of a system*. Thus,

$$\text{Work input} = \text{Work output}$$
$$(\text{Force})_{\text{in}}(\text{distance})_{\text{in}} = (\text{Force})_{\text{out}}(\text{distance})_{\text{out}}$$

In chapter 2, how the muscles and joints function as a lever was discussed. A lever is a simple machine—simple machines are defined as a device for modifying the direction of force, where some examples include levers, pulleys, and wheels and axles. The underlying principle to simple machines is the conservation of energy. Depending on the type of exercise you carry out determines which type of simple machine is relevant. For example, the lever is a perfect example of how resistance and weight training is performed.

When lifting heavy weights, a person should lift the weight close to their body to lessen the torque generated around the lower spine. Resistance training provides continuous tension on the muscles, working them under a constant load. Each time a person lifts weights, they are lifting with an upward force that opposes the force of gravity. The major advantage that resistance bands have compared to free weights is that the bands' resistance is not dependent on gravity. Because of this, it is possible to have more functional movement patterns and a better range of motion that mimic daily activities.

Exercise boosts energy, promotes better sleep and weight loss, and improves mood. The pedometer is a useful tool because it allows an individual to count their number of steps on a day-to-day basis. As highlighted in table 8.1, there are a number of daily activities that can burn calories. For example, going to the grocery store can burn up to 200 calories depending on the amount of time you spend in the store, and how much you 'squat' to pick up items. Cleaning the house can also be beneficial to your health, especially if you decide to mop the floor, which can burn up to 400 calories.

The way that a person floats in water is dependent upon the force of gravity and the buoyant force. Buoyancy is the apparent loss of weight of an object submerged in a fluid. The buoyancy of water decreases a person's body weight by nearly 90%.

Table 8.1. List of daily activities and the amount of calories each burns.

Activity	Number of calories burned
Gardening	600 *calories*
Sleeping (for 8 h)	350 *calories*
Aerobic dancing (1 h)	300 *calories*
Mopping the Floor	400 *calories*
Mowing the Lawn	300 *calories*
Grocery shopping	200 *calories*
Ironing for 30 min	75 *calories*
30 min of kissing	36 *calories*

When a person floats, it means that their buoyant force and gravitational force are equal, yet opposite to each other. Swimming is a great exercise that incorporates the concept of buoyancy, and is a full-body workout. It is very beneficial as it is low impact, provides a natural resistance and promotes cardiovascular health. For example, a normal heart rate ranges between 60–100 bpm; however, this rate is significantly reduced to 17 bpm when swimming.

One of the latest trends is the hamster-wheel desk. This is the best motto of ‘exercise while you work’. People are very consumed with work on a day-to-day basis; however, this new invention provides the opportunity to exercise while working. The advantage to this wheel versus a treadmill is that you can easily set your own pace while you work or to stand still. As the wheel rotates in a vertical circle, the centripetal force acts and the person walks at a slight angle with each step.

We learned in chapter 3 that heat is a measure of energy in transit. Over the last several decades, studies have shown how the appropriate exposure to heat, with the optimum temperature can provide beneficial effects to the body. Hyperthermia or heat shock is when the body is exposed to an elevated, non-physiologic temperature for a short period of time. The temperature of the surrounding environment is increased; however, the body’s core temperature typically remains physiologic. Hyperthermia has been suggested as an alternative for individuals who are unable to adequately exercise. Other advantages of heat shock include increased thermotolerance, decreases in ROS, and improvements in the prevalence of both nitric oxide and heat shock proteins (hsps). Hsps are intracellular soluble proteins that act as chaperones to ensure that cells maintain the right shape and position. Named on the basis of their molecular weight, hsps are also cardioprotective. A key benefit of acute heat is that it overexpresses heat shock proteins, which are proteins that aid in cardioprotection. Heat acclimation is exercising in heat (~40–43 °C) for a brief period of time. The advantages include a better regulation of blood pressure, increases in nitric oxide and an improved exercise performance. The time of duration for this process is critical and is most commonly observed in individuals that are considered to be elite athletes. In each instance of both hyperthermia and heat acclimation, it is important that the body acquired lots of fluids to avoid dehydration.

Hot yoga is when numerous yoga styles are used in the presence of heat to enhance a person’s flexibility in the poses. Depending on the pose, specific parts of the body are lengthened, while other parts of the body are contracted to maintain stability. Due to the heat, the poses are usually easier and detoxification happens. Yoga is also known to improve brain function, lower stress levels, and decrease blood pressure and risk of heart disease. Throughout this text, we have been discussing force. In the event that a force is *too great* or an object is overly stretched, a fracture will occur. When something is stretched beyond its limit, permanent deformation results.

When strenuous activity or overexertion occurs, normal body functions are compromised and inadequate levels of electrolytes are present. Gatorade has electrolytes in their drink that can be useful when this deficiency transpires. The electrolytes can improve an athlete’s physical performance and endurance.

Supplements of nitric oxide are also known to be beneficial in improving exercise performance. Distance runners and elite athletes typically do not handle gravitational forces as well as a person who is not as physically fit. This is because individuals who are fit tend to have a lower blood pressure and the blood vessels are often more flexible. Elastic arteries can establish less of a pressure difference, and store blood. Thus, less blood is forced to flow through the body.

Iron is of great importance for athletic performance. It is needed for oxygen transport, energy production and cell division. A deficiency in iron can cause anemia and poor oxygen delivery to the muscles that are being exercised. Alternatively, cell and tissue injury results when there is too much iron. When there is an excessive amount of iron, the hydroxyl radical is formed.

8.3 Impact of disease

Biophysics is heavily related to disease diagnosis and treatment. The aspects that have been discussed such as mechanics, electrical activity, free radicals and energy all relate to many of the diseases that currently dominate and impact the world. For instance, the microcirculation in both sickle cell disease and diabetes is impaired. During sickle cell disease (SCD), the mechanics of normal blood flow is dysfunctional. Anemia happens when there is a decline in hemoglobin. Typically, a red blood cell is flexible and can readily pass through the blood vessels and the capillaries. However, with SCD, the red blood cells are rigid and less deformable, causing painful episodes, oxygen deprivation and organ damage. To study this, researchers have utilized microfluidics. If polymerization occurs at a slow rate, the red blood cells can remain flexible and continue through normal circulation. However, polymerization at an 'intermediate speed' can be fatal. There is the likelihood that the cells will become rigid and get stuck in the vessel and cause obstructions in flow. In general, fluidics is important for gas exchange from the atmosphere and occurs through the nose, so that the cilia can act like a mechanical filter for impurities.

Type II diabetes is a major cause of death that is characterized by excessive glucose (hyperglycemia), insulin resistance, and vascular dysfunction. Each of these detrimental effects creates chaos amongst the senses of the body, from blurred vision to hearing loss. Similar to sickle cell disease, poor microcirculation due to decreased red cell deformability exists. Disorder in circadian rhythms and nerve pain have also been associated with diabetes. This disease can be controlled by diet and exercise. It is also believed that the probability of acquiring diabetes increases with age. The free radical theory of aging suggests that antioxidants will impede the process of aging by preventing free radicals from oxidizing sensitive biological molecules or reducing the formation of free radicals.

Whether it is the mechanics of the networks throughout the body or complete chaos due to excessive free radicals, an adequate appreciation of biophysics is key to maintaining the normal function of the senses of the body. As a whole, the fundamental components of physics aid in our understanding of overall, efficient health.

IOP Concise Physics

Biophysics of the Senses

Tennille D Presley

Appendix

Further Reading

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