

Effects of Electrical Stimulation on Wound Healing in Patients With Diabetic Ulcers

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OBJECTIVE— To evaluate the effects of two stimulation waveforms on healing rates in patients with diabetes and open ulcers. The hypothesis was that stimulus waveforms with minimal polar characteristics would provide significant healing for this patient sample.

RESEARCH DESIGN AND METHODS— This was a prospective study that enrolled 80 patients with open ulcers. Patients received stimulation with either an asymmetric biphasic (A) or symmetric biphasic (B) square-wave pulse. Amplitudes were set to activate intact peripheral nerves in the skin. Two other groups received either very low levels of stimulation current (MC), or no electrical stimulation (C). When combined these groups were referred to as the control group. Treatment was carried out daily until the wound healed, the patient withdrew from the study, or the physician changed the overall wound management program. Average healing rates were calculated from weekly measures of the wound perimeter and were used for statistical comparison through a one-way analysis of variance.

RESULTS— Stimulation with the A protocol significantly increased the healing rate, enhancing healing by nearly 60% over the control rate of healing. Stimulation with the B protocol did not increase the healing rate when compared with control subjects.

CONCLUSIONS— Electrical stimulation, given daily with a short pulsed, asymmetric biphasic waveform, was effective for enhancement of healing rates for patients with diabetes and open ulcers.

Electrical stimulation has been used for more than 30 years to facilitate wound healing (1–15). Although a number of clinical studies have been published reporting the effects of electrical currents on tissue healing, the practice remains restricted to a few centers or it is only used as a final therapeutic effort. The infrequent use of electrical stimulation as an integral part of standard healing management is attributable to ambiguity centered on the stimulation parameters and the types of patients most successfully managed with this adjunct treatment.

Stimulation programs have ranged from the continuous application of direct

currents over a wound for several hours a day (1–5) to the use of one or more short sessions of pulsed stimulation 3–5 days a week (6,8–11). Protocols have included polarity changes, although the probability of polar effects from some forms of stimulation appear to be minimal (7–10). Recent studies have reported enhanced healing of decubital ulcers, using waveforms with minimal polar capabilities (12–15). In short, the characteristics of stimulation that most affect the healing process are unknown. Whereas a variety of clinically based procedures have been developed, they lack physiological rationale or experimental support.

At least two aspects of electrical currents have the potential to influence tissue healing. The first is the ability of certain types of electrical currents to attract opposite charged particles, thus enhancing the possible migration of cells such as macrophages and fibroblasts (16–20). These effects of polarity are strongest when direct current stimulation is used, as reported by Wolcott et al. (2) in the 1960s. Theories abound regarding the “current of injury” (the flow of charged particles from an injured to an uninjured area of dermis), and the effect this current of injury has on the migration of cells or proliferation of tissue. Wounds that fail to heal have been reported to display reduced levels of the current of injury (16,17). As a wound heals and decreases in size, the current of injury decreases as well (16). The concept of a current of injury facilitating the normal healing process, and the enhancement of that potential by the application of external currents, is what directed early research efforts (1–6).

Clinical techniques have been developed using electrical stimulation in ways relatively independent of these acknowledged physiological phenomena. The original investigators, using direct current stimulation, proposed a protocol that included periodic changes in the polarity of stimulation, although no such changes had been reported physiologically (2). Later investigators began to use short pulsed monophasic waveforms, with the apparent supposition that the polar effects from direct currents were equally likely to occur with the short pulsed stimulation (7–9). Actual polar capabilities of the very short (2–20 μ s), monophasic pulses, with stimulation placed over an open wound, have never been directly addressed in the literature, although some attempts have been made to calculate expected charge dispersion (21).

A second aspect of many electrical currents that could affect the healing process is the activation of cutaneous nerves, which have been reported to create a centrally mediated increase in circulation (22–24). The location and specific type of nerves excited for this response appear to be rather nondiscrete; the level of activation appears to be a more predictable factor. Comfortable levels of sensory stimulation, for those

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A, asymmetric biphasic electrical stimulation; B, symmetric biphasic electrical stimulation; C, no electrical stimulation; DC, direct current; MC, microcurrent stimulation.

