Electrical Stimulation Using Kilohertz-Frequency Alternating Current

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Transcutaneous electrical stimulation using kilohertz-frequency alternating current (AC) became popular in the 1950s with the introduction of "interferential currents," promoted as a means of producing depth-efficient stimulation of nerve and muscle. Later, "Russian current" was adopted as a means of muscle strengthening. This article reviews some clinically relevant, laboratory-based studies that offer an insight into the mechanism of action of kilohertz-frequency AC. It provides some answers to the question: "What are the optimal stimulus parameters for eliciting forceful, yet comfortable, electrically induced muscle contractions?" It is concluded that the stimulation parameters commonly used clinically (Russian and interferential currents) are suboptimal for achieving their stated goals and that greater benefit would be obtained using short-duration (2–4 millisecond), rectangular bursts of kilohertz-frequency AC with a frequency chosen to maximize the desired outcome.

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Two forms of electrical stimulation are commonly used clinically: pulsed current (PC) and burst-modulated alternating current (BMAC). Examples of BMAC are "Russian current" and "interferential current." Burst-modulated alternating current stimulation is claimed to be more comfortable than PC and capable of eliciting greater muscle torque.[1–3]

The response of nerve and muscle to PC electrical stimulation has been studied by physiologists since the late 19th century.[4,5] Consequently, our present understanding of the effects of PC is relatively good. The physiological response to BMAC stimulation is less-well understood.

This article reviews the known physiology and clinically relevant, laboratory-based studies of electrical stimulation, which offer some insight into the mechanism of action of BMAC and provide some answers to the questions "Does BMAC stimulation have an advantage over PC?" and "What are the optimum treatment parameters for BMAC stimulation?"

BMAC Stimulus Parameters

Alternating current (AC) used clinically is normally kilohertz-frequency AC, delivered in bursts, with the burst frequency in the "physiological" range (up to 100 Hz or so). It, therefore, is called "burst-modulated alternating current." Figure 1 illustrates, for comparison, unmodulated AC, monophasic PC, and 2 examples of BMAC.

The currents illustrated in Figures 1A, 1C, and 1D are defined as AC because the waveforms have alternating positive and negative phases with no gap between them. The current shown in Figure 1B is defined as PC because successive phases (the pulses) are separated by an appreciable gap.[6]

Pulsed current is easily described by specifying 3 things: (1) the waveform (eg, rectangular and monophasic, as in Fig. 1B), (2) the pulse duration (normally in the range of 50 microseconds to 1 millisecond), and (3) the pulse frequency (normally in the range of 1 Hz to about 100 Hz).

The description of AC is more complex. Alternating current, by definition, is biphasic, and the biphasic waveform can be sinusoidal or rectangular. The current also can be delivered continuously (Fig. 1A), in rectangular bursts (Fig. 1C), or in sinusoidally modulated bursts (Fig. 1D). Thus, when describing the stimulus, there is the potential for confusion because several parameters must be specified to completely describe the waveform. Figure 2 shows an example of BMAC, with particular parameters identified.

In Figure 2, the burst duration is 4 milliseconds, and because the interval between bursts is 16 milliseconds, the period (the burst repetition time) is 20 milliseconds, or 1/50th of a second. Therefore, the burst repetition frequency is 50 times per second in this example (ie, the burst frequency is 50 Hz). Each burst consists of a number of AC cycles. In this example, each 4-millisecond burst consists of 4 AC sine waves. Each sine wave has a duration of 1 millisecond, or 1/1,000th of a second, so the sine-wave frequency is 1,000 times per second (ie, 1 kHz). The sine-wave frequency is sometimes referred to as the "carrier frequency."[1,2,7] Each 1-millisecond sine wave comprises 2 phases: one positive phase followed by one negative phase, so each phase has a duration of 0.5 milliseconds, or 500 microseconds.

The greater the number of parameters, the greater the number of possible permutations and combinations. This raises the question of whether AC stimulators used clinically have the best combination of parameters for achieving the desired clinical outcome.

