ABSTRACT: We investigated the frequency dependence of motor thresholds over the frequency range 1 kHz to 25 kHz. Alternating current (AC), ramped in intensity, was applied transcutaneously, and the induced wrist extensor torque was measured. Plots of log torque versus stimulus voltage were used to accurately determine thresholds. Three kinds of sinusoidal AC stimuli were compared: continuous, 10 ms bursts at 50 Hz, and 50-Hz single-cycle. Differences were attributed to summation of subthreshold depolarizations. The variation in relative thresholds (continuous/single-cycle and burst/single-cycle) indicates that summation occurs more efficiently at higher kHz frequencies. The observed frequency and waveform dependence provides evidence for high-frequency nerve fiber firing rates and fiber dropout when continuous or modulated AC is used, with the effects increasing with AC frequency. The form of the motor response evoked at high frequencies has features that suggest that frequencies above 10-kHz have little or no useful clinical role in rehabilitation procedures.


VARIATION IN MOTOR THRESHOLD WITH FREQUENCY USING kHz FREQUENCY ALTERNATING CURRENT

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Electrical stimulation is used extensively in rehabilitation. Uses include pain control, muscle re-education, prevention of atrophy, and restoration of function (functional electrical stimulation). Its application for muscle strengthening has also been explored using healthy subjects and elite athletes.15,19 The most commonly used stimulus waveform is low-frequency rectangular pulsed current.

For functional electrical stimulation, muscle strengthening, and prevention of atrophy, a requirement is that the stimulation elicit a sufficiently powerful muscle contraction with minimal discomfort and fatigue. A problem associated with electrical stimulation is that sensory nerve fibers and fibers innervating fast-twitch, fast-fatigue motor units are, because of their larger diameter, more readily recruited than are the fibers innervating fatigue-resistant motor units. In consequence, the rate of fatigue with electrical stimulation is high,2,14 as is the level of sensory stimulation. This problem has been addressed in a number of ways. Studies have investigated the effect of pulse width9 and preconditioning stimuli10 on the selectivity of recruitment. Others have examined the effect of variable-frequency pulse trains3 and stimulation using doublets,1 triplets, and larger bursts of pulses13 on force production and fatigue. Results have been encouraging, but attention has been focused on low-frequency pulsed stimuli, where successive pulses are separated by an interval that exceeds the relative refractory period of α-motoneurons.

Stimulation of nerve and muscle using kHz frequency sinusoidal alternating current (AC) has been less well studied. Nonetheless, it is widely used in rehabilitation,4,17,18,28 and its usefulness for muscle strengthening has been demonstrated in a number of studies.5,6,25,26,32 Sinusoidal AC is typically used clinically at a frequency of 2.5 kHz or 4 kHz, though there is little empirical evidence to justify the choice of a particular frequency. The waveform is normally modulated at low frequency (usually in the range 1 Hz to 150 Hz).

An important difference between stimulation using low-frequency pulsed current and low-frequency...
bursts of kHz frequency AC is that with the latter, the interval between successive pulses is a good deal less than the relative refractory period. For 1-kHz AC, the lowest frequency used in this study, the interval between successive half-cycles is 0.5 ms, which is less than the absolute refractory period of an α-motoneuron. At higher frequencies, the pulse separation is correspondingly reduced. Another (related) difference is that with bursts of AC, nerve fiber depolarization can occur by a process of summation of subthreshold depolarizations. The term “summation” as used in this communication always refers to summation of subthreshold depolarizations of the nerve fiber membrane (rather than the force summation that occurs in the muscle fibers). Summation of subthreshold depolarizations was first proposed by Gildemeister, as an explanation for his observations that the subjective sensation, and whether there was any sensation, associated with bursts of kHz frequency AC depended strongly on the burst duration, i.e., the number of cycles in the burst, and also on the actual frequency. An explanation is that, because of the rectification properties of the nerve fiber membrane, an AC stimulus is able to push the nerve fiber closer to threshold with each successive pulse in a burst. This effect requires that the pulses occur sufficiently rapidly that the membrane does not have time to recover between them. Membrane threshold is reached when successive pulses result in sufficient depolarization to produce an action potential; depolarization is thus expected to occur more readily at higher kHz frequencies. The first quantitative demonstration of this effect appears to have been performed by Schwarz and Volkmer, who measured the change in single-fiber membrane potentials resulting from successive pulses of kHz frequency AC stimuli.

