Comparison of Maximum Tolerated Muscle Torques Produced by 2 Pulse Durations

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Background. Neuromuscular electrical stimulation (NMES) is an effective therapeutic technique for strengthening weak muscles. A positive dose-response relationship exists between the elicited muscle forces during training and strength (force-generating capacity) gains. Patient discomfort limits NMES muscle forces, potentially compromising efficacy.

Objective. The purpose of this study was to compare the NMES muscle torques produced by stimulation trains consisting of 2 different pulse durations.

Design. During a single testing session, the 2 pulse duration conditions (50 and 200 microseconds) were tested on the opposite lower extremities of the participants.

Methods. The study participants were 10 adults without remarkable medical histories. The maximum tolerated isometric knee extensor torque was the primary dependent variable. The peak currents and phase charges that produced the maximally tolerated torques, as well as the sensory, motor, and pain thresholds for the 2 pulse conditions, were compared.

Results. The 200-microsecond pulse duration condition resulted in participants tolerating significantly greater muscle torques; it was associated with significantly greater phase charges but significantly lower peak currents.

Limitations. This study only compared muscle torques in response to stimulation trains consisting of pulses with short (50-microsecond) or medium (200-microsecond) durations and did not examine long (~400- to 600-microsecond) durations. Furthermore, the result of this study may not apply to NMES that uses stimulation patterns other than monophasic, square-wave pulsed current.

Conclusions. It has been suggested that short pulse durations are most appropriate for NMES because they are less likely to recruit nociceptors. The results of this study, however, support the use of a medium pulse duration rather than a short pulse duration when the goal is to produce a maximum torque response from a muscle. These observations may be related to the currents and phase charges for the pain thresholds for the 2 pulse duration conditions.

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Neuromuscular electrical stimulation (NMES) is an effective therapeutic technique for strengthening weak muscles in patient populations.[1–4] Furthermore, a positive dose-response relationship exists between NMES-elicited muscle forces during training and strength (force-generating capacity) gains.[1,2] The goal for strengthening with NMES, therefore, should be to produce the highest forces possible in order to produce the largest and most rapid strength improvements. The muscle force elicited by NMES is limited by patient discomfort, typically not exceeding 80% of the voluntary muscle peak force-producing capacity, thereby potentially compromising the efficacy of strengthening with NMES.[5]

Multiple stimulation parameters affect the force response of muscle, creating a large number of possible NMES parameter combinations. Though there have been many studies investigating modifications to one or more parameters, including frequency, current amplitude, pulse duration, and waveform, these studies often are contradictory, and no optimal setting has been identified.[6–9] The phase charge, a product of current amplitude and pulse duration, of the individual stimulation pulses influences the recruitment of nerves. Nerves can be recruited by many different combinations of these 2 parameters, and different receptors (sensory, motor, and nociceptor) have different phase charge thresholds that can be plotted along a current amplitude–pulse duration curve.[10,11] Van Swearingen[11] suggested that the fact that it takes greater increases in current amplitude at relatively short versus long pulse durations to reach the nociceptor stimulation threshold after the motor threshold has been reached makes short pulse durations more appropriate for NMES. Recruitment of nociceptors is assumed to contribute significantly to the limited muscle forces that patients can tolerate during NMES.[10,11]

The research literature on this subject is difficult to interpret because pulse duration typically has been varied along with other characteristics of the stimulation, such as waveform or current type. Research by De Domenico and Strauss,[12] for example, demonstrates this problem. They compared the maximum tolerated peak quadriceps femoris muscle torques from 7 different types of stimulators and did not identify differences that could be explained by pulse duration, which varied from 25 to 250 microseconds. The only significant difference detected was between the 2 stimulators that produced the lowest torques, and in that case a 25-microsecond pulse duration stimulator produced higher torques than a 100-microsecond pulse duration stimulator. Pulse duration, however, was only one variable that differed between the stimulators; waveform, current type, and frequency also varied.

The purpose of this study was to test the theory that a relatively short versus a medium pulse duration would result in people tolerating greater muscle torques during NMES. We hypothesized that the short pulse duration would allow for the production of higher muscle torques and that higher peak currents and phase charges would be associated with these greater muscle torques. Additionally, we hypothesized that participants' perceived pain or discomfort, based on a numeric pain scale, would be similar at the time they reached the maximum tolerated muscle torques for the 2 pulse duration conditions.