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Table 1—Electrical stimulation parameters

	A	B	MC
Amplitude	Below contraction	Below contraction	4 mA
Phase duration (μ s)	100	300	10
Frequency (pps)	50	50	1
On:off times (s)	7:7	7:7	7:7
Waveform			

with normal peripheral sensation, appear to trigger an increased circulatory response, generalized to the region of the stimulation. On the other hand, intense or painful stimulation, or vigorous activation of muscular contraction, may decrease the circulation to the skin. Thus, low-level sensory stimulation, typically used to reduce ischemic pain, may provide a way to increase the availability of nutrients for a healing wound and enhance the removal of toxic waste products from the wound area (24). Direct current (DC) is unlikely to trigger the sensory nerves required to establish this more regional response (25).

Short pulsed stimulation, which has largely superseded the use of DC stimulation, is generally provided at a low sensory level, with care taken to avoid muscular contractions (8,11). Most electrical stimulators designed to excite peripheral nerves use waveforms that are said to be "balanced," thus minimizing the polar effects of the electrical currents (25). Hence excitation of the peripheral nerve is not wholly dependent upon the polar nature of an electrical current, and symmetric biphasic waveforms are often used to increase the area of neural excitation during an applied electrical current. Whereas activation of peripheral nerves is greatest under the negative pole of pulsed monophasic stimulation, there is also activation at the positive pole, with only a slight decrement in effectiveness (25).

A problem relatively unique to the diabetic population is the frequent presence of peripheral neuropathy in the proximity of the ulcer (26). This neuropathy may be documented through sensory perception testing but may also extend to the nerves that innervate the small vessels, often compromised in the presence of diabetes. Thus, the complex problems of the diabetic patient could result in compromised effectiveness of electrical stimulation, compared with other patients who experience wounds that are difficult to heal. These problems also indicate the need for further

exploration of the stimulus parameters most effective for the specific management of the diabetic population.

Clarification of which aspects of electric currents are most important in providing an enhanced healing effect would provide the clinician better guidelines for the development of healing treatments that included optimal electrical stimulation. If the characteristics of stimulation-enhanced healing programs can be identified, more effective use of the treatment program could lead to its broader application. The increased ability of the clinician to expedite the healing process in hard-to-heal wounds would be hailed by patients, health care workers, and payers alike. The purpose of the present study was to explore the efficacy of the neurally regulated regional influences of electrical stimulation for enhanced wound healing, while minimizing the possible polar characteristics of the stimulation. The study was targeted to the diabetic population with hard-to-heal wounds, because the pathophysiology of both wound production and tissue repair is unique in this patient group.

RESEARCH DESIGN AND METHODS

A total of 80 individuals with diabetes who were admitted to the Ortho/Diabetes Service of Rancho Los Amigos Medical Center were treated with electrical stimulation to enhance wound healing during the study. These patients presented with 114 wounds, all of which were provided with treatment from one of four stimulation protocols. Before beginning the study protocol, each patient was medically cleared by the physician, provided with a detailed explanation of the treatment in their own language, and signed an informed consent. Patients were randomly assigned to one of three stimulation groups (Table 1) or a fourth, nonstimulated control (C) group. Two stimulation treatment groups were provided with currents assumed to be therapeutic, based on

previous studies (10,12–15) (A and B treatment groups). The third stimulation treatment (MC) was originally thought to be a "stimulated control" protocol, with patients receiving stimulation but at such low levels as to have no therapeutic effect. In preliminary data analysis, however, this group appeared to show some therapeutic effects from this anticipated "control" treatment. Treatment MC was therefore continued throughout the study, similar to the other stimulation protocols.

The stimulation protocol was added to the standard wound care management provided to all patients. No modifications to the standard wound care were required to accommodate the stimulation programs. Most inpatient treatments were done early, before the morning dressing changes were completed by the nursing staff. The choice of standard wound care treatment was not affected by the addition of the stimulation protocol.

Patients were maintained on their respective stimulation protocols until their ulcers healed, the physician decided on another form of treatment, or the patient withdrew from the study. The control group received the same stimulation procedures as the MC treatment group, but special leads were used to interrupt the passage of current, and the patient received no electrical stimulation. Patients were maintained on the control protocol for 4 weeks or until their ulcer healed, whichever occurred first. After approximately 1 month of control management, patients whose ulcers remained open were randomly assigned into either the A or B treatment groups for continued management. Only the therapist doing daily stimulation treatment and weekly tracings knew the group assignment of each subject.

