Optimal Frequencies for Electric Stimulation Using Medium-Frequency Alternating Current

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Objective: To determine the effect of single cycles of alternating current of various frequencies on sensory and motor thresholds and on relative thresholds (motor threshold/sensory threshold).

Design: Repeated-measures design.

Setting: Laboratory setting.

Participants: University student and staff volunteers (N=16; mean age, 34y).

Interventions: Single cycles of sinewave frequencies between 1 and 35kHz were delivered at 50Hz. The frequencies were applied in a random order.

Main Outcome Measures: The motor and sensory thresholds were recorded at each applied frequency.

Results: Both sensory and motor thresholds showed a smooth decrease to a minimum at approximately 3kHz. The relative threshold reached a minimum close to 9kHz. Comparison with previous studies showed that although absolute thresholds reach a minimum at a frequency that depends on electrode size, the frequency at which the relative threshold is a minimum was independent of electrode size and independent of whether the stimulus was applied as single pulses or in burst mode.

Conclusions: The optimal frequency for transcutaneous stimulation using medium-frequency alternating current depends on the outcome measure used. It would therefore be desirable for clinical stimulators to provide a selection of carrier frequencies.

Key Words: Electric stimulation; Electrode; Rehabilitation.

MEDIUM-FREQUENCY alternating currents (MFACs), defined as currents in the frequency range 1 to 10kHz, are used extensively in rehabilitation.[1-3] The 2 most commonly used frequencies are 4kHz (interferential currents) and 2.5kHz (Russian currents). A rationale for using currents in the kilohertz frequency range is that the skin acts as a capacitive barrier to the flow of current.[3] As the frequency of the applied current increases, the skin offers a progressively lower impedance. At the kilohertz level, the skin impedance is very low[4,5] so less electrical energy dissipates in the superficial epidermis, and a higher proportion of electrical energy is available to stimulate the underlying tissue. This can be particularly important when motor nerves, usually deeper, are to be stimulated.[4]

MFAC is usually modulated to produce bursts of sinusoidal current. The frequency of these bursts typically ranges from 1 to 150Hz. It is assumed that the nerve fiber response to successive kilohertz frequency pulses, which are produced by each cycle of the alternating current stimulus, will summate to produce a single-action potential in response to each burst of MFAC. Because nerve firing is expected to occur at the modulation frequency, the physiologic and therapeutic effects might be expected to be the same as for low-frequency pulsed currents. On this basis, we would predict little variation in response to carrier frequency other than that caused by changes in skin impedance. That is, the higher the carrier frequency, the more efficient the stimulation of more deeply located nerves.

The situation is, however, more complex. A previous study[6] examined the variation in stimulus intensity (voltage) required to initiate different physiologic responses using MFAC frequencies in the range of 1 to 35kHz. We measured the variation in sensory, motor, and pain thresholds using 10-ms bursts delivered at a burst frequency of 50Hz and found that all thresholds decreased to a minimum at about 10kHz and then increased sharply. The downward trend between 1 and 10kHz, predicted by the decreasing skin impedance, was not sustained at higher frequencies. We also found that the separation between pain and motor thresholds, measured as the ratio pain threshold:motor threshold, was at a maximum at approximately 10kHz. Conversely, the separation between motor and sensory thresholds, measured as the ratio motor threshold:sensory threshold, was at a minimum at this frequency. A conclusion drawn from these findings was that, for the most comfortable stimulation, the optimal frequency is close to 10kHz.

Questions arise as to what extent the findings are generalizable. For example, would using different-size electrodes change the optimal frequency? This question was prompted by a recent study of motor thresholds[7] that compared 10-ms, 50-Hz bursts with single sinewave stimuli using larger electrodes than those used in our previous study (5.5 times the area). With 10-ms bursts applied via the larger electrodes, the resulting graph of motor threshold versus frequency showed a minimum closer to 5kHz than to 10kHz. Motor thresholds from the 2 studies[6,7] (standardized to a mean of 100 to facilitate comparison) are plotted in figure 1. Regression analysis gives best-fit estimates of the minima as 9.3 ± 1.1kHz with the smaller electrodes and 5.1 ± 0.4kHz with the larger electrodes. Another observation of the effect of using larger electrodes[7] with single sinewave stimuli (rather than 10-ms bursts) is that the minimum occurs at a lower frequency (3.8 ± 0.3kHz) but that the change in minimum frequency is smaller. This suggests that electrode size is much more important than whether single sinewave or burst stimulation is used.