Method

Participants

Eleven recreationally active adults (4 female, 7 male; mean age=25.8 years, SD=3.9) without a history of cardiovascular disease, neurological disease, or musculoskeletal dysfunction of the thigh or knee were recruited for the study. Additionally, individuals with cardiac pacemakers or other electronic implants were excluded. Participants who reported or demonstrated an aversion to the sensation of electrical stimulation were removed from the study. All participants gave written informed consent prior to the study.

Procedure

Prior to muscle testing, all participants performed a 5-minute warm-up on a Lode cycle ergometer* at a low work rate. Each participant then was positioned in a HUMAC NORM force dynamometer† to measure knee extensor torque. Nonelastic shoulder and waist straps secured the participant firmly in position. The participant's lower extremity was secured with a pad positioned just superior to the ankle malleoli. The axis of rotation of the dynamometer lever arm was aligned with the axis of rotation at the knee. The dynamometer was set to hold the knee in 90 degrees of flexion in isometric mode. Isometric contractions minimize the discomfort associated with NMES by preventing the stimulated muscles from contracting into a shortened position, which can produce a painful cramping sensation. Electrical stimulation in the form of monophasic, square-wave pulses was delivered by a Digitimer DS7AH stimulator‡ interfaced with a Digitimer DG2A train/delay generator.‡

There were 2 different test conditions for this study: electrical stimulation with 50-microsecond pulse durations and with 200-microsecond

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[*] Lode BV, Zernikepark 16, 9747 AN, Groningen, the Netherlands.

[†] Computer Sports Medicine Inc, 101 Tosca Dr, Stoughton, MA 02072.

[‡] Digitimer Ltd, PO Box 501, Letchworth, Garden City, SG6 9BL United Kingdom.

pulse durations. Based on muscle torque versus pulse duration relationships, a 50-microsecond pulse duration is very short and produces relatively low forces (<20%) compared with pulse durations of approximately 400 to 600 microseconds, which are at the plateau of the relationship and produce the highest forces.[9,13] A 200-microsecond pulse duration is near the midpoint of the relationship, producing approximately 50% to 60% of the torque produced at the longer pulse durations that maximize force production.[9,13] The first test condition was carried out on one of the participants' lower extremities, and the second condition was carried out on the opposite lower extremity. The order in which the participants' lower extremities were tested and the order in which the pulse duration conditions were tested were randomized.

Table 1.
Peak Currents and Phase Charges at the Sensory, Motor, and Pain Thresholds and at the Maximum Tolerated Torques[a]

Variable	Measurement	
Pulse duration (μs)	50	200
Sensory threshold current (mA), $\bar{X}$ (SD)	54 (19)	19 (6)
Sensory threshold phase charge (μC), $\bar{X}$ (SD)	2.7 (0.9)	3.8 (1.1)
Motor threshold current (mA), $\bar{X}$ (SD)	102 (26)	39 (7)*
Motor threshold phase charge (μC), $\bar{X}$ (SD)	5.1 (1.3)	7.8 (1.3)
Pain threshold current (mA), $\bar{X}$ (SD)	384 (129)	185 (74)†
Pain threshold phase charge (μC), $\bar{X}$ (SD)	19.2 (6.5)	36.9 (14.9)†
Peak current at maximum tolerated torque (mA), $\bar{X}$ (SD)	372 (69)	148 (34)†
Phase charge at maximum tolerated torque (μC), $\bar{X}$ (SD)	18.6 (3.5)	29.6 (6.7)†

[a] Asterisk (*) indicates significant difference between conditions at $P<.01$, dagger (†) indicates significant difference between conditions at $P<.001$.

Following positioning in the dynamometer, the participants performed 3 maximal volitional isometric contractions (MVICs) to determine maximum voluntary knee extensor torque capacity. They were given verbal encouragement to promote maximal efforts during these trials. The maximum peak torque produced during the MVICs was used as the reference for determination of the percentage of maximum peak torque produced during electrical stimulation. After MVIC testing, large (7.62-×12.7-cm [3-×5-in]) electrodes[§] were placed on the anterior thigh approximately 30.5 cm (12 in) apart, with the cathode placed proximally over the rectus femoris muscle and the anode placed distally over the vastus medialis muscle.