All inpatients were seen 5 days a week by a physical therapist working on the research project. Three treatment sessions of 30-min duration were provided daily, with a short break between sessions. After each break, the stimulator (UltraStim was distributed in the U.S. by Henley [Houston, TX]) was programmed to automatically restart the treatment session. The patient was instructed to remove the stimulator after the third session. Compliant stimulation time was considered to be 1.5 h per day, with at least one session per day (30 min) defined as semicompliant stimulation. Some patients chose to remain on stimulation for longer periods of time, and this was monitored by the therapist each

Table 2—Demographic data for wound-healing patients

	Protocol			
	A	B	MC	C
n	21	20	19	20
Sex (M/F)	16/5	11/9	14/5	14/6
Age (years)	58 ± 2 (40–82)	50 ± 2 (33–64)	51 ± 2 (30–64)	52 ± 2 (30–66)
Ethnicity				
Non-Hispanic white	9	6	2	2
Hispanic	9	10	13	16
Black	2	4	3	2
Other	1	—	1	—
Diabetes onset (months)	158 ± 20 (6–324)	161 ± 22 (24–384)	188 ± 49 (8–760)	142 ± 22 (1–360)
Vital capacity (N ≈ 2,000–3,250 ml)	3,560 ± 270	2,800 ± 164	2,530 ± 246	2,910 ± 140

Data are means ± SE (range). N, normal.

day through the compliance feature of the stimulation unit.

Subjects treated as outpatients were monitored regularly through clinic appointments, home visits, and frequent phone calls. Compliance with the stimulation treatment was monitored through the compliance meter on the stimulator whenever the patient was seen by the research therapist. Personal follow-up and assessment was done with the research therapist every 2–4 weeks.

Electrical stimulation was provided through conventional carbon rubber electrodes (Medtronic, now Empi [St. Paul, MN]) placed over intact skin, near the edges of the ulcer. The standard electrode configuration for patients receiving the A protocol placed the electrode, which was negative during the leading phase of the waveform, proximal to the wound with the more positive electrode placed distally.

The primary technique used to evaluate wound size was a tracing of the wound edge onto a clear acetate. Wound evaluation was done every week for inpatients, and at each outpatient visit for those treated at home. The tracing was accompanied by a calibrated photograph, to assist in later interpretation of the tracing. Data from each patient were not analyzed until that patient had completed the study protocol, sometimes resulting in a delay of several months before the tracing interpretation was attempted. Because of this delay, the color photograph was invaluable. The surface area of the wound was digitized from the tracing by a technician who was not aware of the specific treatment received by the patient.

When there was significant depth to an ulcer, several techniques were attempted for documentation. The volume of sterile saline required to fill the wound was tried

in some patients but was limited in many others by the shape and location of the ulcer. Depth measures were made from several wounds, but no standard formula was found in the literature to compute a valid volume measure. Thus, although acknowledging that surface area measurements represent only part of the healing process in most wounds, they were the only reasonably reliable measure available.

Data from each patient and each wound were first digitized from the acetate, then entered into a master database for analysis. Descriptive information collected for all patients is shown in Table 2. Compliance with the stimulation protocol was evaluated through 1) the average current recorded by the stimulator and 2) the duration of stimulation time accrued throughout the treatment program. Both of these measures were recorded at each evaluation session.

The mean healing rate was computed for each ulcer. Sequential area measures were subtracted from the preceding measure, and the difference was characterized as a percentage of closure. This value was then divided by the number of days between measures, multiplied by 7, and identified as the weekly healing rate. The average of the sequentially computed weekly healing rates was calculated for the overall mean healing rate:

$$\bar{\Delta} = \left(\frac{1}{[n-1]} \right) \sum_{i=1}^{n-1} \frac{\text{Area}_i - \text{Area}_{i+1}}{\text{Day}_{i+1} - \text{Day}_i} \times 7 \times 100$$

In the above formula, Area_i is the wound area measured on Day_i, whereas Area_{i+1} is

the wound area measured on Day_{i+1}. The values at $i = 1$ represent the day treatment was initiated.

Comparison of mean healing rates was done with a one-way analysis of variance. Evaluation of descriptive data was also done with analysis of variance. Statistical significance was determined at $P \leq 0.05$, using values corrected for multiple comparisons when appropriate. Stepwise regression analyses were used to identify any demographic and health characteristics that related to healing rates.

