CLINICS IN PHYSICAL THERAPY

ELECTROTHERAPY

Edited by

STEVEN L. WOLF

CHURCHILL LIVINGSTONE

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Preface

For the past quarter of a century, physical therapists have been taught that electrical stimulation can have profound effects upon a variety of physiological processes. Yet, until recently, clinicians have viewed the application of electrical stimuli to enhance function, ameliorate pain, or assess neural integrity with a precarious blend of appreciation and confusion. The appreciation apparently stems from an undefined recognition that precisely controlled applications of electricity can positively compliment the "laying on of hands" to benefit recipients of physical therapeutic interventions. The confusion probably evolves from a poor comprehension of the electrophysiological principles underlying the administration of electrotherapeutic and evaluative modalities and perhaps even a consequential fear of many things electric.

Accompanying these perceptions has been the unquestionable onslaught of higher technological advances which, to a large extent, have had an impact upon contemporary medicoelectrical instrumentation. For example, electrical stimulation to evoke spinal or cortical responses for examining central nervous system pathology or assessing the effectiveness of therapeutic treatment was once thought to lie within the domain of a select group of electrophysiologists. Certainly, evoked spinal or cerebral potentials are today very much within the scope of physical rehabilitation clinicians. Transcutaneous electrical nerve stimulation, once used to assess pain perception preceding or following implants designed to modulate pain perception, is a modality now commonly employed by the physical therapist.

We find ourselves in the unique position of actively participating in the use of modern electrotherapeutic equipment. If the feeling that such instrumentation is too complex to be adequately understood and used persists among physical therapy clinicians, then the opportunity to actively participate in the application of recent technical advances will quickly pass us by. This text was written because its contributors felt a commitment to updating our knowledge base in electrotherapy in light of the limited contemporary resources available on the subject. More significant, however, is the common feeling that the information can be presented with considerable documentation and in a thought-provoking manner. Our intent is not to present "cook-book" approaches to the use of electrotherapeutic devices and procedures, although adequate instruction is provided. Our contention is that the clinician should be given the opportunity to understand and think about the principles underlying electrotherapy.

Much of the content is new and does not appear in other texts and monographs on electrotherapy. This notion is particularly true for the chapters provided by Lucinda Baker and Don Lehmkuhl on functional electrical stimulation and evoked potentials, respectively. While most clinicians are familiar with these two concepts, the discussions contained herein are presented with sufficient clarity and detail to enable the reader to gain rapid comprehension *and* to pursue further practical applications.

Stuart Binder has offered a detailed explanation of basic electrophysiological principles and has updated the existing literature on low- and high-voltage stimulation devices. Of particular value in his contribution is an attempt to offer mechanistic explanations for the physiological action of various electrical stimuli. The rekindled interest among clinicians in iontophoresis is addressed by Donna Boone, who provides a detailed historical perspective on this technique and its multifaceted uses.

Dean Currier and John Echternach are acknowledged within the physical therapy community as two of our most outstanding experts in electromyographic and nerve conduction velocity assessments, respectively. Within this text each blends an explanation of technique with comprehensive overviews of essential physiology. The numerous applications for transcutaneous electrical nerve stimulation that are rapidly gaining acceptance among physical therapists are discussed in considerable detail by two superb proponents of this modality, Meryl Gersh and Joe Santiesteban.

Collectively these contributors provide the most contemporary knowledge available in the area of electrotherapy by combining applications and principles in a cohesive manner. Many components within this text may appear to overlap. For example, electrophysiological events are discussed by several authors. Such presentations are quite intentional for two reasons. First, should the reader choose to use this text as a reference or resource book, sufficient but comprehensive information can be obtained within any one chapter, independent of all others. Second, and more important, should the reader select this text as a comprehensive study guide to electrotherapy, presentation of electrophysiological principles from different perspectives will help to identify and reinforce essential concepts necessary to comprehend all existing and many future advances in electrotherapeutic modalities.

In either case, this text is provided in the hope that more physical therapists will pursue an active participation in the use of electrotherapeutic equipment and the multiple benefits that such instrumentation can yield for the assessment and treatment of rehabilitation patients.