BMAC Stimulation Types Used Clinically

Russian Current

Russian current is 2.5-kHz AC, applied in 50-Hz rectangular bursts with a burst duty cycle of 50%. The stimulus waveform is shown in Figure 1C. The burst duration is 10 milliseconds at 50 Hz. Russian current is claimed to be beneficial for muscle strengthening (increasing force-generating capacity). The choice of a 2.5-kHz frequency for Russian current appears to be based on measurements of maximum electrically induced torque (MEIT) by Kots and co-workers[8] using not bursts but a continuous AC stimulus (Fig. 1A) in the frequency range of 100 Hz to 5 kHz.[8,9] The choice of a burst-modulated, 50% duty cycle (Fig. 1C) is based on the observation that there was little difference in MEIT between continuous AC and rectangular bursts with a 50% duty cycle but that with a 50% duty cycle, half as much electrical energy is delivered, so there is less risk for tissue damage.[8,9]

Russian currents became popular despite an equivocal evidence base due to the limited number of studies and their different findings.[3,9] The balance of evidence supports the notion that strengthening can be produced, but at one extreme there is the single-case study reported by Delitto et al,[10] which demonstrated a substantial strength gain, whereas at the other extreme there is the study by St Pierre et al,[11] which demonstrated no strength gain. Other than the original Russian study,[8,9] only 2 subsequent studies have addressed whether 2.5 kHz is the best AC frequency for muscle torque production.[12,13] These 2 studies used 50-Hz bursts of kilohertz-frequency AC,
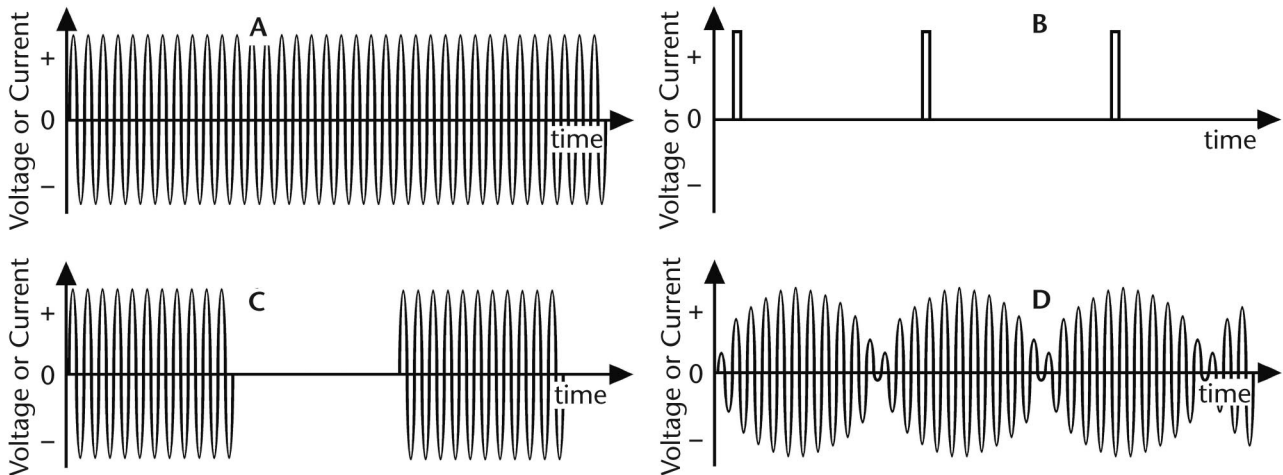
Figure 1.
(A) Steady, unmodulated alternating current; (B) monophasic pulsed current; (C) burst-modulated alternating current with rectangular burst modulation; and (D) burst-modulated alternating current with sinusoidal modulation.

and both studies showed that maximum torque was elicited at a frequency of 1 kHz. It is noteworthy that Andrianova et al[8] reported that 2.5 kHz is optimum if stimulation is applied directly (over the muscle) but that if stimulation is applied indirectly (over the nerve trunk), the optimum frequency is 1 kHz. Thus, it might be concluded that "optimal stimulus parameters" may well depend on electrode positioning and that the popular frequency (2.5 kHz) could be suboptimal for commonly used electrode placements.

