Influence of electrode placement on effective field strength in the superficial digital flexor tendon of horses

Yi-lo Lin, DVM, MSc; Hugo Moolenaar, PhD; P. René van Weeren, DVM, PhD; Chris H. A. van de Lest, PhD

Objective—To determine the relationship between the output of an electrical treatment device and the effective field strength in the superficial digital flexor tendon of horses.

Sample Population—Cadaver horse forelimbs without visible defects (n = 8) and 1 live pony.

Procedure—Microcurrents were generated by a microcurrent electrical therapy device and applied in proximodistal, dorsopalmar, and mediolateral directions in the entire forelimbs, dissected tendons, and the pony with various output settings. Corresponding field strengths in the tendons were measured.

Results—A linear relationship was detected between current and field strength in all conditions and in all 3 directions. In dissected tendons, significant differences were detected among all 3 directions, with highest field strength in the proximodistal direction and lowest in the dorsopalmar direction. In the entire forelimbs, field strength in the proximodistal direction was significantly lower than in the mediolateral direction. Results in the pony were similar to those in the entire forelimbs.

Conclusions and Clinical Relevance—Electrode placement significantly affected field strength in the target tissue. Many surrounding structures caused considerable reduction of field strength in the target tissue. These factors should be taken into account when establishing protocols for electrical current-based therapeutic devices if these devices are proven clinically effective. (Am J Vet Res 2006;67:845–849)

Tendon disorders are a major problem in sports and occupational medicine. Equine flexor tendons are loaded close to their physiologic limit under normal conditions, making them prone to injury. Lesions of the equine SDFT are common in performance horses and often lead to permanent disability because tendon tissue heals poorly through the formation of repair tissue that is functionally inferior to the original tissue. For these reasons, tendon injuries account for substantial losses to the equine industry and are an important threat to equine health.

Many techniques have been tried in attempts to improve tendon healing and minimize the formation of scar tissue. Apart from a limited number of reports on the effect of ultrasound treatment, non-invasive physical techniques have received little attention thus far, although from a practical viewpoint, they are very attractive for use during the prolonged recovery periods that occur in equine tendon healing. Watkins et al. used a pulsing electromagnetic field to treat artificially created tendon lesions. They found a delay in maturation of the scar tissue, probably attributable to a delay in collagen type transformation. A delay in the maturation of the collagen component of the extracellular matrix (ie, the formation of cross-linking) is the rationale behind treatment for tendon lesions with β-aminoproprionitrile fumarate, which has had some popularity in equine medicine. Effects of electrical or electromagnetic treatment that have been reported include alleviation of pain, which might relate to the internalization of substance P receptors, increased cell proliferation in wounds, and stimulation of bone fracture healing. Electrical treatment may further enhance local circulation by increasing the concentration of the vasodilator nitric oxide. This may contribute to modulation of inflammatory reactions and reduction of swelling in the treated area. In rat Achilles tendons, use of a pulsed electromagnetic field results in better collagen alignment and greater reduction of inflammation in tendinitis, compared with sham-treated tendons. Direct current applied in low amperage to rabbit tendons in vitro suppresses adhesion-causing synovial proliferation in the epitendon and promotes active collagen synthesis by the tenocytes. Cell orientation is responsive to electrical fields as well, with current apparently orienting new collagen formation. In a recent study, application of direct pulsating microcurrent (150 Hz) to cultured equine tenocytes stimulated cell metabolism in terms of protein and DNA production at certain current and treatment frequencies. It is also clear that small changes in current may change a beneficial effect at the cell level into a deleterious effect or vice versa. Current passing through the tissue is responsible for the biological effect of electrical therapy. Current (I) is determined by the specific resistance (R), or bioimpedance, of the tissue and the actual field strength (V) according to Ohm’s law (I = V/R). The parts of the body to which electrodes are applied are
multicomposite heterogeneous structures, and the specific bioimpedance of different tissues is not identical. Furthermore, bioimpedance can be expected to change according to fiber direction. These considerations lead to the conclusion that field strengths in various tissues under treatment will not be identical. Therefore, knowledge of the effect of electrode placement on actual field strength in the target tissue is imperative if, at some stage, clinical trials are to be performed. The purpose of the study reported here was to determine the relationship between the output of an MET device and the effective field strength in the SDFT of horses. Our hypothesis was that because of the influence of surrounding tissues and the specific spatial arrangement of the tendon fibers, effective field strength will be affected substantially by electrode placement.