Steven L. Wolf, Ph.D., R.P.T.

Contents

1 Applications of Low- and High-Voltage Electrotherapeutic Currents

Stuart A. Binder

ELECTROPHYSIOLOGIC PRINCIPLES

Electrical currents passed through a biologic system can produce thermal, physiochemical, and physiologic effects. To understand the mechanism of action whereby electrical currents produce these effects, some of the basic terminology and concepts of electricity are reviewed. Next, the characteristics of high- and low-voltage therapeutic current are outlined. Finally, the relationship of the thermal, physiochemical, and physiologic effects of electrotherapeutics to the specific characteristics of clinically used currents will be discussed.

Electrical current is the flow of electrons through a conducting medium as the result of an electromotive force or potential placed across the ends of the conducting pathway. The *ampere* (A) is the unit of measure of current flow: One ampere of current flow is equal to a rate of flow of electrons of 1 coulomb (C)/s. In electrotherapeutics, we usually deal with milliamperes (mA) or thousandths of amperes. The flow of current produces the desired and unwanted effects of electricity on biologic tissue. Therefore, when we talk about the characteristics of the stimulus being used in electrotherapeutics, we are primarily concerned with the current waveform. The rate of current flow depends on two factors: the electromotive force driving the electrons and the amount of resistance offered by the conductor.

Resistance is the property inherent in any material, which opposes an electrical current. The unit of resistance is the *ohm.* One ohm is equivalent to the resistance offered by a column of mercury 106.3 cm long and 1 mm^2 in cross-sectional area at 0 °C.

The material of the conductor(s), length, cross-sectional area, and temperature all determine the resistance of a pathway. For any given material, the availability of free electrons to conduct a current determines the resistance of the material. The greater the number of free electrons, the lower its resistance. Rubber, a material whose electrons are bound closely to their nuclei, has few free electrons and is thus a poor conductor of electricity. Rubber is an insulator. Metals are examples of good conductors. Increasing the length of a pathway increases that pathway's resistance. Increasing the cross-sectional area of a conductor provides more room for the electrodes to move through, thus decreasing resistance. Increasing the temperature of most materials increases the random movement of electrons, which tends to impede the flow of electrons thus increasing resistance. An exception to this thermal effect is seen in some semiconductors. To minimize resistance: the resistance of each part of the current pathway, particularly the skin and the skin-electrode interface must be minimized; the shortest pathway of electron flow must be used; and the largest electrodes that selectively excite the desired tissue must be used.

The terms *electromotive force* (*EMF*), *potential difference,* and *voltage* are often used interchangeably. The EMF is produced by the difference in charge (potential) between two points due to an imbalance in the electron population at the two points. The unit of potential difference is the *volt* (V), defined as that EMF which, when applied to a conductor with a resistance of 1 ohm, produces a current of 1 A.

The relationship of the above three factors—voltage, resistance and current flow—is stated in *Ohm's law:* "The current in an electrical circuit is directly proportional to the voltage and inversely proportional to the resistance."

The formula expressing Ohm's law is:

$$I = V/R$$

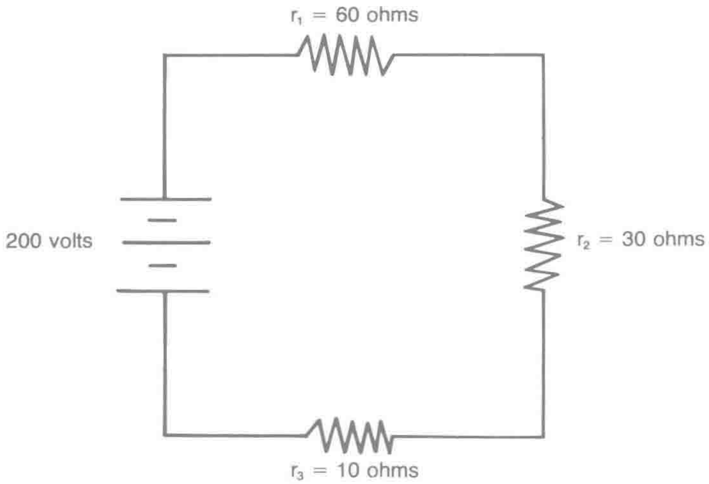
where:

I = current flow measured in amperes
V = voltage measured in volts
R = resistance measured in ohms

Current flow can be altered by changing the applied voltage or the resistance of the circuit. For example, suppose that a piece of electrotherapeutic equipment is designed to provide a constant voltage output; that is, the current varies with resistance. What would be the difference in the observed response if a high impedance produced by poor skin preparation or inadequate moistening of canvas-type electrodes was compared to an identical arrangement employing adequate skin and electrode preparation? More voltage would be required to produce an identical muscle response when the high impedance electrodes were used. The higher resistances offered by the dead skin, superficial oils, and air-electrode interface of the poorly prepared electrode would inversely affect the current flow, with less current flowing through the properly prepared electrodes. At any given voltage, less recruitment of motor nerves would be observed.

In addition to greater voltages, increased discomfort would be reported when the poorly prepared electrodes are used. With poor skin preparation, essentially a mosaic pattern of areas of widely varying resistances would be observed. These wide variations in resistance would produce discrete areas of high and low current flow. The areas of low resistance, due to relatively high moisture and low skin resistance, would show an exceptionally high density of current flow. This high current flow may produce chemical as well as electrical excitation of the nociceptive nerve endings resulting in pain. On the other hand, relatively little current will pass through the areas of high resistance producing relatively little excitation of motor or sensory nerves.

The way the component parts of an electrical circuit are connected to each other may be described as being either in *series* or in *parallel.* Figure 1-1 shows a series circuit. For a series circuit the current flow has only one pathway. Thus the current flow through each component is equal and the total resistance is equal to



a) the total resistance equals

$R_t = r_1 + r_2 + r_3$

$R_t = 60 + 30 + 10$

$R_t = 100$ ohms

b) the current flow through each component equals

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

$I = \frac{200 \text{ volts}}{100 \text{ ohms}}$

$I = 2$ amperes

c) the voltage drop across each resistor equals

$v_1 = I\, r_1$

$v_1 = 2$ amperes $\times$ 60 ohms

$v_1 = 120$ volts

$v_2 = I\, r_2$

$v_2 = 2$ amperes $\times$ 30 ohms

$v_2 = 60$ volts

$v_3 = I\, r_3$

$v_3 = 2$ amperes $\times$ 10 ohms

$v_3 = 20$ volts

Fig. 1-1. Series circuit. Calculations of (a) total resistance, (b) current flow, and (c) voltage drop across each resistor.

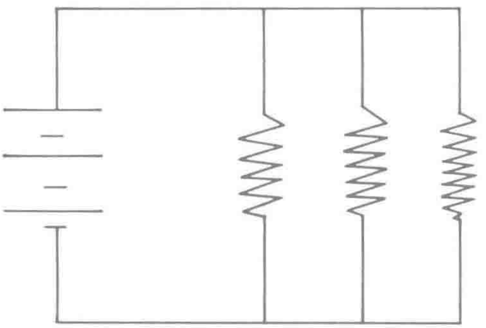
the sum of the individual resistances. Since the current flow is equal through each resistor we note that the voltage drop across each resistor is proportional to its resistances.

For a parallel circuit (Fig. 1-2) the current is provided with alternative pathways to travel. The current flow will take the pathway of least resistance. Thus, the current flow in each of the parallel pathways is inversely proportional to the resistance of the pathway. The voltage drop across each of the pathways is the same while the total resistance is less than any of the individual resistances. Connecting resistances in parallel has the effect of increasing the cross sectional area of the conductor.

Most clinical devices for electrotherapeutics will possess a combination of series and parallel circuits. As an example, if electrodes are placed across an extremity, all of the current will need to pass through the skin immediately under each electrode. This can be considered the series component.