Gildemeister observed that summation effects were more readily apparent at frequencies of 3 kHz or more, i.e., when the half-cycles are separated by 1/(2 × 3000) s or 0.15 ms. Later experimental work using whole nerve trunk preparations to measure compound action potentials provided further evidence for summation of subthreshold depolarizations. Schwarz and Ehrig used bursts of kHz frequency AC with a controlled number of cycles per burst and measured stimulus thresholds for action potential generation in cat sciatic nerve. Threshold–stimulus voltages decreased as the number of cycles per burst increased. The effect became more pronounced with increasing frequency but was evident even at the lowest frequency used (770 Hz).

The present study was designed to assess the frequency dependence of summation with transcutaneous application of current over the frequency range 1 kHz to 25 kHz. We measured motor thresholds and compared single sinewaves with 10-ms bursts of kHz frequency AC at a burst frequency of 50 Hz. Single sinewave pulses were used, rather than a monophasic rectangular pulse, to avoid differences in the electrical impedance at each frequency. When comparing complete sinewaves and bursts, at any given frequency, the tissue impedance is the same. Had monophasic rectangular pulses been used, the impedances at a particular frequency would differ between pulses and bursts of AC, so impedance would be a confounding variable. Continuous AC was also included in the comparison, with the expectation that summation effects would be more evident with a continuous waveform, because the summation process is not restricted to within 10 ms. With continuous AC and 10-ms bursts, electrode polarity effects are not important, as each pulse is subthreshold, and it is the cumulative effect of subthreshold depolarizations that results in an action potential. With single sinewaves, it makes a difference if the electrodes are reversed, because the single-sinewave generator produces a waveform in which the positive half-cycle always precedes the negative half-cycle. Accordingly, single sinewave stimuli were applied, with the proximal electrode acting as the anode (positive–phase leading) and the distal electrode acting as the cathode.

A problem that we had previously found with measuring motor thresholds is that at higher kHz frequencies, the motor response diminishes rapidly, making it difficult to establish precisely the threshold–stimulation intensity. This problem can be overcome by ramping the stimulus intensity to a supra-threshold value in a controlled manner and measuring the resulting muscle torque. For low stimulus intensities, the evoked motor response increases in a manner that is close to exponential. Thus, by plotting the torque using a logarithmic scale, the resulting graph can be extrapolated to an arbitrarily small torque value and the corresponding stimulus intensity can be accurately determined. Accordingly, this method of measuring thresholds was used in the present study.

**MATERIALS AND METHODS**

The 14 subjects participating in the study were volunteers who met the criteria for inclusion. That is, they did not have a pacemaker (or indwelling stimulator), any breaks in the skin under the area where the electrodes were to be placed, and had no known neurologic or musculoskeletal pathology affecting the upper limb to be tested. The group consisted of...
seven women and seven men drawn from staff members and students of the Faculty of Health Sciences (age range, 19–59 years, mean age, 36.3 years). Preliminary tests were carried out to establish that the subjects were able to relax and not intervene during electrical stimulation. This was assessed by the reproducibility of measurements, return to baseline at the end of each 5-s stimulation period, and the shape of the resulting graphs. All participants were judged able to relax. This is perhaps a reflection of the facts that the peak stimulation intensities were not high and all subjects had prior experience with electrical stimulation as part of their professional training. Approval was obtained from the Ethics Committee of the Faculty of Health Sciences prior to the commencement of this study, and all participants gave informed consent.