Materials and Methods

Study overview—Various settings of an MET device were applied to fresh, isolated SDFTs; fresh, intact forelimbs; and an anesthetized pony, with 3 standardized electrode placements. Custom-made probes were used to measure effective field strength, and the relationship between machine settings and field strength was determined.

For the ex vivo study, 8 equine forelimbs without visible defects or diseases were obtained fresh (≤ 6 hours after euthanasia) from a slaughterhouse. For direct current application to the tendon, SDFTs were dissected from the same limbs. The in vivo study was performed with a pony under general anesthesia that afterwards was to be used for a regular practical training session for veterinary students and that was scheduled to be euthanized at the end of the session.

The MET instrument—Microcurrents were produced by an MET device with a current setting of 0 to 3.5 mA and a fixed frequency of 150 Hz. The pulse wave form was a brief monophasic square pulse (duration, 0.8 milliseconds), followed by exponential decay to base level. The device is current constant, meaning it changes voltage if bioimpedance of the target tissue changes. The current was delivered via flat, self-adhering rectangular surface electrodes (dimensions, 5 X 1.5 cm).

Field strength measurement—Field strength was measured in 3 directions in the mid-metacarpal area of the SDFT, including proximodistal, mediolateral, and dorsopalmar. Because the cross-section of the tendon measures only 6 to 8 mm in the dorsopalmar direction but approximatively 20 mm in the mediolateral direction, 2 types of probes were developed to measure the corresponding voltage. The probe for the proximodistal direction was the same as that used for the mediolateral direction. Probes were constructed from a modified 20-gauge stainless steel catheter. The needles were 1.1 mm in diameter, 33 mm long, and coated with nonconducting epoxy, leaving 2.5 mm of the distal portion of the tip exposed. The cap and the plastic top were removed to expose the stainless steel top. One set was made by connecting 2 needles side by side, with a 17-mm distance between the needle tips (type A). The other set was made in a similar fashion, but the distance between the 2 needle tips was 4 mm (type B; Figure 1). The stainless steel tops of both sets could be connected to a computer equipped with an analog-digital voltage converter. To measure the field strength, the distal portions of the tips of the needle sets were inserted > 2 mm into the SDFT. The MET device was set at 0.02, 0.05, 0.2, 0.5, 0.8, 1.0, 1.3, 1.5, 2.0, 2.3, 2.5, 3.0, and 3.5 mA, sequentially. The corresponding voltage was recorded as baseline-to-peak value and was transformed to the field strength by expression as voltage per centimeter, which accounted for the differences in distance between the needle tips for the 2 types of probes.

Measurement conditions and electrode placement—Testing was performed with the live pony, the entire distal portion of the forelimbs, and dissected SDFTs. The pony was anesthetized and positioned in right lateral recumbency. After the metacarpal region was shaved, electrodes linked to the MET device were attached to the skin of the lower portion of the forelimbs. The electrodes were placed in proximodistal, mediolateral, and dorsopalmar directions, with the positive electrode placed proximally, medially, and dorsally, respectively; the actual flow of the electrons was thus in the opposite directions. In the proximodistal direction, electrodes were both placed on the palmar side, one just distal to the carpometacarpal joint and the other just proximal to the metacarpophalangeal (fetlock) joint (a distance of approx 20 cm). A type A probe was inserted through the skin into the tendon in the proximodistal direction (parallel to the axis of tendon) at the palmar side of the mid-metacarpal region of the SDFT for voltage measurement (Figure 2). For the mediolateral direction, electrodes were placed medial and lateral...
to the midmetacarpal region. A type A probe was placed perpendicular into the midmetacarpal region of the SDFT in the transverse direction. In the dorsopalmar direction, 1 electrode was placed on the dorsal part of the midmetacarpal region and the other was placed on the palmar aspect. A type B probe was used in this direction. Probes were placed perpendicular to the limb from the medial side in the midmetacarpal region. For the dissected tendons, a similar setup was used (Figure 3). Each direction was measured in triplicate under each condition. All experiments were performed at room temperature (21°C).