Once the current passes through the skin, various alternative pathways are encountered—fat, blood, muscle, bone, fascia. These are the parallel components. In general, we can correlate the conductivity of biologic tissue to its water content. Muscle and blood are good conductors, fat and bone are poor conductors. Thus, the greatest current flow will be through blood and muscle, and the least through fat and bone.

The characteristics of electrotherapeutic currents include their direction, pulse shape, duration, and amplitude. In direct current (DC), there is a constant flow of electrons in one direction; that is, the polarity of the electrodes are kept



$r_1 = 60$ ohms

$r_2 = 30$ ohms

$r_3 = 10$ ohms

(a) the total resistance equals

$$\frac{1}{R_t} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}$$

$$\frac{1}{R_t} = \frac{1}{60} + \frac{1}{30} + \frac{1}{10}$$

$$\frac{1}{R_t} = \frac{9}{60}$$

$$R_t = 6.67 \text{ ohms}$$

(b) the current flow equals

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

$$I = \frac{200 \text{ volts}}{6.67 \text{ ohms}}$$

$$I = 30 \text{ amperes}$$

(c) the current flow across each resistor equals

$$i_1 = \frac{V}{r_1}$$

$$i_1 = \frac{200}{60} = 3.33 \text{ amperes}$$

$$i_2 = \frac{V}{r_2}$$

$$i_2 = \frac{200}{30} = 6.67 \text{ amperes}$$

$$i_3 = \frac{V}{r_3}$$

$$i_3 = \frac{200}{10} = 20 \text{ amperes}$$

(note identical voltage drop across each resistor)

Fig. 1-2. Parallel circuit. Calculations of (*a*) total effective resistance, (*b*) current flow through total circuit, (*c*) current flow through each resistor.

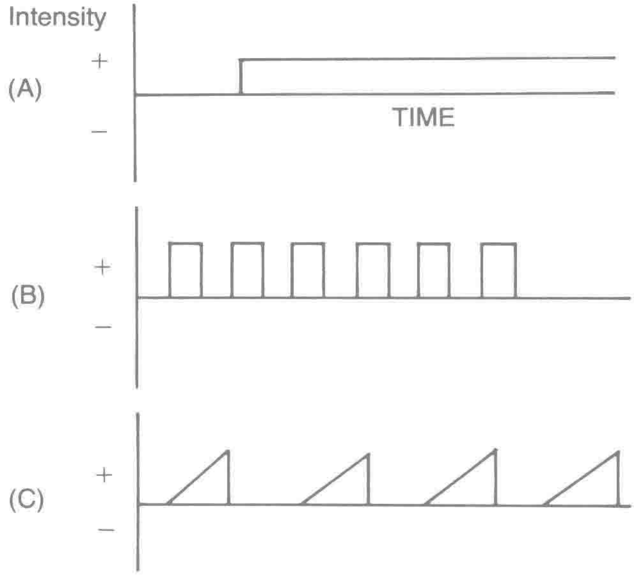


Fig. 1-3. Direct current. (*A*) continuous, (*B*) interrupted, (*C*) sawtooth waveform. Ordinate is current intensity and abscissa is time for (A)–(C).

constant (Fig. 1-3). A modification of the DC is pulsed or interrupted DC. In the interrupted DC the direction of current flow never reverses though the magnitude of current flow is not held constant. Figure 1-4 shows examples of alternating currents (AC). In an AC, the magnitude of the flow of electrons constantly changes and the direction of flow reverses periodically. Since there is a constant reversal of the polarity of the electrodes, we never speak of a positive or a negative pole.

The configuration of the pulse shape of both alternating and direct currents can take on many forms. In electrotherapeutics, that characteristic of the pulse shape with which we are most concerned is the rate of rise of the current. We can have a nearly immediate or rapid rise in the application of the current (Figs. 1-3A and B and 1-4B and C), or we can have a slow rise in the current (Figs. 1-3C and 1-4A). The rate of rise of the currents directly effects the current's ability to excite nervous tissue.

The *duration of the current flow* is the period of time the current flows for each individual wave or pulse. This time period can vary from microseconds for interrupted DC or AC to minutes for an uninterrupted DC. The duration of current flow can be manipulated to selectively recruit specific nerve or muscle fibers.