RESULTS — The 80 patients were originally distributed between the treatment groups as shown in Table 2, which also includes the mean descriptive data from the patients. There were no significant differences between any of the treatment groups based on comparison of the descriptive data.

Several of the diabetic patients were admitted to the study with more than one wound. Additionally, control patients were reassigned to the A or B treatment protocols after 1 month, and their stimulation treated wounds were counted as new treatment wounds. Thus, a total of 114 wounds were treated, with 17 patients managed for more than one ulcer (range 2–6), and 5 patients changed from the control to a treatment protocol. Descriptive data from the 114 wounds are found in Table 3. There were no significant differences among groups in these variables.

Comparison of mean healing rates among the four groups for all treated wounds is found in Fig. 1. Although these data appeared promising, statistical significance was not attained. The data were subsequently restricted to wounds that required more than 8 days of treatment

Table 3—Descriptive data for all wounds at the inception of stimulation

	Protocol			
	A	B	MC	C
No. of wounds	33	28	28	25
Duration of ulcer (days)	109 ± 24 (6–640)	74 ± 21 (6–409)	54 ± 10 (8–240)	59 ± 10 (7–214)
Standard treatment				
Betadine	1	2	—	—
Acetic acid, wet to dry	16	16	23	18
Dry dressing	4	4	3	2
Saline, wet to dry	9	2	1	5
Other	3	4	1	—
Ulcer location				
Toe/metatarsal	17	21	21	21
Heel	6	6	1	2
Shank	10	1	—	1
Knee	—	—	1	—
Other	—	—	5	1
Infected				
Yes	30	27	27	25
No	3	1	1	—
Hb (N ≈ 12–16 g/100 ml)	12 ± 0.3 (7–14)	11 ± 0.4 (8–14)	12 ± 0.8 (8–15)	12 ± 0.3 (8–15)
Glucose (N ≈ 5.6 mmol/l)	10.2 ± 0.7 (4.5–17.3)	10.2 ± 1.1 (3.9–22.6)	10.8 ± 0.9 (4.9–17.3)	9.8 ± 0.7 (5.1–17.4)
Days to discharge	41 ± 6	45 ± 7	47 ± 7	36 ± 4
Reason for discharge				
Healed	15	8	10	12
Noncompliant with stimulation	3	4	6	4
Change of program by physician	7	4	7	6
Withdrawal from study	8	12	5	3

Data are n or means ± SE (range). N, normal.

before healing occurred (healing rates <90%/week), and at least semicompliance with the stimulation program (minimum of 30 min of stimulation per day). The characteristics of the stimulation programs for this group are shown in Table 4. Whereas a pattern of stimulation effect on healing rates was apparent, statistical significance was still not attained (Table 5). The MC treatment was originally considered to be a control treatment. Because of the similarity in findings between the microcurrent and the nonstimulated control, coupled with the original hypothesis, the MC group and C groups were combined into a group referred to as the control subjects, and the statistics were rerun. With a total of 39 wounds, the combined control group was statistically slower to heal than the treatment group A, which received the asymmetric biphasic electrical stimulation (Table 6). The treatment group B, which received the symmetric biphasic stimulation, was not statistically different from the A treatment group, probably because of the high degree of variability in the data. (Fig. 2)

Five patients were initially treated with the control protocol and subsequently

changed to the A or B treatment programs. Three patients had wounds that were switched from control to the A treatment program, receiving stimulation with the asymmetric biphasic waveform. Two of the

three patients doubled their healing rates after the change, whereas the third showed a decrease in healing rate. Two subjects were switched from the control to the B treatment program, which provided the

