Transient Electric Changes Immediately After Surgical Trauma

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Objective: To measure the transient electric changes in skin and muscle tissue immediately after trauma. Design: 1-group time series. Setting: Climate-controlled operating room in a public urban hospital. Patients or Other Participants: Eleven participants (8 females, 3 males) with a mean age of 65.18 ± 11.36 years undergoing total hip arthroplasty.

Intervention(s): An incision approximately 10 cm distal to the posterior superior iliac spine extended distally over the greater trochanter and along the lateral limb. The incision was completed in 2 cuts: (1) skin and subcutaneous fat and (2) muscle tissue.

Main Outcome Measure(s): Three measurement sessions were performed with an electrometer before and after a skin incision and after a muscle incision. Potential differences and current intensity were measured immediately after acute trauma to determine the transient electric changes associated with soft tissue injury.

Results: The electric potentials were significantly more negative after the skin incision ($P = .036$) and skin plus muscle incision ($P = .008$; preincision $0.001 \pm 0.015$ V, skin incision $−0.127 \pm 0.134$ V, skin plus muscle incision $−0.192 \pm 0.153$V). Current intensity changed significantly after the skin plus muscle incision ($P = .008$; preincision $0.046 \pm 0.112$ pA, skin incision $−0.803 \pm 0.904$ pA, skin plus muscle incision $−1.708 \pm 1.302$ pA).

Conclusions: Soft tissue trauma generated negative transient electric changes.

Key Words: muscle, injury, electric stimulation

Key Points
- Previous authors’ examinations of the transient electric properties of acutely injured tissue have led to the use of electromagnetic stimulation to promote healing in chronic skin ulcers and nonunion fractures.
- Surgical trauma induced changes in the electric properties of soft tissue.
- New therapeutic protocols that are based on electric changes in traumatized soft tissue may optimize healing in surgical incisions and muscle injury.
- Individualized therapeutic protocols may be needed to account for each patient’s unique inflammatory response and structural distinctions.

Every physiologic event can be defined by mutually dependent biochemical and bioelectromagnetic characteristics. For example, when a muscle contracts, the cells generate electric potentials due to the flow of ions across the cell membranes.1 When tissue is traumatized, cell membranes are disrupted and negative ions enter the extracellular fluid.2–4 This event is characterized by the development of a negative ionic current.2,4,5 Both the acute negative properties of the tissue and the presence of intracellular ions within the extracellular fluid appear to contribute to the initiation of an inflammatory response, characterized by the release of complement proteins and cytokines from neighboring cells and brief capillary vasoconstriction.3,6,7 As the traumatized cells recover, the ionic current decreases, but the tissue’s electric properties continue to fluctuate, primarily remaining negative due to the presence of inflammatory proteins and cells. The newly established electromagnetic field represents the cellular activity of tissue repair and influences the migration of ions and cells through the injured region, thereby guiding the healing process.4,7,8 Additional in vivo human studies are needed to confirm these theories, which have been examined primarily through in vitro designs.

After acute trauma to healthy animal (cavy) skin, a 1.5 to 9.6 μA (160 to 800 μA/cm²) electric current (electric field of 100 to 200 mV/mm) was measured.9 Based on these measurements, many protocols for managing chronic skin wounds use currents within the range of 50 μA to 1000 μA.10–13 The applied electric currents are designed to simulate the injured tissue’s natural signals, but large randomized clinical trials have not been completed to examine the efficacy and safety of these modalities. Several in vivo and in vitro studies have shown promising results.8,11,14–19

Great strides have been forged in examining the electric properties of skin and bone, leading to the development of accepted clinical applications; however, only limited in vivo research has focused on human muscle and other soft tissues.
Some data from postoperative and in vitro muscle and nerve tissues have demonstrated that these excitable tissues are capable of generating an ionic current with trauma to the cellular membrane. Unfortunately, intraoperative studies in humans have not been performed, limiting our understanding of the initial electric characteristics of surgical incisions. Therefore, our purpose was to evaluate the presence of transient electric changes (e.g., potential differences, current intensity) of soft tissues, immediately after injury during a surgical procedure in human patients.

