The Physics of Electrocution

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Section H2

Introduction

The field of physics encompasses a broad area of knowledge, and thus has far reaching effects. The physiology of the human body is one such topic. With approximately 1,000 people dying each year in the United States due to electrocution and approximately 3,000 patients who survive being admitted to specialized burn units (Spies), understanding both the physics behind electricity and its effects on human physiology is a worthwhile undertaking. Electrical injuries can be very complex so recognizing the mechanisms involved requires a firm comprehension of how electricity works, how the electrical components of the body work in a normal state, and how outside sources of electricity affect change the ordinary physiology.

Electricity

Just like water flows from a region of higher pressure to a region of lower pressure, electrons flow across a potential gradient from high electron concentration to low concentration (Spies). This is called electricity. The potential difference created is represented by volts (V) and is the driving force of the electrons. The amount of electrons flowing, or the volume, is known as the current. The amount of current is designated by amperes. Resistance (R) is defined as any impedance to flow. All of these concepts are related using Ohm's law. Ohm's law. Ohm's law says that the amount of current is equal to the ratio of the voltage and resistance (Kuphaldt):

$$I = \frac{V}{R}$$

There are two designated types of current: alternating current (AC) and direct current (DC) (Jain). DC currents are those in which electricity moves in a continuous direction around a circuit (Kuphaldt). Examples of items that utilize or produce DC current are batteries, car electrical systems, high-tension power lines, and lightning (Spies). AC currents are those used by most power systems, including households. Unlike DC, where the current moves only in one direction, in AC current the direction of flow changes rapidly in a cyclic manner. In a standard US household electric set-up, the current of 110 V flows at 60 cycles per second. The cycles per second is represented by Hertz (Hz).

Human Physiology

The body has its own electrical system. As a whole, the body is considered a conducting dielectric (Lee). Consisting of approximately 60% water, the fluids in intracellular and extracellular compartments are extremely electrolytic (Bier). A highly resistive plasma membrane separates these two regions, creating a potential gradient. Current in the body's tissues is carried by ions in the fluids, providing a conductivity of 1.4 Sm^{-1}.

The varying organs of the body provide different resistivities, which vary from 100 ohms/cm for vascular tissue, 900 ohms/cm for bone, all the way to 5,000 ohms for fat (Matthews). As a whole though, the whole body has an average uniform density of 100 ohms/cm and a dielectric constant of 80 due to the salinity of the internal fluids. Figure 1 shows the differing resistivities of varying sites on the body.