Because the minimum in the graph of motor threshold versus frequency depends strongly on the electrode size, the question arises whether the relative threshold motor threshold/sensory

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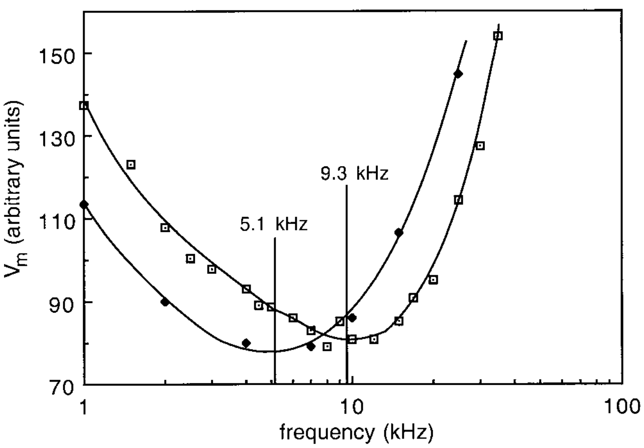

Fig 1. The effect of electrode size on the variation in motor threshold (V_m) with MFAC frequency. MFAC 10-ms bursts applied at a burst frequency of 50Hz. Minimum threshold frequencies are shown for each. Legend: ⊡, small electrodes (3.2cm^2); ◆, large electrodes (17.6cm^2).

threshold, and by inference the optimal frequency for comfortable motor stimulation, varies in the same way. In a previous study,[6] we found that the separation between sensory and pain thresholds increased smoothly with frequency in the range 1 to 35kHz, whereas the separation between motor and pain thresholds reached a maximum at about 10kHz. Consequently, relative to the sensory threshold, the motor threshold decreased to a minimum around 10kHz and then increased. Figure 2 shows graphs of pain threshold/motor threshold and motor threshold/sensory threshold using data from that previous study.[6]

Unfortunately, in our recent study,[7] which used larger electrodes, we only measured motor thresholds using burst mode stimulation. Because we did not measure sensory or pain thresholds, no comparison of relative thresholds (pain/motor or motor/sensory) could be made. The question of whether the optimal frequency for comfortable motor stimulation depends on electrode size therefore remained unanswered, as did the relative contribution of burst mode stimulation.

The present study examined the MFAC frequency dependence of sensory and motor thresholds using larger electrodes (the same size as used in our previous study[7]) and MFAC single sinewave pulses. We did not measure pain thresholds because, with larger electrodes and a single pulse rather than a burst of pulses, the stimulus intensities required at the higher frequencies were beyond the output capability of the stimulator.

METHOD

The 16 subjects participating in the present 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 in which the electrodes were to be placed, or known neurologic or musculoskeletal pathologies affecting the upper limb to be tested. The group of subjects consisted of 8 women and 8 men drawn from staff members and students of the university (age range, 21–54y; mean, 34y). Approval for the study was obtained from the Ethics Committee of the Faculty of Health Sciences of La Trobe University, Victoria, Australia, before the study began.

After the procedure to be used was explained to each subject, conductive rubber electrodes[a] (44×40mm) were attached to the skin on the left forearm. The forearm skin was first prepared by washing with mild soap, and the proximal electrode was placed 1cm 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.

A stimulator was built to produce single sinewave alternating current pulses with adjustable frequencies; this device is described in a previous study.[7] It consisted of a sinewave generator (1–35kHz) and chopping circuit that could be set to produce single-cycle sinewaves at 50Hz. A zero-crossing detector was used to ensure that only complete sinewaves were gated. All MFAC test frequencies (1, 1.5, 2, 2.5, 3, 4, 4.5, 5, 6, 7, 8, 9, 10, 12, 15, 17, 20, 25, 30, 35kHz) were applied, cathode distally, in a randomized frequency order.

As each frequency was presented to a subject, an experimenter recorded the threshold voltage required to elicit the sensory or motor response being tested. The sensory threshold was defined as the level of applied current at which the subject first perceived cutaneous sensation when the intensity of the applied current was slowly increased. The motor threshold was defined as the lowest level of applied current to produce a minimally perceptible (to the experimenter) contraction of the stimulated muscle. All sensory threshold measurements were made before any motor thresholds were measured because previous experience has shown that sensory thresholds are markedly elevated by prior stimulation to the motor threshold.