Following an explanation to each subject of the procedure to be used, the forearm skin was prepared by washing with mild soap. Conductive rubber electrodes with self-adhesive conductive electrode pads (TENS carbon electrodes type 00200-090 and Dermatrod-A electrode skin mounts type 00200-070; American Imex, Irvine, California) measuring 44 mm × 40 mm were attached to the skin on the left forearm. The proximal electrode was placed 1 cm distal on a line from the humeroradial joint to the inferior radioulnar joint. The distal electrode was placed midway on the same line so that it lay over the extensor digitorum muscle. The subject’s forearm was then positioned in a device built expressly for the purpose of measuring isometric wrist extensor torque, described previously. The stimulator is a device built expressly for the purposes of the study and consisting of a sinewave generator (1 kHz to 25 kHz) and chopping circuit, which could be set to produce either 10-ms bursts of AC separated by a 10-ms off-period (50-Hz frequency) or single-cycle sinewaves at 50 Hz. The chopping circuit was bypassed for continuous sinewave output. Figure 1 shows the stimulus waveforms. A zero-crossing detector was used to ensure that when single sinewave output was selected, only complete sinewaves were gated. In the case of bursts, the waveform was not zero-crossing. Incomplete sinewaves at the start and end of the burst is a potential problem only at low (<1 kHz) frequencies and when the number of pulses per burst is small. The worst case in the present experiments was 1-kHz AC where there are 10 sinewaves per burst. Because each sinewave in the burst is subthreshold, it matters little if the first and last sinewaves in the burst are randomly chopped.

A data acquisition unit (MP100 workstation using AcqKnowledge 3 software, Biopac Systems Inc., Santa Barbara, California) was used to record torque in these experiments while simultaneously producing an output voltage ramp signal that was used to control the stimulus intensity. The waveform ramped from zero to maximum over a period of 5 s, then immediately dropped to zero.

Over the 5-s ramp period, torque and ramp voltage were recorded by sampling every 100 ms. The resulting record was then used to plot graphs of torque versus stimulating voltage at each AC frequency and for each stimulus waveform. Ramp voltage was recorded rather than the peak voltage of individual AC pulses, as recording a 25-kHz sinusalidal AC signal requires a sampling frequency well in excess of the maximum sampling frequency of the data acquisition unit (32 kHz) or an impractically long sampling time, to ensure that the peak voltage is captured. The validity of measuring ramp voltage rather than individual AC pulse voltages was assured by prior calibration using long sample times.

Subjects were presented with seven separate AC frequencies ranging from 1 kHz to 25 kHz. All test frequencies (1, 2, 4, 7, 10, 15, and 25 kHz) were applied in a randomized order that was different for each subject. After completion of the sequence of frequencies, the procedure was repeated, at least 1 day later, using the reverse sequential order. Thus, two sets of data at each frequency were obtained for each subject. Sequences were allocated from two 7 × 7 Latin square arrangements in order to minimize any order effects across the group. At each AC frequency, the three conditions (continuous, burst, and single sinewave) were applied before proceeding to the next AC frequency. Condition ordering was allocated by repetitive sequential selection from a list of possible orders.

The start of each set of measurements at a par-
ticular AC frequency involved setting the stimulus intensity to elicit an extensor torque of N\(\cdot\)m. This figure was chosen as a result of preliminary testing which found that the stimulus intensities needed to elicit 5N\(\cdot\)m torque (about 10\% of a maximum voluntary contraction) were perceived as comfortable by most subjects. Preliminary experimentation showed that the stimulus intensities required to elicit 5N\(\cdot\)m torque were similar for continuous and bursts of AC and also that these were appreciably less than when using single sinewaves. This suggested the possibility of using the same intensity setting so that continuous- and burst-mode stimulation could be directly compared. Accordingly, the intensity was not reset when switching between burst- and continuous-mode stimulation. Ramping was disabled to produce manually controlled output, and the subject was asked to rotate the output control of the stimulator while observing the electrically induced torque on the computer screen and to increase the stimulation intensity until the required torque was reached. The experimenter monitored the stimulation intensity on a cathode-ray oscilloscope and recorded the peak stimulus intensity. The experimenter then flipped a switch to change from manual control to computer control of the intensity. After a 1-min rest period, ramping of the intensity was initiated and torque and ramp voltage were recorded at 100-ms intervals for the 5-s duration of the measurements. The peak intensity measurement on the oscilloscope provided the calibration factor needed to convert measured ramp voltage to actual stimulating voltage.

Subjects were reminded that they could withdraw if they wished, at any stage of the study. All subjects chose to continue with the full series of trials.