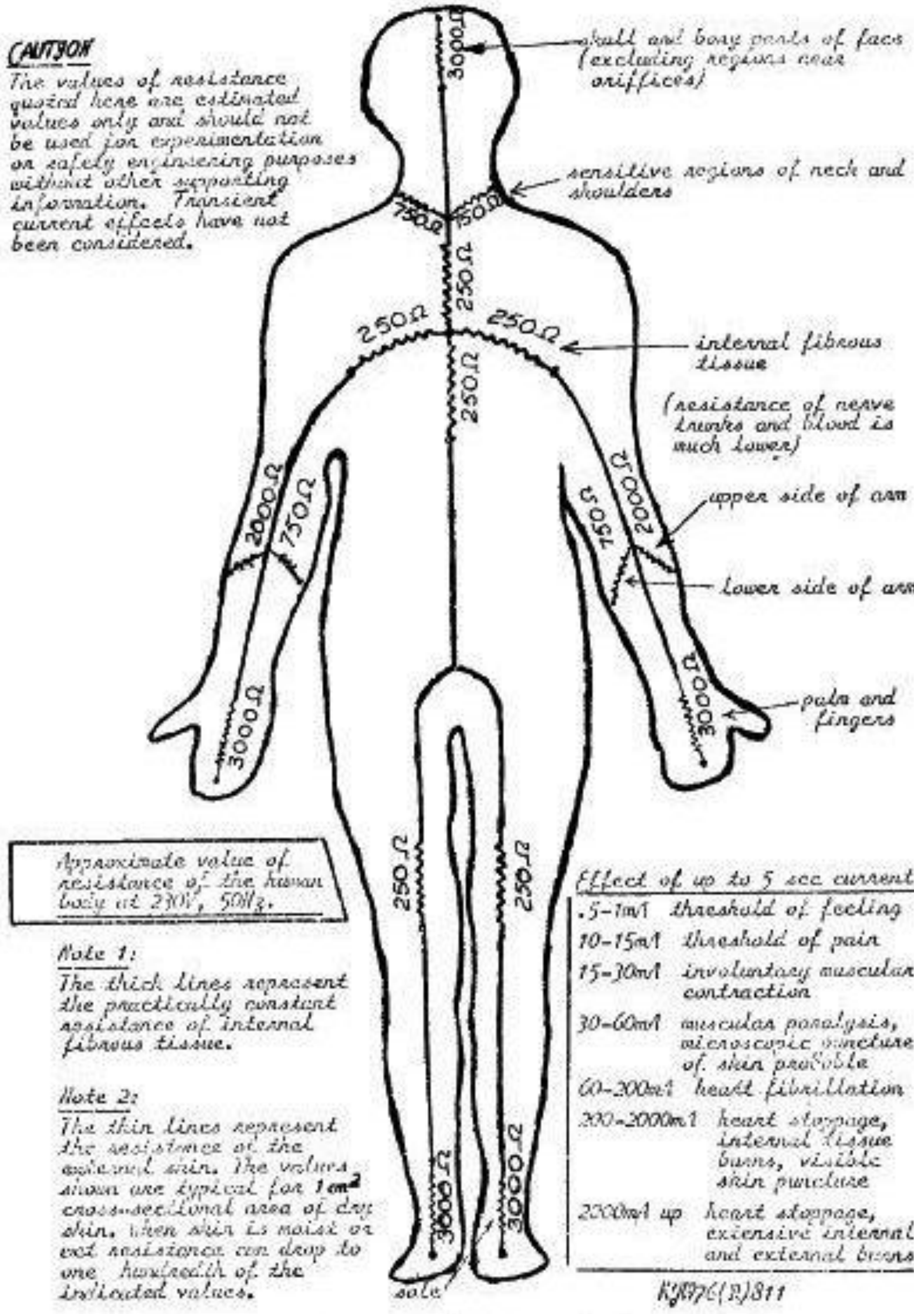

Figure 1 (Matthews)

The body's electrical system is important for normal functioning. For example, the most significant aspect as related to potential hazards due to electrocution is the nervous system (Kuphaldt). The nervous system is a network of specialized cells called neurons that process and carry out actions directed by signals responsible for body function. The organs of the nervous system include the brain, spinal cord, and all the sensory and motor organs. The communication between neurons is achieved by creating electrical signals in response to stimulation by chemical compounds known as neurotransmitters or by releasing neurotransmitters in response to these tiny electrical impulses. These actions are what cause the fingers to move, the heart to beat, the diaphragm to contract, and every other vital action of the body.

Physiological Effects of Electrocution

Thermal Injuries

The main cause of damage due to electrocution is related to the amount of current that flows through the body (Spies). This can cause fatal heart arrhythmias or apnea, the cessation of breathing. When electricity is applied to tissues which have high resistivity, such as the skin, bones, and fat, they tend to increase in temperature and coalesce. Joule's law describes the amount of thermal energy that develops due to electricity. Thermal energy leading to tissue damage is related to the squared function of current, resistance, and time:

$$Energy\ (thermal) = I^2 \times R \times T.$$

As shown in *Figure 1* applying electricity to different areas of the body will have different effects, due to the variations in resistance. Other factors which may change the amount of thermal energy due to resistance include water. Dry skin, which has a higher resistivity than wet skin, may experience great external damage, but will limit the conduction of current to internal structures. Wet skin allows the current to pass through into the body, causing extensive injuries to internal organs. The amount of voltage also has an effect on thermal injuries. Higher voltage injuries may cause more internal damage then external damage, thus an injury may be much more severe than it looks. Estimates show that 20 to 35 mA per mm^2 for a period of 20 seconds can raise skin temperature to 50ºC (122ºF), a temperature which can cause first-degree burns with skin swelling and blistering (Jain). Increasing the current to 75 mA per mm^2 raises skin temperature to 90ºC (194ºF). Temperatures of this magnitude can cause charring and perforation of skin.

The most severe electro-thermal injuries (injuries due to the conversion of the electrical current to heat energy) occur in the bones (Spies). Electrocution can destroy the very matrix of the bones. This is because bones retain heat longer than muscles (Jain). Bone damage may also be caused due to electrically induced skeletal muscle contractions that are so forceful as to either break the bones or cause a fall that can dislocate or fracture them.