METHODS

Research Design

A 1-group time-series design was used to evaluate the influence of surgical trauma in humans on the 2 dependent variables measured in vivo. The dependent variables were potential differences at the injury site measured in volts (V) and current intensity at the injury site measured in amperes (A). The independent variable was the incision (preincision, skin incision, skin plus muscle [SM] incision).

Participants

We studied 11 participants with a mean age of 65.18 ± 11.36 years. The tested population included 8 females (right hip = 7, left hip = 1) and 3 males (right hip = 2, left hip = 1). All patients were instructed to fast for at least 8 hours before the surgery. Anesthesia was administered to all patients before surgery: 6 patients underwent spinal anesthesia and sedation, 3 received general anesthesia, and 2 received a combination.

Exclusionary criteria included a history of hip surgery or fracture within 12 months prior to the current surgery. Volunteers were further excluded if they were currently nonambulatory or reported neurovascular complications leading to atrophy of the gluteal muscle region. Medical clearance for surgery and the attending surgeon’s approval on a case-by-case review excluded additional volunteers. Current medications were not used as an exclusionary criterion. In accordance with the university’s institutional review board, which approved the study, appropriate written participant consent was obtained before data collection. Health Insurance Portability and Accountability Act (HIPAA) guidelines regarding patient privacy were adhered to throughout the study.

Instrumentation

We used an electrometer (model 610B; Keithley Instruments, Inc, Cleveland, OH) with 10-ft (3.05-m) low-noise coaxial leads (Keithley Instruments, Inc) and Ag-AgCl solid-gel electrodes (Neuroline 700; Ambu, Inc, Linthicum, MD) to measure the voltages and current intensities. The leads and electrodes were gas sterilized in accordance with hospital standards and guidelines. The electrometer was warmed up for at least 1 hour and then calibrated before data collection began. Recalibration to the zero position was performed after any movement of the electrometer. The Keithley electrometer as a voltmeter produces meter noise of ±3 × 10⁻¹⁵ amperes. The grid current is less than 23 × 10⁻¹⁴ A. While measuring amperes, the accuracy of the electrometer is ±2% of the full scale (ampere ICC [3, 1] = 0.851).

To validate the instrumentation, the intact skin measurements were compared with previously reported measures. Barker et al.² reported transcutaneous potentials in humans using a Keithley electrometer 600B. Transcutaneous potentials are surface measures referenced to a subdermal ground and ranged from −0.011 V to −0.058 V. Based on these results, we determined that 2 surface electrodes with similar preparation should have potential differences of ±0.047 V. Edelberg explained that ideally, 2 surface electrodes would be reflecting the potential differences between the 2 sites and that a potential difference of zero would indicate that the two locations have “the same potential with respect to their interior.” After the administration of the anesthesia, a skin measurement was performed on clean, shaven (as needed) skin, before any incisions were made. The ground Ag-AgCl solid-gel electrode was placed over the anterior superior iliac spine and the active Ag-AgCl solid-gel electrode at the intended midpoint of the surgical incision. Three measurements for each variable were recorded and averaged (0.001 ± 0.015 V, 0.046 ± 0.112 pA). The reported values were within the range predicted by the data of Barker et al.² To further assess the instrumentation, we correlated the current intensity and potential differences recorded throughout our testing. Based on the Ohm law (resistance × current intensity = potential difference), these 2 variables are directly related. A statistically significant correlation was observed between the 2 variables during all conditions (preoperative r₁₀ = .822, P < .01; postoperative skin r₁₀ = .901, P < .001; postoperative muscle r₁₀ = .975, P < .001). These analyses help to demonstrate that our instrumentation provided valid measurements.

PROCEDURES

Preoperative Period

Patients willing to participate were given a written consent and medical history form to review and complete. After obtaining consent, we used the medical history and the preoperative testing results in consultation with the attending surgeon to determine whether the patient was an appropriate candidate for participation in the study.