RESULTS
Baseline torque measurements obtained in the 1 s prior to ramping the stimulus intensity were averaged and subtracted from the raw torque measurements, to obtain corrected torque figures. In this way, torque produced by the weight of the subject’s hand resting on the apparatus was separated from that due to the electrically induced contraction. The ramp voltage (0–5 V) was scaled using a multiplication factor so that the peak voltage was equal to that measured by the experimenter when the peak stimulation intensity was set.

Figure 2 shows a graph of one set of results for a single subject. Torque is plotted against peak-to-peak stimulus voltage. For all subjects and for frequencies less than 10-kHz, all graphs had a similar shape. Each showed an initial, exponential-like increase followed by a gradual roll-over. The onset and amount of roll-over varied between subjects. Because the behavior at higher torques was possibly due to some activation of the wrist flexors at high stimulation intensities, greatest attention was focused on the initial, low-torque behavior.

To assess whether the early, low-torque behavior followed an exponential increase, graphs were plotted using a logarithmic scale for the torque axis. Figure 3 shows the same data as that in Figure 2, plotted in this way. Torque values less than 1\% of the peak torque were omitted from these plots (values less than 0.05N), as these were barely discernible from the baseline scatter of the measurements and would have unacceptably large errors. As Figure 3 shows, the early part of the logarithmic plots was substantially linear, indicating an exponential rela-
tionship between torque and stimulating voltage at low torques. A line of best fit was drawn and used to determine the motor threshold, which was (somewhat arbitrarily) taken as the stimulus voltage required to elicit a torque equal to 2% of the peak torque (a torque value of 0.1N). Although this method overestimates the true threshold, the effect is systematic so that between-condition comparisons would be affected negligibly.

At frequencies below 10 kHz, smooth, continuous graphs like that shown in Figure 2 were always obtained. At frequencies of 10 kHz and above, three curious effects were occasionally seen: (1) the appearance of a sudden spike in the torque graph at a stimulation intensity well below the threshold as previously defined; (2) the appearance of a dip immediately prior to the rapid increase in torque with stimulus voltage; and (3) “raggedness,” i.e., a lack of smoothness in the above-threshold torque variation. Representative graphs are shown in Figure 4. Although Figure 4A shows all three effects, the effects did not often occur together.

When first observed, spikes and raggedness were thought to be artifacts and the dips due to the subject not being fully relaxed prior to stimulation. With accumulation of data, it became apparent that this was not the case, as their occurrence was frequency dependent and, to an extent, predictable. The effects were seen only at frequencies of 10 kHz or more, and the incidence increased with increasing AC frequency. Table 1 summarizes the frequency of occurrence of spikes, dips and raggedness. Dips were counted only if the magnitude of the dip was greater than 2% of the peak torque (greater than 0.1N). In practice, this meant that no dip was counted if it was less than 2.8% of the maximum (0.14N). Spikes were counted only if the magnitude of the spike was greater than 50% of the peak torque. This was because spikes were very much “all or none”: when they occurred, they were large—no spikes less than 50% of maximum were seen. The criterion for raggedness was the appearance of sudden jumps or drops in the suprathreshold region that were greater than 10% of the peak torque. In practice, it was not necessary to perform detailed measurements to assess raggedness, as it also tended to be all or none (compare Figs. 2 and 4).

Table 1 shows that spikes occurred relatively infrequently. There were only five occurrences at 15 kHz, in a total of 84 data sets. At 25 kHz, there were 10 occurrences. Spikes occurred most frequently (6 out of 10 cases) with the 25 kHz AC delivered in 10-ms bursts at 50 Hz. Dips occurred more frequently than did spikes, and again the incidence was higher at higher AC frequencies. It was also noted

<table>
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<th>No. of dips</th>
<th>No. of ragged graphs</th>
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</table>

FIGURE 4. Variation in wrist extensor torque with stimulation intensity for two subjects at an AC frequency of 25 kHz. Stimulus mode was 10-ms bursts at 50 Hz. Note the spike (i), dips (ii), and raggedness (iii).
that dips seemed to occur just as frequently with single sinewaves as with a burst or continuous stimulus waveform. Raggedness occurred more frequently than did spikes or dips, and the incidence was higher at higher AC frequencies. Raggedness also seemed to be associated with burst and continuous stimuli but rarely with the single sinewave stimulus waveform.