The *amplitude* of the current flow is the magnitude of the current. The *peak current* is the maximum amplitude the current assumes at any point without regard to its duration. The *average current* is the average current flowing between two successive peaks. Thus we can have a waveform with a high peak current though a low average current. An example of such a waveform is the current produced by so-called high voltage generators. The thermal and physiochemical effects of electrotherapeutic currents are primarily a function of the average current, while most physiologic effects are more dependent on peak current.

In addition to the characteristics of individual pulses, most electrotherapeutic currents employ *trains of pulse*. These pulse trains also take on various characteristics. Figure 1-5 shows trains of square waves. Depending upon the interval of time between each pulse, individual muscle contractions or sensations may be realized with each individual pulse. As the interval between pulses is shortened the responses begin to summate. A tetanic contraction or a report of stronger sensation, with the loss of the perception of individual pulses, may be observed if the frequency of stimulation is adequate. The motor or sensory response lasts as long as the train of impulses.

The characteristics of the impulse train can be modified in ways other than the interpulse interval. The current may be *surged* rather than merely interrupted. In a surging current the intensity of each successive pulse in the train gradually increases until the pre-set intensity is reached. A surged current permits a gradual build-up in the strength of contraction as well as intensity of sensation. The duration of each train of impulses and the interval of time between trains can be varied. This on-off cycle time may be used to produce intermittent muscle contractions during an exercise session.

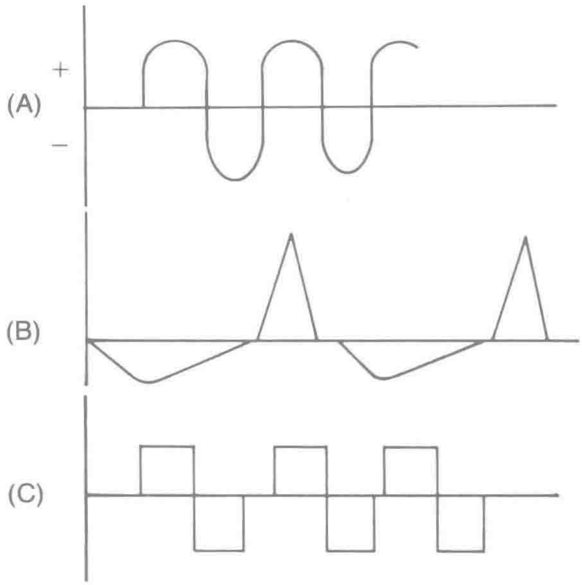


Fig. 1-4. Alternating currents: (*A*) sine wave, (*B*) original faradic current, (*C*) alternating square wave.

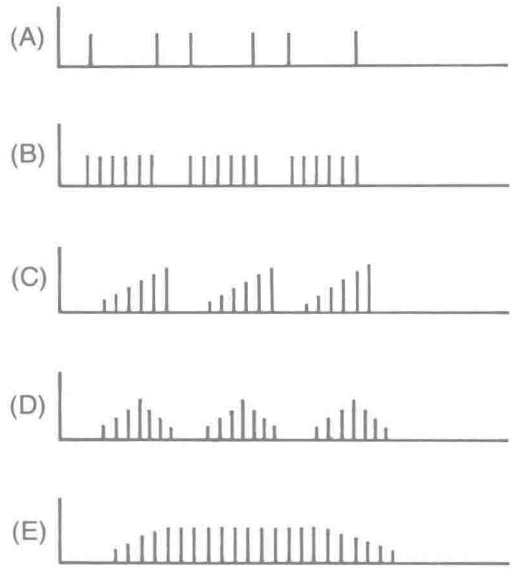


Fig. 1-5. Trains of pulses, (*A*) individual spikes, (*B*) interrupted train of pulses, (*C*) surged build-up, (*D*) surged build-up and decline, (*E*) long duration, surged build-up and decline. (Adapted from Scott PM: Clayton's Electrotherapy and Actinotherapy. 7th edn. Baltimore, The Williams and Wilkins Company, 1975.)