The testing protocol for each pulse duration condition had 2 parts: (1) to determine the thresholds for sensory, motor, and pain responses and (2) to determine the maximum tolerated peak torque produced by a train of electrical stimulation. Determination of sensory, motor, and pain thresholds utilized a 5-pps, 1-second train of electrical stimulation. A low-frequency stimulation train was used to determine the thresholds in order to avoid high muscle forces that might affect the pain threshold by producing discomfort independent of the recruitment of nociceptors. During threshold testing, an investigator blinded to the stimulation parameters recorded the participants' self-reports of sensory and pain thresholds, as well as determining when visible muscle twitches first occurred, indicating the motor threshold was reached. Participants reported their level of discomfort after delivery of each stimulation train throughout all stages of testing using an 11-point nu-

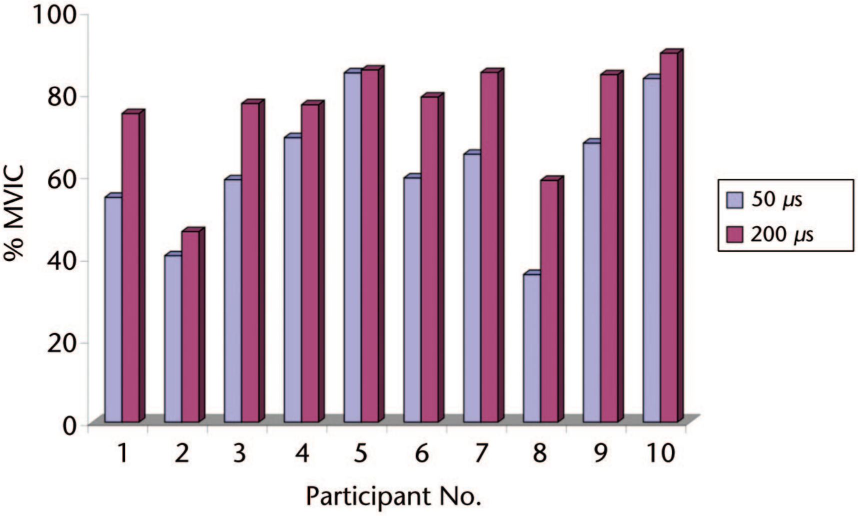

Figure 1.
Individual participant data for the percentage of maximal volitional isometric contraction (MVIC) produced during neuromuscular electrical stimulation in response to stimulation trains containing 50- or 200-microsecond monophasic, square-wave pulses.

[§] Vision Quest Industries Inc, 18011 Mitchell S, Ste A, Irvine, CA 92614.

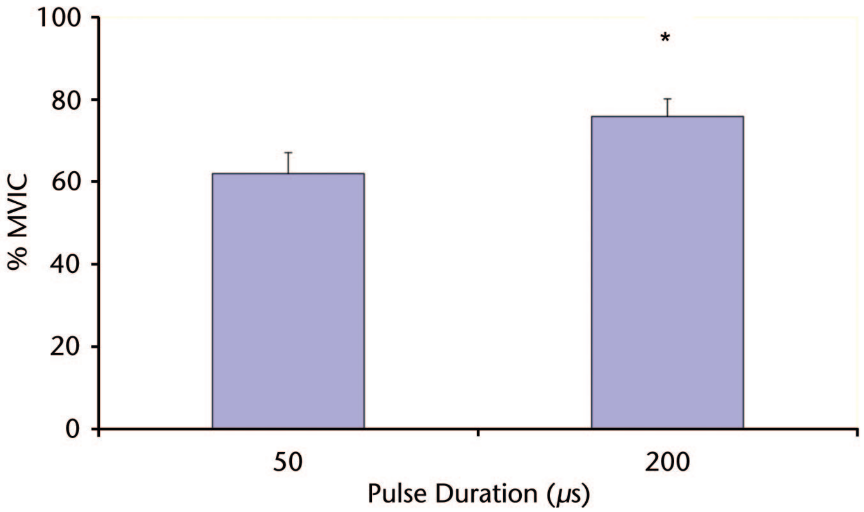

Figure 2.
Means and standard errors of the percentage of maximal volitional isometric contraction (MVIC) produced in response to the 50- or 200-microsecond pulse duration stimulation trains. Asterisk (*) indicates significant difference between 50- or 200-microsecond pulse duration conditions ($P<.001$).

meric pain scale (0 representing "no pain" and 10 representing "worst pain imaginable").