Despite the appearance of occasional spikes, dips, and raggedness, log-linear graphs of torque versus stimulus voltage (Fig. 3) always had an initial, linear region that could be used to establish the motor threshold. Motor thresholds obtained by extrapolating the line of best fit to a torque of 0.1N were averaged across the 14 subjects (28 measurements) at each AC frequency and for each stimulus type. Plots showing the frequency dependence of the threshold values are shown in Figure 5. Error bars are not shown, because between-subject variance was very large and obscures the frequency dependence. A two-way repeated-measures analysis of variance (ANOVA) was performed to separate the frequency dependence and stimulus-type dependence from the between-subject variance. Between-subject variance was appreciable (F[12,273] = 1.67, P = .07). The frequency dependence was, nonetheless, convincingly demonstrated (F[6,273] = 30.7, P = 4 × 10−28) as was the stimulus type dependence (F[2,273] = 50.3, P = 3 × 10−19).

**DISCUSSION**

As Figure 5 shows, motor thresholds decrease in the range 1 kHz to about 5 kHz. An explanation is that the skin acts as a capacitative barrier to flow of current through the underlying tissue, which is principally resistive due to its high state of hydration and the associated ion content.16 The accelerating increase in thresholds above 5 kHz presumably reflects the decreasing sensitivity of nerve fibers. A decrease in sensitivity at higher frequencies is predicted by the capacitative nature of the fiber membrane11 and could also be influenced by the membrane ion-gating time constants.

Figure 5 also shows that motor thresholds are appreciably lower when continuous or 10-ms bursts of AC are used rather than single sinewaves. This provides clear evidence for summation. An interesting observation is that the differences between the continuous AC stimulation thresholds and those for 10-ms bursts are very small. The continuous thresholds are lower at low AC frequencies, an effect readily attributable to greater summation, but the situation reverses at high frequencies. Regression analysis of the ratio (continuous threshold)/(10-ms–burst threshold) revealed that although small in absolute terms, the variation is real and not random. The regression coefficient (Pearson’s r) is .95.

To quantify lowering of the motor threshold, values of (continuous threshold)/(single-sinewave threshold) and (10-ms–burst threshold)/(single-sinewave threshold) were calculated at each AC frequency. The values are plotted in Figure 6. Between 1 kHz and 10 kHz, the continuous and burst relative thresholds show a marked decrease (approximately 16 and 22%, respectively), indicating that summation becomes more effective with increasing frequency. The downward trend is appreciably reduced above 10 kHz.

A predicted consequence of summation30 is that with low-frequency bursts of AC of sufficient duration, nerves will fire at exact multiples, i.e., harmon-
ics, of the burst frequency. With a 10-ms burst of AC, membrane threshold is reached when successive pulses in the burst result in sufficient depolarization to produce an action potential at, or just before, the end of a burst. In this case, the firing frequency will equal the burst frequency. At a higher stimulation intensity, fewer pulses in each burst need to summate to produce the action potential. Thus, action potentials are produced sooner within each burst. At a sufficiently high stimulation intensity, an individual fiber may suddenly switch from firing at 50 Hz to firing at 100 Hz. This happens when the nerve has time to recover sufficiently for a second action potential to be generated before the end of the 10-ms burst. At a still higher intensity, the fiber may suddenly switch from firing at 100 Hz to firing at 150 Hz, and so on. Consequently, as the intensity is increased, there is an upward shift in the average firing frequency as harmonic excitation is induced. An inevitable consequence is a greater rate of fatigue and fiber drop-out.