**Statistical analysis**—Statistical analysis was performed with software. Differences among models (entire forelimbs, dissected tendons, and the pony) and directions were evaluated by use of linear regression. Differences among regression lines were evaluated by comparing the sum of squares of the regression lines through the individual data sets and by the sum of squares of the regression line through the combined data set by use of F statistics. For data obtained from the pony, it was determined whether the values were within the range of values obtained from the entire forelimbs or the dissected tendons. Differences were considered significant at \( P < 0.05 \).

**Results**

In the entire forelimbs and the pony, total bioimpedance was considerably greater than in the dissected tendons and current settings of 0.02 and 0.05 mA appeared to be too low to result in measurable field strength. Apart from this observation, linear relationships between the applied current and the resulting field strength were found in all conditions and in all directions (\( P < 0.001 \); Figure 4). Because values found in the pony were comparable to those found in the entire forelimbs in all directions, the data were combined. In the entire forelimbs, the field strength corresponding to a specific machine setting was lowest when the current was applied in the proximodistal direction and highest when applied in mediolateral direction. However, only the difference between values obtained in the mediolateral and proximodistal directions was significant. In the dissected tendons, application of current in the proximodistal direction resulted in the highest field strengths, followed by the mediolateral and dorsopalmar directions, and differences among all 3 directions were significant.

For the current that generated the highest field strength, field strengths in the dissected tendons were approximately 5 times that in the entire forelimbs. In comparison of the slopes of the curves representing the relationship between current and field strength (Figures 4 and 5), the slopes of the curves representing the same current directions were significantly different between the dissected tendons and the entire forelimbs. In the proximodistal direction, the slope had a coefficient of 1.07 in the dissected tendons and 0.13 in the entire forelimbs (\( P = 0.005 \)). In the mediolateral direction, the slope was 0.76 in the dissected tendons and 0.18 in the entire forelimbs (\( P = 0.005 \)). In the dorsopalmar direction, the slope was 0.26 in the dissected tendons and 0.14 in the entire forelimbs (\( P < 0.001 \)). These data indicated that an increase in output current caused more effects in dissected tendons than in entire forelimbs.
The effect of electrical stimulation of biological structures is related to the current flow through the target tissue. Results of the present study clearly revealed that the effective field strength in the target tissue may vary greatly with the plane in which the current is applied and with the tissues located between electrodes and target tissue. The main conclusion from this study was, therefore, that the current output of any therapeutic device has to be considered an unreliable indicator of actual field strength in the target tissue and hence of potential therapeutic effect. We did not vary the direction of the current (ie, the positions of the negative and positive electrodes). To the authors’ knowledge, there are no data on possible semiconductivity of biological tissues. For the major part of the present study, cadaver specimens were used. Previous research reveals that the electrical characteristics of dissected tissue gradually change over time, with bioimpedance rapidly decreasing within approximately 2 days of dissection. For this reason, the limbs and tendons used in this experiment were tested within 6 hours after euthanasia of the horses. Linear relationships were evident between current and field strength in all conditions. This indicated that the bioimpedance of the tissue did not change with increasing applied current, at least within the limited current range that was used in this study. The current passed through only a single tissue type when dissected tendons were used. Because tendon tissue is homogeneous and has an almost uniform cross-sectional area, the slope of the curve was indicative of tendon bioimpedance in different directions. The measured bioimpedance was significantly higher in the proximodistal direction than in the other directions. This may have been because the electric field generated in the tendon by the electrodes that were placed one above the other on the same side of the tendon was not homogeneous over the entire cross-section of the tendon; a higher field strength was at the side of electrode placement. Furthermore, because of this electrode configuration and in contrast to the other positions, the probes were not placed on a straight line between the electrodes. Bioimpedance was lowest in the dorsopalmar direction. This may have been associated with the packing density of the collagen fibers, which is not necessarily the same in the dorsopalmal and mediolateral directions, or with differences in minor molecular components such as decorin, which is bound to the collagen fibers and interacts with chains from neighboring fibrils to form interfibrillar bridges. The distal portion of the forelimb is not a homogeneous structure but is composed of skin, bone, tendons, and other tissues. The bioimpedance of different tissues is not constant; therefore, the distal portion of the forelimb cannot be viewed as a homogeneous conductor, and the overall bioimpedance can be viewed as a circuit of in-series and parallel connections of several shorter segments. In the proximodistal and mediolateral directions, most of the electric current will pass through skin and tendons. In the dorsopalmar direction, the third metacarpal bone is between the electrodes. However, because the bioimpedance of bone is high, the current might bypass the bone. The eventual effective field strengths were not significantly different for the dorsopalmar direction, compared with 2 other directions in the transverse plane. It should be noted that the cross-sectional shape of the SDFT is like a crescent and the real distance between the voltage probes in the mediolateral direction is thus slightly longer than the linear distance. Because this is a constant error independent of current strength, no correction was deemed necessary. However, real field strength in the mediolateral direction would be somewhat lower than indicated. The application of current in the proximodistal direction (along a line in the sagittal plane of the limb) resulted in lower corresponding field strengths, indicating a higher bioimpedance in this direction.