Testing Procedures

Before surgery, the skin was shaved and cleaned as part of the surgical preparation process. After anesthesia was administered, Ag-AgCl solid-gel surface ground electrodes were placed over the anterior superior iliac spine. Another Ag-AgCl solid-gel electrode was used as the active electrode to record the first set of voltage measurements on the clean skin at the intended incision site’s midpoint. A separate measurement was taken at the same site to assess current intensity. An average of 3 trials was recorded for the 2 variables at each condition.

To ensure proper positioning for a posterior surgical approach, the patient was placed on the unaffected side. An incision was made approximately 10 cm distal to the posterior superior iliac spine and extending distally over the greater trochanter along the mid-lateral axis of the limb (approximately
To evaluate the offset potentials between the bare lead and Ag-AgCl electrode, we measured offset potentials 3 times with separate electrodes in a saline bath (−0.166 V).

Statistical Analysis

A 1-way (condition) analysis of variance with repeated measures on condition to determine if a significant difference in current intensity existed between healthy and injured tissue. The location of significance was determined with paired-samples t tests with Bonferroni adjustments. A Pearson product moment correlation was calculated to determine the relation between electric potentials and current intensity. A .05 level of probability was considered significant. The effect sizes are reported as the analysis of variance effect size index (f) and defined as small (f = 0.10), medium (f = 0.25), or large (f = 0.40).

RESULTS

Potential Differences

The analysis of variance demonstrated a significant difference, which we investigated further (F1,60,16.19 = 7.198, P = .004, f = 1.06, observed power = .910; Figure 2). The skin incision displayed a significant difference between the preincision (0.001 ± 0.015 V) and skin incision conditions (−0.127 ± 0.134 V; P = .36). However, the muscle incision did not produce a statistical change in potentials (P = .785). The SM incision led to a significant negative change in electric potentials (−0.192 ± 0.153 V) when compared with healthy intact skin (P = .008). Figure 2 represents the changes in electric potentials generated by the surgical incisions.

Current Intensity

The surgical trauma led to a significant difference in current intensity (F1,78,14.22 = 12.02, P = .001, f = 1.22, observed power = 0.973; Figure 3). The SM incision produced a significant negative change (P = .008; preincision = 0.046 ± 0.112 pA, skin incision = −0.803 ± 0.904 pA, SM = −1.708 ± 1.302 pA). Figure 3 represents the changes in current intensity generated by the surgical incisions.

DISCUSSION

Our objective was to evaluate the transient electric properties of soft tissue immediately after surgical trauma in humans. The trauma of surgery did alter the transient electric properties, as demonstrated by the significant changes in potentials and current intensity after the skin and SM incisions. However, a significant change was not observed when advancing the incision into muscle. We are the first to intraoperatively evaluate the transient electric properties of human surgical incisions and muscle tissue in vivo. To date, surgical incisions have been primarily examined in the postoperative period, and muscle tissue was primarily evaluated in excised tissues.5,20–22

The difference in potentials measured in this study reflected the negative change in wound potentials as compared with the ground electrode on the intact skin over the anterior superior iliac spine. These findings are in agreement with an extensive body of literature indicating that acute trauma typically leads to a negative shift in electric properties.5,9,24–26 The wound became electrically negative relative to intact skin, potentially because of the leakage of intracellular anions into the extracellular fluid. The presence of increased anions in the extracellular fluid changes the electrochemical environment and has been theorized to lead to local alterations in cellular physiology.4,7,27–29 The electrochemical gradient can cause a redistribution of charged proteins and lipids in the plasma membrane.
of nearby cells, including ion channels, thereby increasing the local fluxes of ions.\textsuperscript{16} Furthermore, the presence of a small local electrical field (10 to 100 mV/mm) could alter the membrane potentials, leading to an increased number of open ion channels and an increased electromotive force driving those ions through the channels.\textsuperscript{8,14,30} Both outcomes could lead to changes in the cellular activity and structure, such as the stimulation of protein kinase A, an enzyme responsible for the phosphorylation of many substrates within a cell.\textsuperscript{8,14} Furthermore, protein kinase A helps to regulate the migration of a cell under the influence of an electric field.\textsuperscript{14} All of these cellular changes mark the tissue’s initial response to trauma and the initiation of the inflammatory response.