Although a nerve firing frequency of 100 Hz would result in greater short-term force production than 50 Hz, firing frequencies of 150 Hz and higher harmonics will not. At higher harmonic-excitation frequencies, high-frequency fatigue (a phenomenon seen only with electrical stimulation) will occur very rapidly. This form of fatigue is thought to originate either from neurotransmitter depletion or failure of the action potential to propagate over the muscle fiber T-tubule system. Direct nerve stimulation at 50 Hz for a period of as little as 0.2 s has been shown to produce a marked drop in acetylcholine release at the neuromuscular junction. Although the drop in acetylcholine release needs to be large before neuromuscular transmission is affected, a sufficient drop could occur in a fraction of a second if the firing frequency is several multiples of 50 Hz. Propagation failure could also occur very rapidly with nerve firing rates that are higher multiples of 50 Hz. Thus, although the specific mechanism likely to operate is a subject of speculation, that fatigue and drop-out would occur very rapidly is not.

If summation occurs more readily at higher frequencies, the fiber firing rates should be higher, particularly with a continuous-AC waveform, and fiber dropout effects should be seen. Specifically, during the 5-s ramp to maximum, drop-out should result in less overall torque production with a continuous-AC waveform and, consequently, a reduced average torque. Relative values of the average torque were calculated by dividing the continuous-sinewave averages by their burst-mode counterparts. No direct comparison could be made between single-sinewave average torques and those of either continuous- or burst-mode, as different peak stimulus intensities were used for ramping. Because the burst- and continuous-mode measurements at each frequency were obtained using the same peak-stimulus intensity, a direct comparison could be made. Figure 7 shows a plot of the relative average torques. The relative average torque decreases by about 40% between 1 kHz and 15 kHz, and there is a departure from the trend at 25 kHz. A value close to 1.0 at 1 kHz suggests either no fiber drop-out at this frequency or (perhaps less likely) equal amounts of drop-out with burst and continuous waveforms. The systematic decrease with increasing frequency is consistent with the notion that the rate of drop-out increases more rapidly with frequency with a continuous waveform.

The threshold measurements thus provide evidence for summation which results in nerve fiber recruitment at stimulus intensities well below those needed for recruitment with single pulses of current. The decrease in relative threshold with increasing frequency indicates that summation occurs more readily at higher kHz frequencies. A predicted consequence of summation is that, when stimulated at intensities above threshold, fibers will fire at multiples of their base or starting frequency, leading to fiber fatigue and drop-out. The variation in relative average torque with frequency (Fig. 7) is readily explicable in terms of more effective summation at higher frequencies and greater summation effects with a continuous AC waveform.

What remains to be explained is the reason that the trends seen between 1 kHz and 10 kHz (Figs. 6 and 7) do not seem to be followed at higher frequencies and the reason that spikes, dips, and raggedness
appear in the torque versus stimulus-voltage graphs but only at high frequencies.

The frequency of occurrence of dips is similar for continuous-, burst-, and single-sinewave stimulation (Table 1). Any explanation must therefore be independent of summation and harmonic excitation, which could not occur with a single-sinewave stimulus. A possible explanation is block of tonic activity. The Hodgkin–Huxley membrane equations predict that subthreshold stimulation will produce conduction block by partial depolarization of the nerve fiber membrane. If the membrane is partly depolarized, there is an inactivation of the sodium gates and the greater the (subthreshold) depolarization, the less excitable is the membrane. This prediction has been verified experimentally in single-fiber studies. Tonic muscle activity is a result of low-frequency asynchronous firing of motor nerve fibers, which induces a low-level “resting” tension in the muscle. Block of transmission of tonic action potentials would result in a dip in the torque-stimulus voltage graph when the normal baseline activity is blocked. That this does not show in all subjects perhaps reflects a lower level of baseline activity in some, making any diminution too small to be noticeable.

Subthreshold spikes and raggedness were found almost exclusively with continuous- and burst-stimulus waveforms and therefore are likely to be a consequence of rapid repetition of the sinusoidal pulses. Raggedness can be attributed to high levels of fiber drop-out. As noted previously, at stimulus intensities above threshold, harmonic excitation is predicted as a result of rapid summation, and this occurs more readily at higher kHz frequencies. In the absence of drop-out, we would expect a smooth, continuous increase in torque up to some maximum. The jaggedness of graphs such as those shown in Figure 4 suggests sudden drop-out involving an appreciable proportion of the excited fibers. Thus, the graphs have rapid rises as a result of the “normal” process of recruitment and harmonic excitation and sudden dips as nerve fibers, stimulated suprathreshold, and firing at higher harmonics of the base frequency abruptly cease to produce a motor response.