CHARACTERISTICS OF HIGH- AND LOW-VOLTAGE THERAPEUTIC CURRENTS

The division between high- and low-voltage currents is more arbitrary than absolute. By convention, *high-voltage generators* produce over 150 V. Similarly, any generator that produces less than 150 V may be considered a *low-voltage generator*. High-voltage generators produce short duration (usually less than 100 μs), high peak (up to 2.0 A), and low-average currents (less than 1.5 mA). The waveform most commonly used is a twin-peaked pulse with 40 to 80 μs spacing between pulses (Fig. 1-6). Trains of pulses, ranging from 1 to 100 pulses/s are usually available with most generators. High-voltage currents may be surged, interrupted or continuous. The high-voltage current is an interrupted DC with the positive or negative polarity given to either electrode.

The particular current characteristics will vary according to the particular application for which the generator has been built. The pulse durations for direct current devices vary from approximately 100 μs to continuous DC. Square or modified square wave pulses with an abrupt rise and fall of the current are most commonly used, though exceptions to the square wave are occasionally used (see Fig. 1-7). Trapezoidal, triangular and saw-tooth waveforms are used to selectively stimulate denervated muscle fibers. Figure 1-8 shows a bidirectional spiked pulse used to prevent the chemical effects of DC with chronic stimulation. This wave is commonly used for cardiac pacemakers.

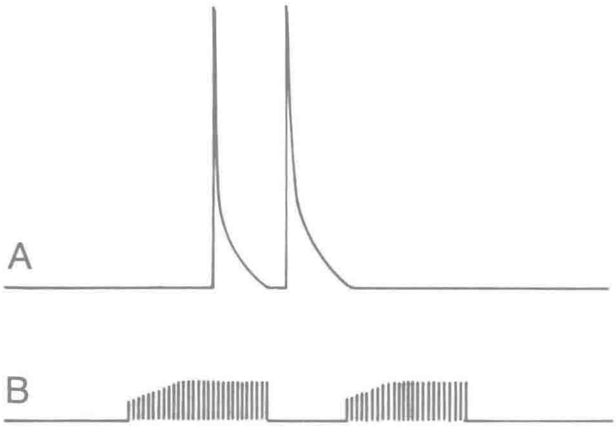


Fig. 1-6. Output of high voltage generator. (*A*) single twin-peaked pulse (*B*) surged output at 80 Hz.

Most of the currents defined as AC possess a rectangular or modified faradic waveform (Figs. 1-4B and C). The sinusoidal wave (Fig. 1-4A) is seldom, if ever, used. The original faradic current (Fig. 1-5B) produced by the faradic coil is now produced by electronic means and consists of a rapid rise and fall of unidirectional (direct) current impulses.[1] The duration of each faradic pulse lasts approximately 1 ms. The rectangular waves may have a duration of .1 to 1000 ms.

The *peak currents* for AC and DC low-voltage devices are relative low compared to the high-voltage devices. The average current for the continuous DC

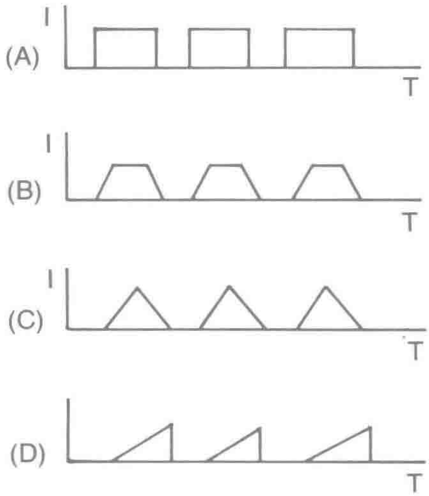


Fig. 1-7. Modified DC pulses. (*A*) Interrupted square. (*B*) Trapezodial. (*C*) Triangular. (*D*) Sawtooth. (Adapted from Scott PM: Clayton's Electrotherapy and Actinotherapy. 7th edn. Baltimore, The Williams and Wilkins Company, 1975.)