Interferential Currents
Interferential currents are reported to be the most popular form of electrical stimulation used in clinical practice in the United Kingdom and other European countries and in Australia.[1] Interferential stimulators produce 2 independent kilohertz-frequency AC currents of constant intensity (Fig. 1A) applied by 2 separate pairs of electrodes, which are positioned diagonally opposed to produce an "interference" effect (Fig. 1D) in the central region of intersection of the currents (Fig. 3).[1,2,7]

The currents are applied continuously at constant intensity (Fig. 1A), but they have different frequencies (eg, 4,000 and 4,050 Hz), and in the tissue between the electrodes, the 2 currents interfere. It is stated[1,2,7] that the currents reinforce in the central region of intersection (Fig. 3A) to produce a stimulus waveform that is sinusoidally modulated at a frequency equal to the difference between the 2 AC frequencies (Fig. 3B, top). The stimulation waveform, therefore, resembles that illustrated in Figure 1D and would have a modulation frequency of 50 Hz in this example. This argument is misleading because it ignores the effect of
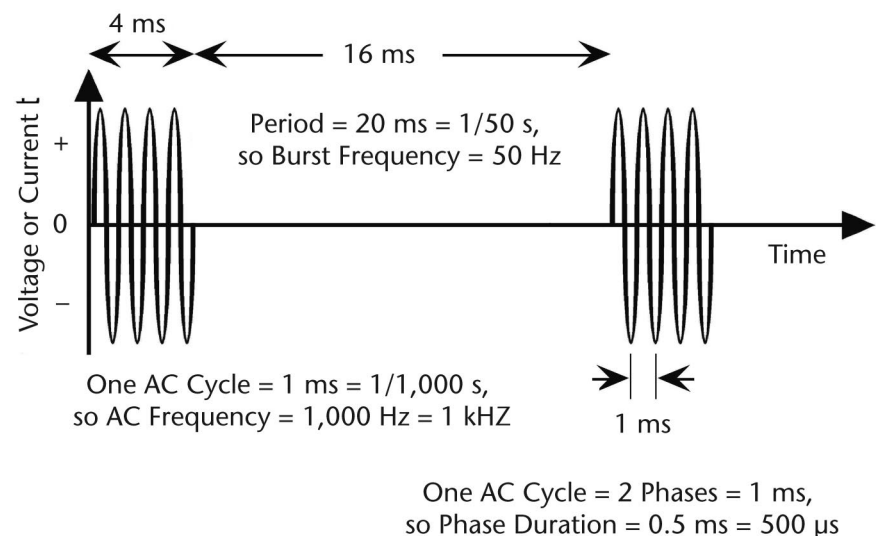
Figure 2.
An example of burst-modulated alternating current. A minimum of 5 parameters must be specified in order to describe the waveform. In this example, the waves are sinusoidal, the alternating current (AC) frequency is 1 kHz, the bursts are rectangular, the burst frequency is 50 Hz, and the burst duration is 4 milliseconds.
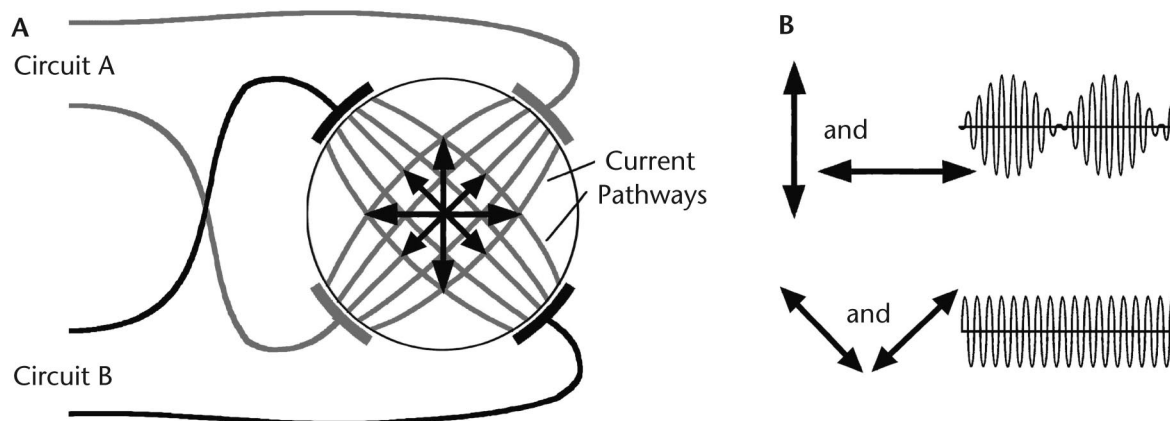
Figure 3.
(A) Interferential currents are claimed to produce maximum stimulation in the region of intersection of the 2 diagonally opposed currents, as shown. (B) The actual stimulation intensity experienced by nerve fibers has maximum modulation if the fibers are oriented optimally and zero modulation when fibers are oriented along one of the current pathways.