The second phase of testing determined the maximum tolerated torque produced in response to a train of electrical stimulation of 1-second duration with a frequency of 75 pps. The motor threshold obtained in the threshold testing was used as the starting current amplitude. After a brief rest period (1–2 minutes, used for adjustment of the stimulator), one train of stimulation was delivered approximately every 30 seconds as the current amplitude was incrementally increased until the participants reached the maximum amplitude that they were willing to tolerate or reported a perceived pain level of 7 or higher. The current increases ranged from 5 to 50 mA, depending on the pulse duration, the size of the participant, and the elicited torque response (eg, larger increments were used at the beginning of the testing, when the torque responses were relatively weak). Participants were aware that we were interested in measuring the maximum muscle torque that they were willing to tolerate in response to NMES and that reporting a pain level greater than 6 would terminate the testing session. Therefore, for most participants, 7 became the value they reported when they reached the maximum intensity that they were willing to tolerate. Torque production was recorded for each stimulation train delivered. Participants were instructed to "relax and let the stimulation make your muscle contract." During testing, the participants were blinded to the stimulation parameters and the muscle torque output. After completion of this stage of testing, the participants were given a brief rest before testing of the second pulse duration condition commenced on the opposite lower extremity with the same protocol.

Data Analysis

Means and standard deviations were calculated for the electrically stimulated percentages of the maximum MVIC torques, the peak currents and phase charges that elicited the maximum torque responses, and the sensory, motor, and pain thresholds for both pulse duration conditions. The phase charges were calculated as the product of the current and the pulse duration because the stimulator delivered monophasic, square-wave pulses and are reported in microcoulombs. Statistica software[‖] was used to analyze the data. Separate repeated-measures, 2-way analyses were used to compare the peak currents and phase charges required to reach sensory, motor, and pain threshold responses during each pulse duration condition. Paired *t* tests, with a Bonferroni correction for multiple comparisons, were used for *post hoc* testing. Paired *t* tests also were used to compare the mean differences in maximum torques and the peak currents and phase charges that elicited the maximum responses during the 50- and 200-microsecond pulse duration conditions.

Results

Ten participants were included in the data analysis; one participant did not complete the testing due to an aversion to electrical stimulation. For the peak currents, there were significant main effects for the threshold type and pulse duration condition, as well as a significant interaction effect. Similar results were observed for the phase charges ($P<.001$ for all comparisons). Significant differences of interest identified with the *post hoc* analyses were greater peak currents at the motor and pain thresholds in the 50-microsecond pulse duration condition versus the 200-microsecond pulse duration condition, and although there was no difference in phase charges at the motor thresholds, lower phase charges elicited pain in the 50-microsecond condition versus the 200-microsecond condition (Tab. 1).

[‖] StatSoft Inc, 2300 E 14th S, Tulsa, OK 74104.