Spikes were seen only at 15 kHz and 25 kHz, and of the 15 occurrences, six were found when 25 kHz AC in 10-ms bursts at 50 Hz was used. If the onset of the spike, rather than the onset of rapidly rising torque, is taken as threshold, then it is likely that the leveling out seen in Figure 6 would not exist. Unfortunately, only about 10% of the graphs showed a spike (15 of the total of 168 data sets), so this hypothesis is difficult to test. However, of the 15 occurrences of spikes, six were found with 10-ms, 50-Hz bursts at 25 kHz, and it is noteworthy that the spike threshold was, on average, 30% of the threshold as defined. This indicates that if a true threshold could be measured, the graph in Figure 6 would have a much lower 25-kHz end point. The implication of infrequent spike occurrences is that, more often than not, some nerve fibers are blocked at subthreshold stimulation intensities. The occurrence of subthreshold spikes can be explained as due to some nerve fibers undergoing a brief flurry of high-frequency action potential generation before undergoing block. That the spikes occur only rarely, together with the observation of elevated thresholds above 10 kHz for all subjects, suggests that on most occasions, drop-out occurs without any prior motor activity. This cannot be explained by neurotransmitter depletion or failure at the level of the muscle fiber, as, if either of these were the process, motor activity would always precede drop-out. The implication is that block is occurring at the level of the nerve fiber membrane and that it can occur without generation of action potentials.

A study by Solomonow et al., who used high-frequency stimulation (600-Hz pulses) to block imposed motor activity, found that a 2-s block imposed during a 30-s contraction was associated with greater fatigue than when the contraction was not blocked. This implies increased neural activity induced by the blocking stimulus and suggests neurotransmitter depletion as the mechanism. Bowman and McNeal measured single-fiber activity induced by high-frequency stimuli and found that at and below 1 kHz, nerve firing frequencies were equal to, or were a subharmonic of, the stimulus frequency and that true conduction block did not occur. This indicates that the cessation of muscle fiber activity found in earlier work was occurring at or beyond the motor end plate. True block was found only at frequencies of 4 kHz or higher. It was induced more readily at higher kHz frequencies and, if the blocking stimulus was applied abruptly, block was always preceded by high-frequency nerve firing. The duration of the high-frequency firing became shorter with higher blocking frequencies. The authors found, however, that high-frequency firing was not a necessary precursor to conduction block. Using a 4-kHz continuous-waveform stimulus abruptly applied at full intensity, high-frequency nerve fiber firing rates were always produced. After a few seconds of high-frequency firing, electrical activity ceased and conduction block was induced. When the stimulus was slowly ramped in intensity, rather than abruptly applied at full intensity, conduction block was produced without any prior high-frequency firing. The authors concluded that muscle relaxation can be produced by two separate means. One is by causing
the nerve to fire at very high frequencies, causing sufficient neurotransmitter depletion to produce transmission failure. The second is by blocking the nerve fiber in the region closest to the stimulating electrode.

The findings of the present study are consistent with the notion that both neurotransmitter depletion and direct nerve block are phenomena associated with kHz-frequency transcutaneous stimulation and that the effects increase with increasing frequency. The results help to explain the findings of an earlier study, which used 10-ms bursts of AC at a burst frequency of 50 Hz, and found that electrically induced torque at the pain tolerance threshold decreased systematically with frequency in the range 1 kHz to 15 kHz.31 They also help to explain the shape of fatigue graphs,30 which show a progressively increasing rate of fatigue in increasing AC frequency in the range 1 kHz to 10 kHz.

A clinically significant finding of the present study is that the motor response to AC frequencies above 10 kHz displays features that are undesirable in a rehabilitation context. Thus, although higher AC frequencies may offer advantages such as greater separation between motor and pain thresholds29 and AC frequencies may offer advantages such as greater selectivity of neural stimulation.22 Thus, although higher AC frequencies may offer advantages such as greater separation between motor and pain thresholds29 and that the effects increase with increasing frequency.

REFERENCES