tissue inhomogeneity and, perhaps more importantly, nerve fiber orientation.[14,15] Nerve fibers oriented along an axis directly between one pair of electrodes will experience continuous, unmodulated AC, while only those angled optimally between the 2 axes will experience fully modulated AC (Fig. 3). The optimum angle depends on the relative intensities of the current. If the current intensities are equal, the optimum angle is 45 degrees to the current paths (ie, horizontally or vertically in Fig. 3A), but in practice the currents will not be equal due to the variation with position (relative to the electrodes) and the variation in electrical impedance of different tissues (fat, muscle, connective tissue, and bone) in the current pathway.[15] Unless the orientation of the nerve fibers is optimal, the stimulus modulation will be partial. Thus, with interferential currents, the actual stimulus waveform applied to the nerve fibers is not known and can vary between unmodulated and fully modulated AC (Fig. 3B), depending on the nerve fiber orientation and location relative to the electrode placement.

Premodulated Interferential Current
Most interferential stimulators also offer premodulated interferential current. The term "premodulated interferential" is something of a misnomer because it refers to current that is fully modulated (as in Fig. 1D) and applied between one pair of electrodes. Thus, by definition, this current is no longer interferential (ie, no longer produced by the interference of 2 currents). The current is simply kilohertz-frequency AC, modulated at a low frequency, typically in the range of 1 to 120 Hz.[1,2,7] Unlike "true" interferential current, the amount of modulation of the stimulation waveform does not depend on the nerve fiber orientation relative to the electrodes. The stimulus waveform is simply that provided by the stimulator and, therefore, is predictable.

If the "premodulated" current is sinusoidally modulated (as produced by traditional interferential stimulators and shown in Fig. 1D), some parts of the burst will be below threshold while other parts of the burst will be above threshold. Thus, the effective burst duration for any

given nerve fiber is uncertain and will vary with stimulation intensity, which varies with proximity to the electrodes. Nerve fibers close to the electrodes will be stimulated suprathreshold for a larger part of each burst than those further away; thus, the effective burst duration will vary. Some modern interferential stimulators use rectangular burst modulation (Fig. 1C), so there is no uncertainty as to the effective duration: the burst is either fully "on" or "off."

Importance of Modulation
Effect of Burst Duration on Thresholds
As noted earlier, Russian current is burst modulated with a rectangular envelope (Fig. 1C). Premodulated interferential current may be either rectangular burst modulated (Fig. 1C) or, more commonly, sinusoidally modulated (Fig. 1D), whereas with "true" interferential currents, the stimulus experienced by a nerve fiber may be continuous (unmodulated), fully modulated, or partially modulated, depending on the fiber location and orientation relative to the electrodes.

The first published report of the effect of modulation appears to be the report by Soloviev published in 1963.[16] Soloviev used AC stimulation over the frequency range of 2 to 8 kHz and found that there was little difference in motor threshold regardless of whether the current applied was continuous or burst modulated at 50 Hz with a 50% duty cycle. A 2001 study of motor thresholds by Ward and Robertson[17] again showed little difference, this time over the frequency range of 1 to 25 kHz. It should be noted, however, that only continuous AC and 50% duty cycle, 50-Hz bursts were compared, so the comparison was between 10-millisecond bursts and continuous AC.

In 2007, Ward and Lucas-Toumbourou[18] reported a study of sensory, motor, and pain thresholds using AC frequencies of 1 kHz and 4 kHz applied as 50-Hz bursts. They used burst durations in the range of 0.25 to 20 milliseconds and found that thresholds decreased to a plateau with increasing burst duration. An interesting finding of this study was that the plateau in threshold with burst duration depended on the response evoked (ie, sensory, motor, or pain threshold, with values of 5 to 7, 10, and >20 milliseconds, respectively). Thus, motor thresholds decrease with increasing burst duration, but at burst durations above about 10 milliseconds, there is no further decrease. These findings explain the lack of differences found in the earlier studies, when only 10-millisecond bursts and continuous AC were compared. The most intriguing finding of the study, however, was that the burst duration plateaus were different for sensory, motor, and pain thresholds. This means that there will be optimal burst durations where the pain/sensory threshold and pain/motor threshold ratios are maximum. Ward and Lucas-Toumbourou estimated an optimal burst duration for both sen-

sory and motor stimulation as 2 to 3 milliseconds. This is appreciably shorter than the burst durations commonly used clinically (typically 10 milliseconds for Russian current and greater or similar for interferential currents).