\textbf{Current Intensity}

Significant differences in current intensity were produced by the SM incisions. In previous research, significant differences have been reported for in vivo skin wounds and in situ muscle trauma.\textsuperscript{9,21,22} The lack of significance in our measurements may reflect faster closure of the cell membranes than the several minutes reported in muscle cells.\textsuperscript{2} The period between the two incisions offered additional time to reseal skin and subcutaneous tissue’s cell membranes before the muscle incision current measurements were taken. Another possible reason for the significant change after the skin incision but not the muscle incision relates to the amount of tissue trauma generated with each incision. During the current study, we did not measure the depth of penetration of each wound, but the skin and subcutaneous fat incision typically represented a deeper incision than the isolated muscle incision. Thus, the theory that increased cellular trauma (caused by a deeper incision) results in a greater inflammatory response and increased changes among the transient electric properties would be supported.\textsuperscript{9,31}

\textbf{Variability}

Throughout our study, the potential differences and current intensity demonstrated a large SD among patients. However, within each subject, the repeated trials demonstrated high re-liability, as indicated by the ICCs. The large variability among participants may be attributed to the degree of tissue trauma produced in each patient. The depths of the incisions were not measured and were not consistent among patients (primarily because of the differences in muscle and adipose tissue masses). Carbon et al.\textsuperscript{20} reported high variability in the shape of the electric fields around a skin incision. They suggested that minute changes in the wound shape could produce large variability in the electric field geometry. Furthermore, the inter-subject variability may have been high because of the hydration level of each patient’s skin. The presurgical fasting may have caused various degrees of dehydration among the participants in this study. Dryer skin typically has greater resistance than moist skin; we were unable to quantify the skin’s water content. Other factors that can alter the skin resistance were controlled as a result of the surgical conditions (anxiety level, room temperature, relative humidity, time of day [morning], and atmospheric pressure).\textsuperscript{23} Age may be another influence on variability. Participants in this study were between 46 and 77 years of age. Previous researchers\textsuperscript{32–36} have demonstrated that age may influence the extracellular matrix of soft tissues and modulate the inflammatory response. Both physical changes and an altered inflammatory process may influence the electric properties of injured tissue. Although differences in the incisions’ depth and geometry, age, and the skin’s hydration level may account for some of the increased variability, an individual response to trauma may also occur.\textsuperscript{37–39} Investigations\textsuperscript{37–39} into inflammation have demonstrated that a large amount of variability occurs among patients, both in the degree of inflammatory markers produced and in which inflammatory proteins are expressed. This finding has led several researchers\textsuperscript{37,38,40} examining osteoarthritis and rheumatoid arthritis to suggest that clinicians need a method of assessing this variability to promote optimal therapy. Unfortunately, no decisive model has been developed to fulfill this goal to date.

Our data demonstrate that surgical trauma induced changes in the electric properties of soft tissue. The large variability produced by the surgical incisions may have been a result of various degrees or geometry of trauma, differences in skin.

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure2.png}
\caption{Average electric potentials with SD bars ($F_{1,80,16.19} = 7.198$, $P = .004$, observed power = .910). The electric potentials were significantly more negative after the skin incision (* indicates $P = .036$) and skin plus muscle incision († indicates $P = .008$).}
\end{figure}
resistance, patient age, or an individual inflammatory response. All of these factors, which can vary naturally among patients, need to be explored further to determine their potential effects on the management of acute injuries.

Clinical Relevance

Previous researchers’ examinations\(^1\)\(^-\)\(^4\),\(^6\),\(^7\) of the transient electric properties of acutely injured tissue have led to the use of electromagnetic stimulation (eg, low-intensity direct current stimulation, pulsed electromagnetic fields) to promote the healing process in chronic skin ulcers and nonunion fractures. Our study may represent one of the first steps toward developing new therapeutic protocols to promote optimal healing conditions in surgical incisions and muscle trauma.

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