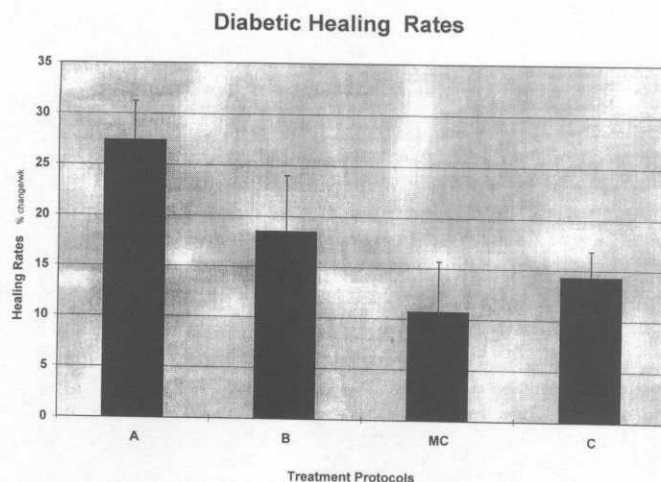


Figure 1—Mean healing rates from each treatment protocol, including all wounds (n = 114). Although the healing rates appear different, statistical significance was not achieved. A, asymmetric biphasic stimulation; B, symmetric biphasic stimulation; MC, microcurrent stimulation; C, control group—no current delivered to the patient.

Table 4—Description of stimulation programs for semicompliant subjects

	Protocol			
	A	B	MC	TC
No. of wounds	29	24	20	19
Amplitude of stimulation (mA)	64.9 ± 2.7 (24–85)	62.8 ± 3.6 (30–85)	4.0	0
Amount of stimulation (h/day)	1.1 ± 0.1 (0.9–3.3)	1.5 ± 0.2 (1.0–4.6)	0.9 ± 0.1 (0.5–1.8)	0.8 ± 0.1 (0.5–1.3)
Days to discharge	40 ± 6	48 ± 8	43 ± 8	40 ± 4

Data are means ± SE (range).

symmetric biphasic waveform. There was no improvement in healing rate for either of these subjects. It is difficult to draw conclusions from these changes, because the number of subjects involved was very small and the variability in healing rates between subjects is very large.

Stepwise regression analysis was used to identify characteristics of the patient's general health that might account for the average healing rates. This evaluation was done both as a full sample and with wounds divided by the stimulation treatment received. No descriptive variable significantly correlated with the average healing rate for the full sample. No other descriptive variable was related to the average healing rate for the total sample.

For the patients who received stimulation A, the asymmetric waveform, three variables characterized the average healing rate: ulcer area at the beginning of the treatment, the ulcer duration, and the number of hours per day the patient used the stimulation. These three factors accounted for nearly 50% of the variability in the average healing rate of the patients receiving the A treatment. No descriptive variables were significantly related to the average healing rate in any of the other patient groups.

All patients received standard wound management in addition to the stimulation protocols being tested. Stratification of healing rates by the standard treatments failed to demonstrate any significant differences in healing rates. Further subdividing the patient groups by their standard treatment and the stimulation treatment also did not demonstrate any differences, and there was no interaction between the standard treatment and the stimulation protocols, even when the data were restricted to the three most commonly used standard treatment programs (Table 7).

CONCLUSIONS— This study found the addition of asymmetric biphasic electrical stimulation to be effective in expedit-

ing wound healing for diabetic subjects. Healing rates more than doubled when wounds receiving the asymmetric stimulation were compared with those that did not receive electrical stimulation. No other characteristic of the subjects or their general state of health accounted for this increase in healing. This finding is in agreement with the one other study that evaluated the effects of electrical stimulation on wound healing in a diabetic sample (10). Although healing rates were not calculated by these authors, they reported an increase in the number of healed wounds by the 8th week, and a significant reduction in the size of all remaining wounds by the 12th week of treatment.

Early studies reporting the affects of electrical stimulation on wound healing evaluated the treatment in heterogeneous samples; patients with diabetes, those with pressure ulcers after spinal cord injury or various forms of brain trauma, and ulcers in the presence of general senility and overall debilitation were treated as a single group (1–9). The pathophysiology of wound development, as well as wound healing, can vary from one diagnostic group to another. The present study is the second to report on a diagnostic-specific sample of adults with diabetic ulcers. Both of these studies have been successful in showing the efficacy of stimulation in the diabetic sample.

The healing rates from the present study were notably lower than healing rates cal-

culated for a sample of spinal cord-injured patients treated for pressure ulcers with the same stimulation protocols as reported here (15). The two studies were done simultaneously by the same research therapists and with the same equipment. Whereas the average healing rate was 64%/wk for the spinal cord-injured patients receiving the asymmetric biphasic stimulation, the average healing rate for the same protocol in this diabetic sample was <30%/week. This pattern between patients with decubital ulcers and individuals with vascular lesions was also reported by Karba et al. (13). Although it appears that the addition of electrical stimulation to standard wound management programs for individuals with diabetic ulcers is an effective technique for enhancing the healing process, the pathophysiology associated with the ulcer plays a significant role in anticipated treatment outcomes. Further research with diagnostic-specific patient samples is critical to establish both efficacy and treatment modifications dictated by the particular pathophysiology of wound generation and its subsequent repair. The specifics of which stimulation waveform, placement of stimulation electrodes, and duration of stimulation treatment remain somewhat ambiguous for diabetic patients at this time, but general principles of treatment are beginning to become more apparent.