Effect of Burst Duration on MEIT and Discomfort

Andrianova et al[8] used different AC frequencies in the range of 100 Hz to 5 kHz and compared not thresholds but maximum torque production using continuous (unmodulated) AC and AC bursts (modulated at 50 Hz with a 50% duty cycle [ie, 10-millisecond burst duration]). They concluded that there was little difference in MEIT with burst-mode or continuous stimulation, but they did not make any statistical comparisons. Their published data (reproduced in Tab. 3 of the perspective article by Ward and Shkuratova[9]) however, show that across the frequency range, the torques produced by burst-modulated currents were, on average, 14% higher (SD=12%). Ward and Shkuratova[9] conducted a paired *t*-test comparison across frequencies, using Andrianova and colleagues' published data,[8] and found that this difference is significant (P=.03) (ie, torques are significantly higher when a rectangular burst-modulated stimulus of 10 milliseconds' duration is used rather than a continuous AC stimulus).

Bankov,[19] in 1980, compared 5-kHz AC, modulated at 60 Hz, using stimulation intensities that produced just enough contraction of the biceps brachii muscle to maintain the elbow at 90 degrees of flexion with the upper arm vertical (an antigravity flexion level of muscle activity). He compared rectangular bursts of 1, 2, and 5 milliseconds' duration and reported that the 1-millisecond burst was the most comfortable. Another study reported by Bankov in the same year[20] compared 60-Hz sinusoi-

dally modulated bursts of AC, which varied in their modulation depth from 0% (steady, continuous AC; Fig. 1A) to 100% (fully modulated; Fig. 1D), and hypermodulated bursts of AC (gaps between bursts). He reported that force increased with the degree of modulation but that the associated discomfort showed little variation. A conclusion is that shorter burst durations produce more force at the same level of discomfort. In 1981, Bankov and Daskalov[21] compared 5-kHz AC applied in 2-millisecond bursts with PC of varying pulse widths. Each was applied 3 seconds on and 3 seconds off at an intensity that produced antigravity flexion of the biceps muscle. The 5-kHz stimulus was found to be more comfortable. These early studies, thus, had 2 major findings: (1) that for a given level of force production, burst-modulated AC is preferable to continuous AC or PC, and (2) a short AC burst duration (1 or 2 milliseconds) is optimal for least discomfort.

A recent study[13] measured MEIT and relative discomfort using 50-Hz bursts of AC in the frequency range of 0.5 to 20 kHz. Burst durations ranging from the shortest possible (1 cycle) to the longest (continuous AC) were used. Maximum torque was produced at a frequency of 1 kHz and a burst duration of 2 milliseconds (10% duty cycle). Minimum discomfort occurred at a frequency of 4 kHz and a burst duration of 4 milliseconds (20% duty cycle). Continuous AC produced the least torque and the greatest discomfort at all frequencies. Single cycles (biphasic PC) produced significantly less torque than 2-millisecond bursts and were more uncomfortable. A later study[22] compared Russian current (2.5-kHz AC applied in 10-millisecond bursts) and "Aussie current" (1-kHz AC applied in 4-millisecond bursts) with PC of the same phase duration (200 and 500

microseconds, respectively) in terms of discomfort and torque production. The AC bursts (Fig. 1C) were more comfortable than their PC counterparts. Both Aussie current and the 2 forms of PC produced similarly high torques, but, perhaps surprisingly, Russian current evoked less.

Thus, it seems reasonable to conclude that a stimulus waveform that consists of kilohertz-frequency AC in short-duration bursts (2–4 milliseconds) is more comfortable and elicits greater MEIT than PC, continuous AC, Russian current, or interferential current stimulation.

The "Conventional Wisdom"

Historical Claims Concerning Interferential Currents

Nemec[23-26] promoted the therapeutic use of interferential currents and advocated the use of sinusoidal AC at frequencies around 5 kHz. He argued that the 2 currents of slightly different frequency "interfere" in tissue, producing maximum stimulation in the region of intersection of the 2 current paths, and that the resulting (endogenous) current at depth would be modulated at the "beat" frequency, which is the difference in frequency of the 2 currents (Fig. 3).[1,7]

Nemec[23-26] gave 3 arguments for the use of interferential current rather than PC:

1. Skin impedance is lower at high AC frequencies; therefore, less electrical energy is dissipated in the skin and, consequently, there is less sensory stimulation and discomfort than with low-frequency PC.