Muscular Injuries

Inside the body, if the current is of adequate magnitude, it will override the body's own electrical system (Kuphaldt). This prevents the nervous system from sending proper reflex signals. Skeletal muscles may involuntary contract due to the outside electrical signal. If a person receives an electric shock by grasping a wire, muscular contraction will cause him to hold the wire more tightly. This immobilization is referred to as tetanus and can only by resolved by stopping the current. Tasers and other similar devices use this concept to immobilize a person by delivering a high-voltage pulse between two electrodes.

Because of this response, AC is three times more dangerous than DC of a similar voltage (Jain). Because the current travels in one direction, shock from DC causes a single muscle contraction. In this instance, the person is thrown away from the source of contact. AC however, causes repetitive stimulation, resulting in muscular contractions which can induce tetanus. The amount of AC required to cause these types of injuries increases proportionally to frequency. 20 to 30 mA can cause tetanus of respiratory muscles. 50 to 150 mA can cause heart arrhythmias. *Table 1* describes the type and amount of current require to produce different types of injuries.

Table 1: Physiological Effects Due to Electrical Current			
Bodily Effect	**Direct Current (DC)**	**60 Hz AC**	**10 kHz AC**
Slight sensation felt at hand(s)	Men = 1.0 mA Women = 0.6 mA	0.4 mA 0.3 mA	7 mA 5 mA
Threshold of perception	Men = 5.2 mA Women – 3.5 mA	1 mA 0.7 mA	12 mA 8 mA
Painful, but voluntary muscle control maintained	Men = 62 mA Women = 41 mA	9 mA 6 mA	55 mA 37 mA
Painful, unable to let go of wires	Men = 76 mA Women = 51 mA	16 mA 10.5 mA	75 mA 50 mA
Severe pain, difficulty breathing	Men = 90 mA Women = 60 mA	23 mA 15 mA	94 mA 63 mA
Possible heart fibrillation after 3 seconds	Men = 500 mA Women = 500 mA	100 mA 100 mA	

Cardiovascular Injuries

Other muscles affected by electric current include the heart and the diaphragm, the organ response for controlling the lungs. Tetanus of these muscles for an extended period of time can cause death. Electrical shocks with lower currents that cannot induce tetanus may still alter the signals from the nervous system, changing the rhythm of the heart heat. This change may last for some time after the shock, due to damage of the cardiac muscle from the conversion of the current to thermal energy (Spies). Fibrillation is a very common arrhythmia induced by electric shock, especially low-voltage alternating currents. In fibrillation, the heart beats so fast that it cannot complete a full contraction (Kuphaldt). Instead of a full beat, it flutters, and is unable to pump a sufficient amount of blood to the body. Medical professionals use a device called a defibrillator to “jump start” the heart into a normal sinus rhythm. Defibrillation works by immediately depolarizing all of the cardiac muscles simultaneously, by means of a large DC pulse (Matthews). The heart’s “pacemaker,” which is responsible for controlling the pacing of the rhythms, recovers first and hopefully restarts its normal functions. Several hundred Joules are delivered to the body within approximately 5 ms by means of discharging a capacitor from several thousand volts.

Brain Injuries

The central nervous system, made up of the brain and spinal cord, is also affected by electric shock (Spies). Loss of consciousness and memory problems are common injuries. Some patients experience a phenomenon known as Keraunoparalysis, a reversible paralysis associated with sensory disturbances and peripheral vasoconstriction. Other injuries include rupture of the ear drums, hypoxic encephalopathy (lack of oxygen to the brain, which may result in stroke), and intracerebral hemorrhage.

Treatment

Before starting any emergency procedures, turning off the power supply by opening a disconnect switch or circuit breaker is of utmost importance. The amount of voltage present across the victim's body could be of enough magnitude to also shock the rescuer.

Prognosis for patients who survive the initial shock due to electrocution is very good (Jain). Immediately, attention should be provided to the resuscitation of the respiratory and cardiac functions. CPR is recommended to reestablish breathing and heart rhythms. As mentioned before, defibrillation may be needed to return a heart to normal sinus rhythm if the patient experiences fibrillation. It is important to keep the victim still in order to prevent physiological shock (Kuphaldt). This is different from the shock due to the electrical current; physiological shock is due to insufficient blood flow.

Conclusion

Understanding the physics of electricity is valuable due to the ever present uses of electricity in a modern society. However, with the use of electricity comes the dangers inherent in it. Knowledge of the human body and its own electrical system is important for determining a baseline understanding of what is normal. Concepts of physics can then be applied to better know the physiological changes due to electrical shock.

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