Enhanced wound healing with electrical stimulation has been attributed to increased blood flow (22,24). Current the-

Table 5—Healing rates of diabetic wounds at least semicompliant with stimulation and requiring 8 days or more to heal

	Protocol			
	A	B	MC	Control
Healing rates	27.0 ± 4.0	16.4 ± 6.1	17.2 ± 4.8	17.3 ± 2.3
No. of wounds	29	24	20	19

Data are means ± SE or n.

Table 6—Healing rates of diabetic wounds at least semicompliant with stimulation and requiring 8 days or more to heal—combined control groups

	Protocol		
	A	B	Control
Healing rate	27.0 ± 4.0*	16.4 ± 6.1	17.3 ± 2.7
No. of wounds	29	24	39

Data are means ± SE or n. *A is statistically significantly greater than control.

ory proposes that this response is mediated through the electrical excitation of peripheral sensory nerves. The relatively low healing rates recorded in the present diabetic study may be related to the neuropathy frequently seen in the distal extremities of diabetic patients (26), as well as the choice of pulse duration and electrode placement used in the current study. The pulse duration used in the A protocol was very short (100 μ s), rendering the stimulation inadequate for excitation of peripheral nerves which are small in size, or minimally myelinated (25). Thus, nerves that are even slightly affected by diabetic neuropathy would tend to be less excited with this form of electrical stimulation than those in normal skin. The pulse duration used in the present study was chosen to mimic those used in a variety of other studies. The typical "high-voltage stimulator" uses waveforms of even shorter duration (2–20 μ s), which would be even less likely to excite nerves that are only marginally functional. It would seem that the use of a longer pulse duration, 500 μ s up to 1 ms, would allow more complete activation of damaged peripheral nerves in the distal extremities.

The electrodes for the present study were placed in close proximity to the area of the ulcer. This usually placed the electrodes on the distal extremities, in the area of greatest neuropathy for most patients. A decreased recruitment of marginally functioning sensory nerves may account for the lower average healing rates reported in the diabetic sample when this study is compared with the sample of spinal cord-injured patients. Placement of electrodes more proximally within a dermatomal pattern may provide more extensive recruitment of sensory nerve fibers.

Lundeberg et al. (10) used electrodes over intact skin in proximity to the treated ulcers, but chose a stimulation pulse duration of 1 ms, a duration often more successful in exciting neurons that are small and only lightly myelinated. The reported

response of Lundeberg's subjects was not very different from the findings of the present study, however, indicating that there may have been only a small difference in ease of neuron excitation between the two stimulus pulse durations. Certainly assessment of peripheral neuropathy in the area of electrical stimulation would provide potentially important information regarding the choice of stimulus pulse duration in this specific patient group. In addition, because the increased circulatory effect is rather generalized, placement of stimulating electrodes proximally, where there is presumably less neuropathy, may provide a greater change in healing rates than placement around a distal ulcer.

The present study and the report by Lundeberg et al. (10) both used stimulation waveforms that appear to have minimal polar effects. Lundeberg et al. (10) report that their waveform was an "alternating . . . square-wave pulse," although they also state that "the polarity of the treatment electrode . . . was changed after each treat-

ment." The most effective waveform for healing in the present study was an electrically balanced asymmetric biphasic square-wave, with the electrode configuration standardized. Because the delivery time of the primary pulse was so much shorter than the secondary, balancing pulse (100 μ s vs. 20 ms), there may have been some slight polar responses to the asymmetric biphasic pulse, particularly in tissues deep to the electrodes. Although these polar effects may be relatively small, they cannot be entirely ruled out (21). Although other studies have reported the use of pulsed monophasic stimulus waveforms, the number of ions moved, e.g., the degree of the polar response with these very short pulse durations, is also unknown (21). Interestingly, the symmetric biphasic square-wave used in the present study generated healing rates that were not statistically different from the asymmetric waveform, but certainly looked more like the data from the control group. If polarity had no place in the enhancement of wound healing, the symmetric biphasic waveform would be hypothesized to be most effective, because both electrodes would be equally active in recruiting sensory nerves to generate an increase in blood flow and hence an improved healing response. The lack of healing responses seen in the present study when the symmetric biphasic waveform was used, and a less than optimal response demonstrated in the spinal cord-injured patient sample (15), indicates the presence