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

For each subject, graphs of sensory and motor thresholds versus MFAC frequency were plotted. The graphs showed a similar systematic variation with MFAC frequency and some scatter, which apparently was because of the order of presentation of the stimulus frequencies. When the results were averaged across the 16 subjects, the relatively smooth curves shown in figure 3 were obtained.

Two features of the graphs are particularly noteworthy, namely, the positions of the minima and the slope of the early part of each graph. Each graph has a broad, shallow minimum. For the sensory threshold graph, the minimum is at 3.0± 0.4kHz. The motor threshold graph has a minimum at 3.4± 0.3kHz. The slope of the motor threshold graph between 1kHz and the minimum is clearly not as great as that found with

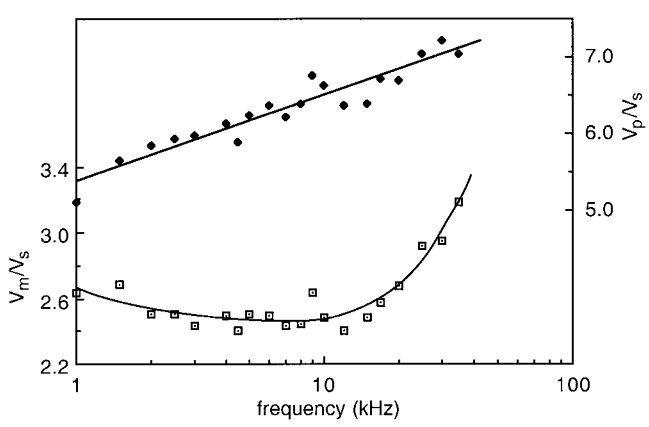

Fig 2. The variation in relative threshold with MFAC frequency. MFAC 10-ms bursts applied at a burst frequency of 50Hz with small electrodes (3.2 cm^2). Legend: ⊡, motor threshold/sensory threshold (V_m/V_s); ◆, pain threshold/sensory threshold (V_p/V_s).

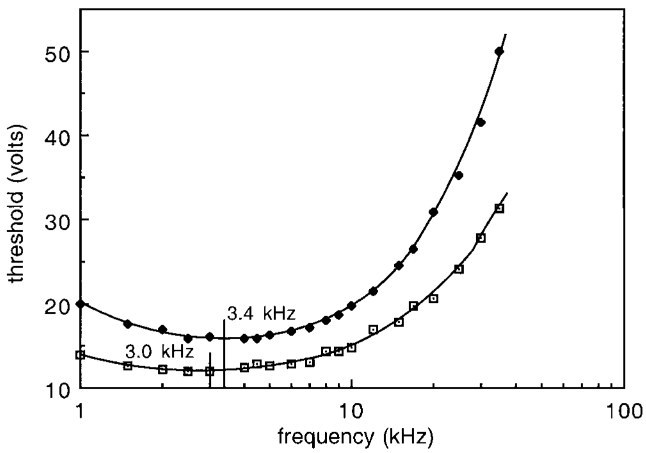

Fig 3. The variation in sensory and motor thresholds with MFAC frequency. Single-sinewave stimuli applied at a frequency of 50Hz using large electrodes (17.6cm^2). Minimum threshold frequencies are shown for each. Legend: ⊡, sensory threshold (V_s); ◆, motor threshold (V_m).

10-ms burst stimulation (see fig 1), either with the same size or smaller electrodes.

The data plotted in figure 3 were used to calculate the ratio (motor threshold:sensory threshold) at each frequency. These relative threshold values are plotted in figure 4, together with relative threshold values from our previous study,[6] which used smaller electrodes and 10-ms burst stimulation at 50Hz.

The most interesting feature of the relative threshold graphs is that the minima occur at essentially the same frequency. The results of the present study, using large electrodes and single-sinewave stimuli, showed a minimum at 9.2±2.1kHz while results of our previous study,[6] which used small electrodes and 10-ms burst stimulation, showed a minimum at 8.4±2.1kHz. The closeness of the minima with respect to their standard deviations indicates that the difference was statistically insignificant. Combining these 2 results to produce a weighted mean gives a best estimate of the minimum, the optimum frequency for comfortable low-level motor stimulation. The weighted mean is 8.8±1.5kHz.

DISCUSSION

Several conclusions can be drawn from the findings of the present study when compared with previous findings.