2. When the constant-intensity currents intersect and interfere, the resulting current will be modulated in intensity at the beat frequency (the difference between the 2 AC frequencies) and will produce endogenous low-frequency stimulation (ie, at depth, rather than superficially).

3. Currents interfere in tissue, producing maximum stimulation at the region of intersection of the 2 current paths, where a "clover-like" pattern of stimulation is produced.[1,7]

The first point is incorrect for 2 reasons. First, the skin impedance to PC depends on the phase duration, not the pulse frequency.[1,2,5,27-29] The skin impedance to low-frequency AC is much higher than to kilohertz-frequency AC because the phase duration is much longer. If the PC has the same phase duration as the kilohertz-frequency AC, the skin impedance is the same even if the pulse frequency is low.[1,2,5,27-29] Conventional PC typically has a phase duration similar to that of interferential current. Thus, the argument that interferential current would meet with a lower impedance is without any basis. Second, a lower skin impedance does not mean less stimulation of sensory and pain fibers in the skin and, therefore, less discomfort. The high skin impedance with long phase durations (eg, with low-frequency AC) is due to the skin capacitance, which is due almost entirely to the stratum corneum: the dead, scaly, relatively dry, outermost layer.[1,2,5,27,28] The stratum corneum has no sensory, pain, or other kind of nerve fibers.[30,31] These fibers are located beneath, in the dermis, which is well hydrated and of similar conductivity to the deeper tissues.[5,30,31]

The second and third points are oversimplifications. There are 3 important things to consider with interferential stimulation:

1. An interference pattern of stimulation is produced everywhere, not just at the predicted region of intersection of the currents, and the extent of modulation of the resulting current will depend on the location and orientation of the nerve fibers relative to the electrodes.[1,2,14,15] This means that throughout the tissue volume, fibers orientated at an optimum angle will experience a fully modulated current, whereas those at other angles (the majority) will be subject to a partially modulated or unmodulated stimulus.[1,2,14,15]

2. Current spreading means that there will not be a region at the center of intersection of the currents where maximum stimulation occurs. Although the stimulation at depth might be expected to be greater, current spreading would be expected to significantly reduce the value of any reinforcement effect.[1,14,15]

3. It might be expected that the current intensity at depth would be greater with quadripolar stimulation than with bipolar stimulation because of interference and reinforcement. Lambert et al[15] demonstrated that this is not true. When currents are applied using conventional interferential stimulation, the pattern of stimulation is not focused centrally. It is more diffuse due to current flow between adjacent electrodes because of the shorter-distance, lower-resistance pathways.

Thus, the depth efficiency claims for interferential current are not substantiated. This, together with the uncertain degree of modulation of the stimulus, calls into question whether the "interference" effect of interferential current is of any value. Ozcan et al[32] addressed this question when they assessed the relative discomfort of true and premodulated interferential currents (delivered in 50-Hz bursts, 10 milliseconds on and

10 milliseconds off). Premodulated interferential current was found to be significantly more comfortable than true interferential current and more effective for muscle contraction.

Historical Claims Concerning Russian Current

A talk given by Kots,[33] of the Central Institute of Physical Culture, Moscow, at a conference hosted by Concordia University, Montreal, in 1977 laid the foundation for what became known in the Western world as Russian current electrical stimulation.[9] Kots reported strength gains of up to 40% in elite Russian athletes stimulated with 2.5-kHz AC applied in 10-millisecond rectangular bursts at a frequency of 50 Hz. His protocol used currents with a 10-second on period followed by a 50-second rest period, applied 10 times in each stimulation session (ie, 10-minute treatment sessions). Treatment was applied daily over a period of weeks.

As noted previously, Russian currents became popular despite an equivocal evidence base due to the limited number of studies and their different findings.[3,9] The choice, by Kots' group, of 10-millisecond bursts (50% duty cycle) was because of their observation that it evoked just as much muscle torque as continuous AC but, because of the burst modulation, the average current applied to tissue was halved. The effect of different burst durations was not explored. Bankov[19,20] and Bankov and Daskalov,[21] in the 1980s, examined the effect of burst duration and found that, for the same level of force production, short-duration bursts are more comfortable. An inference is that greater levels of force would be produced at the same level of discomfort if short-duration bursts were used. This is supported by the recent work of Ward et al,[13] who measured torque at the pain tolerance limit and found that the greatest MEIT is produced

using 2-millisecond bursts of AC with a frequency of 1 kHz.