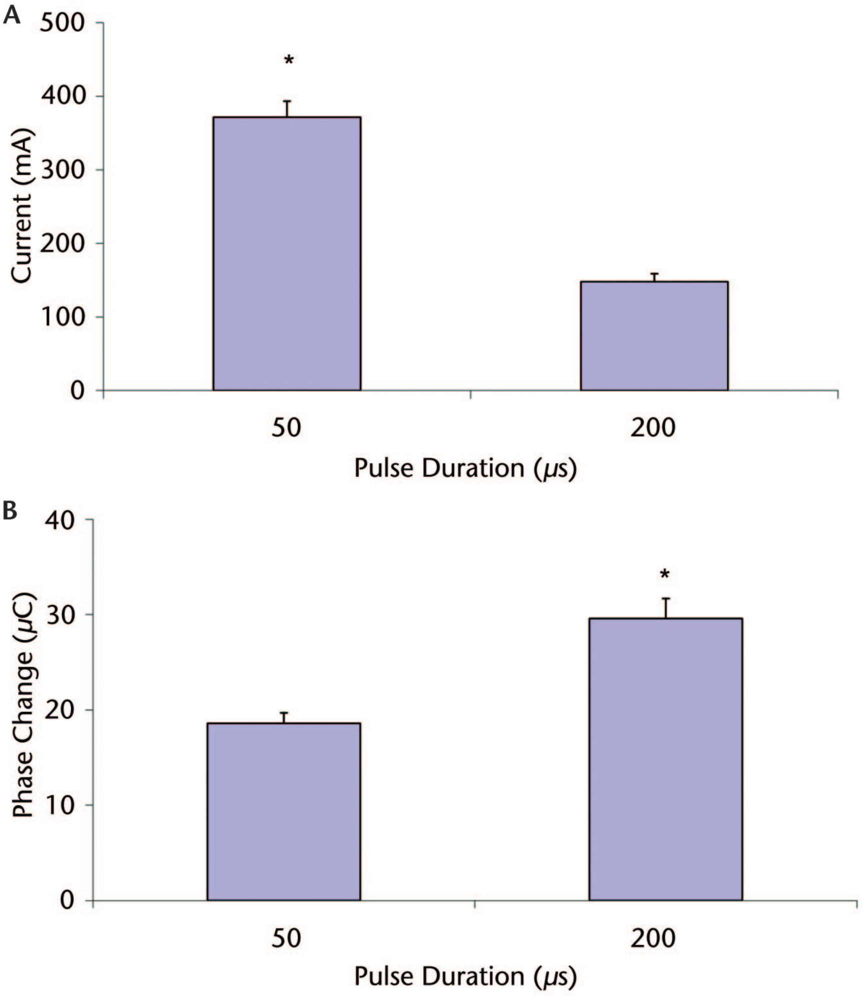

Figure 3.
Means and standard errors for the currents (A) and phase charges (B) that produced the maximum tolerated neuromuscular electrical stimulation torques in the 50- and 200-microsecond pulse duration conditions. Lower peak currents but higher phase charges occurred in the 200-microsecond condition that produced greater torques. Asterisk (*) indicates significant difference between conditions ($P<.001$ for both).

For all 10 participants, a greater percentage of the available muscle torque was produced in the 200-microsecond pulse duration condition (Fig. 1). The 200-microsecond pulse duration condition elicited 14% more of the available knee extensor torque ($\bar{X}=76\%$, SD=13%) compared with the 50-microsecond pulse condition ($\bar{X}=62\%$, SD=16%), which was statistically significant ($P<.001$) (Fig. 2). The peak currents at the maximally tolerated torques in the 200-microsecond condition ($\bar{X}=148$ mA, SD=34) were only 40% of those in the 50-microsecond condition ($\bar{X}=372$ mA, SD=69) (Fig. 3A), whereas the phase charges were 59% greater ($\bar{X}=29.6$ μC, SD=6.7 versus $\bar{X}=18.6$ μC, SD=3.5) ($P<.001$ for both) (Fig. 3B).

Differences between self-reported pain levels at the maximally tolerated muscle torques were minimally variable between the 2 test conditions and, therefore, did not permit statistical analysis (Tab. 2). However, it is notable that 8 participants reported identical pain ratings for both pulse duration conditions at the time testing was stopped, whereas the 2 remaining participants reported lower pain levels in the 200-microsecond condition at termination of testing.

Discussion and Conclusions

The primary purpose of this study was to investigate the effect of 2 different pulse durations on the NMES-elicited muscle torques that participants could tolerate. Contrary to our hypothesis, the 50-microsecond pulse duration condition did not result in greater muscle torques compared with the 200-microsecond pulse duration condition. The opposite was the case for both the group data and for the individual data from all 10 participants tested: greater muscle torques were elicited during the 200-microsecond condition. We do not think that the participants tolerated greater discomfort during the 200-microsecond condition because most participants reported the same value on the pain scale for both conditions at the time testing was terminated, and the 2 participants who did not, reported lower values for the 200-microsecond condition than they did for the 50-microsecond condition.