Variation in Thresholds

If optimal frequency is taken as meaning the frequency at which minimum stimulus voltage is needed to reach sensory or motor threshold, then there is no fixed optimal frequency because these thresholds depend on electrode size (see fig 1).

A likely explanation for the minimum threshold voltage depending on electrode size is that the measured threshold reflects a balance between the effects of decreasing skin impedance with increasing MFAC frequency and decreasing sensitivity of nerve fibers. The nerve fiber membrane, like the skin, acts as a capacitative barrier.[8] This means that when a stimulus is applied to the nerve fiber, current must flow for a sufficient period of time to charge the membrane enough to produce an action potential. If the stimulus duration is short, then a higher intensity is needed to reach the nerve-firing threshold. This, of course, is the explanation for the strength-duration behavior seen with rectangular pulsed current stimulation and also explains the nerve fiber response to single-cycle MFAC stimulation. The higher the MFAC frequency, the shorter the duration of the sinusoidal pulses and the greater the stimulus intensity needed to reach threshold. Thus the nerve fiber effectively becomes less sensitive, that is, a higher stimulus intensity must be applied to it to produce depolarization of the membrane at higher MFAC frequencies. The frequency at which the threshold is a minimum therefore depends on the balance between decreasing skin impedance and decreasing nerve fiber sensitivity. At lower frequencies, threshold decreases because of the domination of the decrease in skin impedance. At higher frequencies, threshold increased because of the decreasing sensitivity of the nerve fiber membrane.

On this basis, the shift of the minimum in figure 1 can be attributed to a change in the skin impedance with the change in electrode size. Because the skin impedance is reduced with larger electrodes, whereas the nerve fiber properties are unchanged, the balance is shifted and the minimum in the graph occurs at a lower frequency.

Comparison of figures 1 and 3 shows that the shape of the threshold graphs is different for 10-ms burst and single-sinewave stimulation. Thresholds decrease more rapidly over the lower kilohertz frequency range with 10-ms bursts. This is readily explained in terms of the so-called Gildemeister effect. Gildemeister[9,10] established that, with bursts of MFAC, the longer the burst duration, the lower the threshold. This is because, at kilohertz frequencies, the current pulses are sufficiently close together for summation of subthreshold stimuli to occur. Successive pulses within an MFAC burst push the nerve fiber membrane closer to threshold until an action potential is produced. Thus, threshold is reached at a lower-stimulus intensity than would be needed for a single pulse. Gildemeister also established that summation becomes more effective at higher MFAC frequencies with the effect continuing to frequencies as high as 100kHz (the highest used in his studies in which he noted that thermal effects began to outweigh direct electrical effects on nerve). The more rapid decrease in threshold with burst mode stimulation is, we argue, a direct consequence of summation, which is more efficient at higher frequencies because successive pulses are closer together.

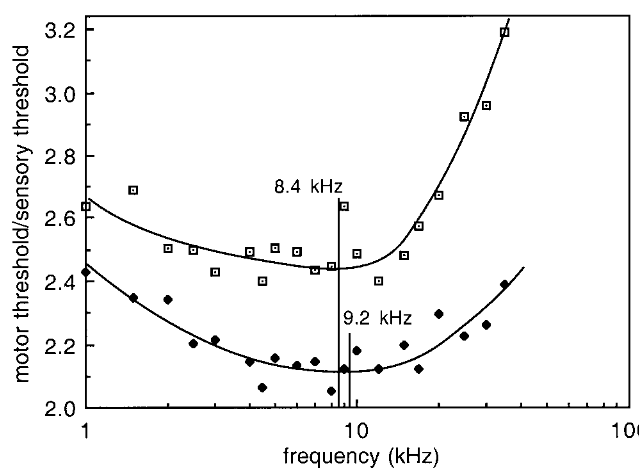

Fig 4. The variation in motor threshold/sensory threshold (V_m/V_s) with MFAC frequency. Minimum relative threshold frequencies are shown for each. Legend: ⊡, relative thresholds using small electrodes and 10-ms bursts of MFAC at 50Hz; ◆, relative thresholds using large electrodes and single-sinewave stimuli at 50Hz (present study).