Thus, the rationale for the clinical use of Russian current is called into question. The evidence is that stimulation with short-duration bursts of kilohertz-frequency AC would be preferable and that a burst duration of 2 milliseconds appears to be optimal for torque production.

Discussion—The Known Electrophysiology

The available laboratory-based evidence indicates that short-duration bursts of kilohertz-frequency AC have advantages over Russian current, interferential current, and PC and that there are optimal frequencies and burst durations for achieving the desired outcome. There are 4 interrelated electrophysiological factors that could help explain the empirical findings: summation, multiple firing, high-frequency fatigue, and neural block.

Summation

With kilohertz-frequency AC stimulation, there is the possibility of summation, a phenomenon first described by Gildemeister.[34,35] Gildemeister reported that when bursts of kilohertz-frequency AC are applied transcutaneously, the threshold voltage for sensory nerve excitation decreases as the burst duration is increased. This phenomenon, later called the "Gildemeister Effect," occurs because, with each successive pulse in the AC wave-train, the nerve fiber membrane is pushed closer to threshold. Membrane threshold is reached when successive pulses result in sufficient depolarization to produce an action potential. Gildemeister observed a limit to the summation effect. As the number of cycles per burst was increased, the threshold decreased, but only up to a point. Beyond a certain burst duration, no further decrease in threshold was observed. He called this

maximum burst duration (ie, time over which pulses could summate) the "Nutzzeit" or "utilization time."

As noted previously, a recent study by Ward and Lucas-Toumbourou[18] showed that the apparent utilization time was different for sensory, motor, and pain thresholds and, consequently, that relative thresholds (pain/motor and pain/sensory) vary with burst duration. These authors found that optimum discrimination (biggest separation between thresholds [ie, maximum relative thresholds]) occurred at burst durations of 2 to 4 milliseconds.

High-Frequency Fatigue

When electrical stimulation is applied to elicit a motor response using PC frequencies higher than physiological or at the high end of the physiological range (ie, greater than about 50 Hz), it is possible to produce a blockage of muscle activity due to propagation failure or neurotransmitter depletion.[36-38] This is responsible for the phenomenon of "high-frequency fatigue,"[38,39] which is characterized by its associated rapid recovery. If a stimulus frequency of 80 Hz, for instance, is used to elicit muscle contraction, the resulting muscle force declines rapidly, but if a brief rest period (a few seconds) is allowed, marked recovery occurs.[38,39] This is quite different from "low-frequency fatigue," which is much more akin to normal physiological fatigue, where the force decline is much slower and the recovery time is much longer.

One form of high-frequency fatigue, propagation failure, can occur when action potentials are induced in motoneurons at sufficiently high frequency. This can result in action potential failure at branch points where a motor nerve divides to innervate individual muscle fibers. Failure also can occur at the neuromuscular junction because neurotransmitter

depletion is possible at relatively high stimulation frequencies.[40] Beyond the neuromuscular junction, transmission failure can occur at the level of the t-tubule system. Normally, the wave of depolarization of a muscle fiber action potential is transmitted over the muscle fiber membrane and throughout the t-tubule system, activating the contractile elements. When sufficiently high frequency action potentials are induced, the t-tubule membranes do not have time to recover between action potentials and muscle fiber contraction ceases.[39,40] Whichever the mechanism, whether propagation failure or neurotransmitter depletion, a blockage of muscle contraction at stimulation frequencies around and above about 50 Hz is the result, and the effect is described as high-frequency fatigue.

Summation and Multiple Firing

When the stimulus is PC applied at low frequency (less than 100 Hz), it can be confidently concluded that, provided that the pulse intensity is sufficiently above threshold, the nerve fiber firing frequency will equal the pulse frequency. The firing frequency could be less if successive pulses occur within the relative refractory period and the stimulus intensity is not sufficiently high, but the firing frequency could never be higher than the PC frequency. With bursts of AC, however, there is the possibility that a single burst will result in multiple action potentials as a result of summation[41–44]; therefore, the firing frequency could be some multiple of the burst frequency. If the first few pulses in a burst summate, the nerve fiber could fire, go through a brief period of refractoriness, and then fire again. If this process happens rapidly and, therefore, is repeated during the burst, the nerve fiber firing frequency will be a multiple of the burst frequency. There is sound experimental evidence for this effect.[41–45]