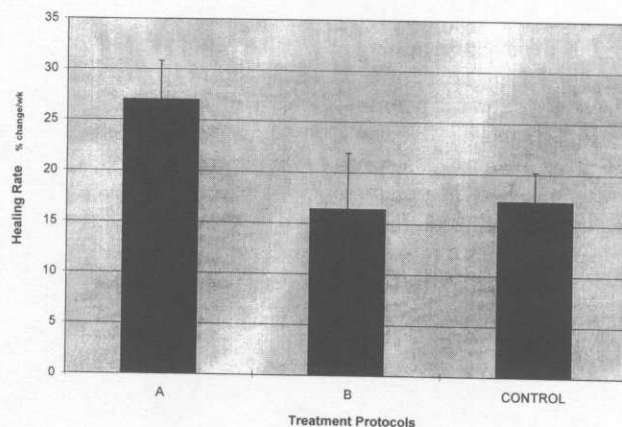
Diabetic Healing Rates

Figure 2—Mean healing rates for wounds receiving compliant levels of stimulation and healing at <90%/week (requiring more than 8 days to heal) and showing at least semicompliant stimulation levels (minimum of 30 min a day) (n = 92). The MC and C treatment protocols are combined together, because both were originally designated as Control. Statistically significant differences were seen between the A protocol and the control protocol. Patients receiving the B protocol were not significantly different than either the A protocol or control groups.

Table 7—Healing rates comparing standard treatments and stimulation protocols

	Protocol			
	A	B	MC	TC
Acetic acid				
Healing rate	24.3 ± 6.1	25.5 ± 8.1	17.4 ± 5.7	19.0 ± 2.5
No. of wounds	14	13	16	14
Saline				
Healing rates	29.2 ± 9.7	19.7 ± 19.3	3.0	7.0 ± 7.2
No. of wounds	8	3	1	3
Dry dressing				
Healing rate	34.0 ± 9.0	-7.8 ± 17.6	31.0 ± 7.0	21.0 ± 3.0
No. of wounds	3	4	2	2

Data are means ± SE or n.

of more than one mechanism through which electrical stimulation may enhance wound healing. A combined effect of polar and nonpolar, local, and more regional responses may function together when optimal healing is achieved through electrical stimulation.

The present study provided patients with 90 min of cycled stimulation on a 5- to 7-day-a-week schedule. Compliance to the 90-min treatment was monitored and maintained, so that the average stimulation time per day ranged from 30 min to the full 90 min. This protocol was slightly more aggressive than some previously reported (6–11). In a study of stimulation-enhanced healing in pigs, Davis and Ovington (27) reported an optimal effect with 60 min of treatment, and that the addition of another 5 or 23 h of stimulation did not increase the healing rate (27). In the present study, daily treatment times were found to be significantly related to the calculated healing rates in the group receiving the asymmetric biphasic stimulation. The correlation was weak, however, indicating that the treatment was adequate, and more extended stimulation time did not dramatically affect the healing rate.

Electrical stimulation, using an asymmetric biphasic square waveform, was effective for increasing healing rates in diabetic patients with open ulcers. Whereas healing rates were more than doubled in the group receiving electrical stimulation, the enhanced healing rate was still below that computed from a sample of spinal cord-injured patients with pressure ulcers. This study demonstrated that the addition of electrical stimulation was superior to healing without any stimulation. The definitive choice of stimulus waveform and pulse duration, and the physiological mechanisms by which stimulation affects

wound healing, remain somewhat obscure. Increased peripheral circulation is a probable mechanism of healing, but at this time polar effects directly onto the healing tissue cannot be entirely ruled out. Optimal choices for stimulus pulse duration and electrode placements in the diabetic patient population, who typically demonstrate peripheral neuropathy associated with hard-to-heal ulcers, require additional study; the present study demonstrated therapeutic effects with short pulsed stimulation placed over areas of probable neuropathy.

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