Variation in Relative Threshold

Although the minima in the sensory and motor threshold graphs depend on electrode size, the minimum in the relative threshold graphs does not. The ratio (motor threshold:sensory threshold) has the same minimum with a more than 5-fold increase in the electrode size. The motor threshold is closest to the sensory threshold at this frequency and, based on the findings of our previous study (fig 2),[6] is therefore furthest from the pain threshold. Whether the MFAC is applied in 10-ms bursts or as single sinewaves affects the shape of the graphs but makes little or no difference to the optimal frequency. The lack of any appreciable variation suggests that the optimal frequency is determined by the electrical characteristics of the nerve fibers and not the electrical properties of the skin or the duration of delivery. The conclusion of our earlier study[6] that the optimal frequency for the most comfortable stimulation is close to 10kHz is now shown to apply regardless of electrode size, burst, or single-sinewave stimulation. This lends further support to our previous contention[6] that the frequencies commonly used for Russian and interferential stimulation, 2.5 and 4kHz respectively, are less than optimal for comfortable motor stimulation.

Optimal in What Sense?

The question of what is the optimal frequency for stimulation using MFAC currents has no answer. It depends on the desired outcome. Our earlier study,[6] which measured sensory, motor, and pain thresholds, found a maximum discrimination between motor and pain thresholds (and, conversely, minimum separation between motor and sensory thresholds) at around 10kHz. The present study confirms this finding and refines the estimate to a frequency of 8.8 ± 1.5kHz. The clinical implication is that if the objective is to produce low-level muscle contractions, such as those that might be used for muscle reeducation or stimulation of lymphatic drainage, with least risk of pain and minimal supra-threshold sensory stimulation, a frequency close to 9kHz is optimal.

The present study also establishes that the optimal frequency for threshold stimulation, that is, the frequency when the absolute threshold is lowest, depends on the electrode size. The larger the electrode size, the lower the optimal frequency.

Although 9kHz may be an optimal frequency for pain-free, low-force muscle contractions, it is not an optimal frequency for force production. A previous study[11] that measured torque production using small electrodes ($3.2cm^2$) and examined frequencies in the range 1 to 15kHz delivered as 10-ms bursts at 50Hz, found that maximum electrically induced torque was produced at 1kHz. A conclusion was that the optimal frequency for torque production is 1kHz or less. It has yet to be established whether this conclusion is also applicable to single-sinewave stimuli.

Implications for Low-Frequency Pulse Stimulation

Transcutaneous electric nerve stimulation is often applied using low-frequency, short-duration rectangular pulses. The finding of the present study, that there is an optimum frequency for low-level force production, which is the same for single sinewave stimuli and bursts of MFAC, is of direct relevance to low-frequency pulse stimulation. If there is an optimum frequency for single sinewave stimulation, then there should also be an optimal pulse width for low-frequency rectangular pulsed current. The argument is as follows. The relative threshold (motor threshold/sensory threshold) has a minimum at about 9kHz. At an MFAC frequency of 9kHz, the sinewave duration is 1/9000 seconds or $110\mu s$. The equivalent rectangular pulse width is one half of this value (about $55\mu s$). Hence, a pulse width close to $55\mu s$ should be optimal for low-level motor stimulation. The only study that has examined sensory, motor, and pain discrimination as a function of pulse width using transcutaneous stimulation appears to be Alon et al[12]; and although relative values appear to show an optimum at 50 or $100\mu s$, the limited number of pulse widths examined and the overall scatter in the results prevent any firm conclusions from being drawn. This finding suggests that the effect of pulse width on sensory, motor, and pain responses using low-frequency rectangular pulse stimulation should be reexamined. It also suggests that the effect of pulse width on maximum torque production merits reexamination. If the frequency for maximum torque production using MFAC burst stimulation is 1kHz, there exists the possibility of an optimum pulse width of $500\mu s$. Further study of optimal pulse widths for low-frequency rectangular pulsed current is clearly indicated.

CONCLUSION

The optimal frequency for transcutaneous stimulation clearly depends on the outcome measure used. The results of the present study, taken together with previous findings, indicate an optimal frequency for pain-free, low-force muscle contractions of close to 9kHz. This figure is independent of electrode size and burst-mode or single-sinewave delivery. By contrast, the frequency at which the absolute threshold is lowest depends on electrode size. The frequency for maximum torque production with 10-ms burst mode delivery was shown in a previous study to be 1kHz or less. The implication is that clinical MFAC stimulators, whether offering Russian or interferential currents, should provide a selection of carrier frequencies to accommodate different desired outcomes.

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