The phase charge at the maximum tolerated muscle torques was 59% greater in the 200-microsecond pulse duration condition than in the 50-microsecond pulse duration condition. This finding was not surprising given that the greater torques produced during the 200-microsecond condition almost certainly resulted from the recruitment of a greater number of motor units. Our findings are in agreement with previous research that showed NMES-generated muscle torque was proportional to the phase charge.[14] The phase charge is considered to be one of the most important characteristics of electrical stimulation that influences the biological response.[10]

Table 2.
Reported Pain Ratings on a Scale of 0 to 10 Points When Testing Was Stopped During the Determination of the Maximum Tolerated Knee Extensor Muscle Torques

Participant No.	50-μs Pulse Duration	200-μs Pulse Duration
1	7	7
2	7	7
3	7	5
4	7	7
5	5	3
6	7	7
7	7	7
8	7	7
9	7	7
10	5	5

More difficult to account for is the observation that participants tolerated greater phase charges and produced more torque in the 200-microsecond pulse duration condition, rather than tolerating similar phase charges and producing similar torques in both conditions. One possible explanation is that although phase charge is an important characteristic that influences motor unit recruitment, it is less important in determining the recruitment of nociceptors. The threshold testing suggests this as well. There was no difference in the phase charges of the motor thresholds, whereas the phase charges for the pain thresholds were significantly less in the 50-microsecond condition and the peak currents were significantly greater. This observation suggests that peak current rather than phase charge may be an important stimulation parameter in determining the recruitment of nociceptors. Important to note, however, is that during the determination of the maximum tolerated torques, the peak currents in the 200-microsecond condition were considerably lower than those in the 50-microsecond condition. Consequently, peak current may be an important determinant of the phase charge that recruits nociceptors at short pulse durations, thereby limiting muscle torques, but not the primary determinant of the maximum phase charge and muscle torques a person tolerates at medium-length pulse durations.

The above discussion is based on the presumption that recruitment of nociceptors is the physiological mechanism that limits NMES muscle torques. Previous research, however, suggests that the discomfort associated with NMES is affected by the muscle forces produced, not just the recruitment of nociceptors.[15] Our study also suggests an important influence of muscle forces on the discomfort associated with NMES. In the 50-microsecond condition, the peak currents and phase charges that produced the maximum tolerated torques were only slightly lower than those that produced pain during the threshold testing and were not significantly different from each other. These observations may suggest that recruitment of nociceptors was the primary mechanism that limited the maximum torques tolerated in the 50-microsecond condition. In contrast, for the 200-microsecond condition, there was a larger difference between the peak currents and phase charges that produced the maximum tolerated torques and those that produced pain during the threshold testing, with a tendency for the peak currents and phase charges to be lower at the maximum tolerated torques ($P=.07$). This observation suggests that in the higher ranges of NMES-elicited muscle forces that people can tolerate, it is the forces themselves rather than the recruitment of nociceptors that may primarily influence discomfort.

We chose to stop testing when a participant reported a pain rating of 7 or higher out of 10 in order to address concerns of the institutional review board regarding causing excessive pain. This choice is a potential limitation to the internal validity of the study. Participants, however, were aware that we were interested in measuring the maximum NMES-elicited muscle torques they were willing to tolerate and that a pain rating of 7 or higher would stop the testing. As long as participants used a similar level of discomfort to stop testing in the 2 conditions, and we can think of no reason why they would not have, our conclusion that participants were able to tolerate greater torques in the 200-microsecond pulse duration condition compared with the 50-microsecond pulse duration condition appears valid. Our primary motivation in reporting the pain ratings was to demonstrate that the reason for the differences between the 2 conditions was not due to participants opting to tolerate more discomfort in one condition versus the other condition.

Regardless of the mechanisms that limit the NMES-elicited muscle forces a person can tolerate, the findings of this study may be important for selection of stimulation parameters to maximize the efficacy of NMES strengthening. Short pulse durations do not appear to be advantageous, rather just the opposite; when a monophasic, square-wave, pulsed current was used, a medium-length pulse duration allowed the participants to tolerate significantly higher knee extensor torques, with levels of discomfort similar to those produced by a short pulse duration. Further work is needed to determine whether 200 microseconds is the optimal pulse duration for eliciting muscle forces with monophasic, square-wave pulsed current or whether longer pulse durations that maximize the effect of pulse duration on motor unit recruitment are optimal. Additionally, the results of this study may not apply to other types of electrical stimulation, such as pulsed current with biphasic waves, alternating current, or other types of waveforms.

All authors provided concept/idea/research design, writing, data collection and analysis, and participants. Dr Scott provided project management and facilities/equipment.

This study was approved by the University and Medical Center Institutional Review Board of East Carolina University.

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