In the voltage-current relationship, no differences between values obtained in a live pony and ex vivo limbs were found. The electrical impedance of a tissue is known to change with the load applied to that tissue, but in this instance, the pony was anesthetized and there was no load on the tendons. Blood flow might have an effect in living animals because MET increases local blood circulation. However, electrical conductivity of blood depends on flow volume, and the relative contribution in tendons of blood to total volume of the limb is small, so the effects of changes in blood flow volume probably can be neglected. As expected, there were significant differences in bioimpedance between the dissected tendons and the entire forelimbs in all directions. In the distal portion of the forelimbs, the current must pass through the skin and other tissues before reaching the target tissue. The sum of the bioimpedances of all the tissues makes up the total bioimpedance. Depending on the direction of current, the total bioimpedance may be high enough to decrease the therapeutic effects of the electrical stimulation. In a previous in vitro study, 0.5 mA stimulated tenocytes without damaging them, although there may be many reasons that direct extrapolation of these data may be incorrect and additional research on the effectiveness of electric treatments must be performed before the data can be used for clinical recommendations. However, this empirically derived value may serve as an example. If applied to this experiment, a field strength of 0.17 V/cm is required to generate 0.5 mA in the dorsopalmar direction in tendon, which means that 0.87 mA should be applied at the skin in vivo. For the mediolateral direction, these values are 0.56 V/cm and 3.0 mA, respectively. However, in the proximodistal direction, the corresponding current for 0.63 V/cm in the limb was 4.7 mA, which exceeds the maximum capacity of the machine. Therefore, the dorsopalmar direction will be the most efficient in generating sufficient current to influence tenocytes.

Physiologic electrical fields can also control the direction of cell migration. In general, cells oriented parallel to an electric field will reorient perpendicular to the electric field. After injury, proliferating tenocytes and synthesized collagen are randomly organized, which may result in the formation of inferi-
or tissue. Creation of an electrical field in the dor-so-palmar direction, perpendicular to the longitudinal loading axis, might be helpful in tissue remodeling and realignment of cells and collagen fibers.

Tissue composition and electrode placement strongly affect effective field strength in the target tissue. Knowledge of these effects is necessary for further assessment of MET devices with respect to their potential value for clinical use.

a. APS MK I.1, Medeuza, BV Biltoven, Utrecht, The Netherlands.

b. Vasocan, Braunüle, 20G 1¼ inch, B Braun Melsungen AG, Melsungen, Germany.


d. Prism, version 4.0, GraphPad Software Inc, San Diego, Calif.

References