A problem with multiple firing is that it could detract from the desired outcome. For example, a motoneuron firing frequency of 50 Hz might elicit an optimally forceful muscle contraction, so 50-Hz PC would be a good option. If long-duration 50-Hz bursts are used, however, the induced firing frequency could be a multiple of 50 Hz. This would initially result in a slightly greater muscle force, but the rate of fatigue would be higher. There also would be a greater amount of high-frequency fatigue. A recent study by Laufer and Elboim[44] compared fatigue rates using 50-Hz bursts of 2.5-kHz AC with a burst duration of 10 milliseconds (Russian current), 50-Hz biphasic PC with the same phase duration (200 microseconds), 50-Hz bursts with a burst duration of 4 milliseconds, and 20-Hz bursts with a burst duration of 10 milliseconds. They reported that Russian current was the most rapidly fatiguing, PC was the least rapidly fatiguing, and the 2 currents of shorter burst duration were intermediate and equally fatiguing. A conclusion is that for motor stimulation using kilohertz-frequency AC bursts, if the duration is greater than 2 milliseconds, multiple firing is likely to occur and the fatigue rate will be compromised.

Neural Block

With kilohertz-frequency AC stimulation, another effect can be produced: direct conduction block of the nerve fiber. A direct observation of neural block was reported by Tanner,[46] who measured compound action potentials produced in exposed sciatic nerve in response to direct, repetitive stimuli from a low-frequency pulse generator and found that neural activity could be blocked using a 20-kHz AC stimulus applied to the nerve trunk between the pulse generator and the recording electrodes. As the AC stimulus intensity was progressively increased, first the fast (large-diameter) fiber re-

sponses disappeared, followed by the slower (intermediate-diameter) fiber responses and then the slowest (small-diameter) fiber responses.

Bowman and McNeal[45] examined the α-motoneuron response to blocking signals in the frequency range of 100 Hz to 10 kHz. With high-intensity 2-kHz AC stimulation, they observed that following a brief period of firing at a very high rate (about 1 kHz), there was a progressive decrease in firing frequency, which occurred over a time frame of tens of seconds, after which activity ceased and complete conduction block occurred. At higher AC frequencies (4 kHz or more), the rate of decrease in activity was higher, with the firing frequency dropping to zero in less than a second and with stimulus intensities of 5 times the threshold. Bowman and McNeal concluded that neural block occurs more readily at multiples of threshold stimulation intensities and that the effects occur more rapidly at higher kilohertz frequencies.

Direct studies of neural block with AC stimulation, to date, have all used continuous AC. There do not appear to be any reported studies of the blocking effectiveness of burst-modulated AC, so it is not known to what extent neural block contributes to the effects observed. Indirect evidence for neural block was found by Ward and Robertson,[17] who measured motor thresholds using continuous kilohertz-frequency AC, 50-Hz bursts, and single sine waves in the range of 1 to 25 kHz. Irregularities in the graphs of force versus stimulus intensity were consistent with multiple firing followed by nerve block. The effects were more pronounced at higher kHz frequencies and were greater with continuous stimulation than with 50-Hz bursts.

Whether neural block is of practical significance with electrical stimula-

tion as used clinically thus remains uncertain, but it would affect MEIT, as α-motoneurons are more susceptible to neural block than pain (A-δ and C) fibers because of their larger diameter. This means that muscle force could be diminished without any diminution of pain sensation.

Conclusion

In assessing the relative merits of different forms of motor electrical stimulation, 2 factors are highly relevant: relative discomfort of stimulation and the ability to elicit maximum muscle torque. These factors, in turn, depend on the neurophysiological responses of different nerve fiber types to electrical stimulation.

With kilohertz-frequency AC stimulation, summation and multiple firing, high-frequency fatigue, and neural block can potentially affect the neurophysiological response. The effects will vary, depending on the AC frequency and burst duration.

Both the historical evidence and more recent findings indicate that the stimulation parameters commonly used clinically (Russian and interferential currents) are suboptimal for achieving their stated goals and that greater benefit would be obtained using short-duration (2- to 4-millisecond) bursts of kilohertz-frequency AC, with a frequency chosen to maximize the desired outcome. For maximum muscle torque production, a frequency of 1 to 2.5 kHz is indicated, with a burst duration of 2 milliseconds or so. For minimal discomfort (but less muscle torque), a frequency of 4 kHz is indicated, with a burst duration of 4 milliseconds.

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