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A Quantitative, Pooled Analysis and Systematic Review of Controlled Trials on the Impact of Electrical Stimulation Settings and Placement on Pressure Ulcer Healing Rates in Persons With Spinal Cord Injuries

Liang Liu, MBBS, PhD; Julie Moody, MSc, RCN; and Angela Gall, FRCP

Abstract
Pressure ulcers (PrUs) are among the most common secondary complications following spinal cord injury (SCI). External electrical current applied to a wound is believed to mimic the body’s natural bioelectricity and to restart and stimulate endogenous electrical fields to promote wound healing. A systematic review was conducted to critically appraise and synthesize updated evidence on the impact of electrical stimulation (ES) versus standard wound care (comprising cleansing, dressing, nutrition, and debridement as necessary) and/or sham stimulation on PrU healing rates in persons with SCIs. Medline, Embase, the Cumulative Index for Nursing and Allied Health Literature (CINAHL), PsycINFO, and Cochrane Central were searched using the terms spinal cord injury, electrical stimulation, and pressure ulcer in free text and MESH terms. Publications were limited to peer-reviewed, randomized controlled trials (RCTs) and non-RCTs (CCTs) published in English from 1985 to 2014. The methodological quality of the RCTs was evaluated using the Jadad scale; CCTs were assessed using the Downs and Black tool. Pooled analyses were performed to calculate the mean difference (MD) for continuous data, odds ratio (OR) for dichotomous data, and 95% confidence intervals (CI). A total of 8 trials were reviewed — 6 RCTs and 2 CCTs included a total of 517 SCI participants who had at least 1 PrU. The number of patients per study ranged from 7 to 150 and the number of wounds from 7 to 192. Comparison models included ES irrespective of current type and placement of electrodes against sham/no ES (7 trials), ES delivered by electrodes overlaid on the ulcer versus sham/no ES (4 trials), ES delivered by electrodes placed on intact skin around the ulcer versus sham/no ES (4 trials), ES delivered by electrodes overlaid on the wound bed versus placed on intact skin around the ulcer (1 trial), ES with pulsed current versus sham/no ES (6 trials), ES with constant current versus sham/no ES (2 trials), pulsed current ES versus constant current ES (1 trial), number of PrUs closed (2 trials), and incidence of PrU worsened by ES versus sham/no ES (2 trials). The overall quality of studies was moderate; 2 trials were rated as good quality, 2 were poor quality, and 4 were moderate. Evidence showed ES increased the rate of PrU healing in patients with SCI (MD 4.97, 95% CI 1.97–7.98, \( P = 0.00 \); \( N = 7 \) studies and 559 ulcers), and a higher proportion of ulcers healed (OR 2.68, 95% CI 1.17–6.14, \( P = 0.02 \); \( N = 2 \) studies and 226 ulcers). The data suggest pulsed current ES increased the healing rate (MD 6.27, 95% CI 2.77–9.78, \( P = 0.0005 \); \( N = 6 \) studies and 509 ulcers) more than constant current (MD 4.50, 95% CI 1.19–10.18, \( P = 0.12 \); \( N = 2 \) studies and 200 ulcers). In addition, wounds with electrodes overlaying the wound bed seemed to heal ulcer faster than wounds with electrodes placed on intact skin around the ulcer. Future preclinical, in vivo models and clinical trials examining the impact of electrodes configuration for PrU healing are warranted.

Keywords: systematic review, electric stimulation, pressure ulcer, spinal cord injury


Potential Conflicts of Interest: none disclosed

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The National Pressure Ulcer Advisory Panel/European Pressure Ulcer Advisory Panel (NPUAP/EPUAP) describes a pressure ulcer (PrU) as an area of localized damage to the skin as a result of prolonged pressure alone or pressure in combination with shearing forces. A PrU is typically categorized into 4 key stages depending on ulcer depth and severity. PrUs are among the most common secondary complications following spinal cord injury (SCI). According to the Model SCI System Statistical Centre, the annual incidence rate of PrUs is 14.7% in the first post-injury year and noted to steadily increase thereafter. It is estimated that up to 85% of people living with SCI develop a PrU during their lifetime.

According to the NPUAP/EPUAP guideline, a systematic review of 12 studies, and a survey once a PrU has developed, it significantly increases the burden on the individual with SCI and/or his/her caregivers and has substantial detrimental impact on the quality of life, independence, and dignity of the patient. If a PrU is severe, it can lead to further disabilities, need for surgical interventions, and fatal infections. Krause et al surveyed 1017 patients with SCI to examine the relationship between PrU and life adjustment after SCI and found PrUs adversely impacted nearly every area of life studied, including quality of life and independent living.

Apart from personal consequences, PrUs also represent a significant cost burden for health and social care systems. According to the National Institute of Health and Care Excellence (NICE) guideline, in addition to the costs of standard care, the daily costs of treating a PrU are estimated to range from £43 to £374 in the United Kingdom. Resources required for treating a PrU include nursing time, dressings, antibiotics, diagnostic tests, and high-specification, pressure-reducing devices. Although the exact cost of PrU management in SCI is unknown, the total cost of treating PrUs has been estimated to be between £1.4 billion and £2.1 billion per year; the average cost to treat 1 Stage IV PrU is £14,108 per episode in the general population.

Treatment for PrUs can vary depending on the grade/stage of the ulcer. The standard care of PrUs varies across individual settings. Although the management of PrUs recommended by clinical guidelines includes offloading, improving nutrition, cleansing, debridement, and dressing, the general principles of Stage I ulcer treatment incorporate pressure relief, careful clinical monitoring, cleansing, and dressings to promote hydration; Stage II ulcers may require pressure relief using a high-specification foam mattress/cushion or dynamic support surface and a moist dressing for reepithelialization; and Stage III and Stage IV ulcers usually require advanced nonsurgical or surgical treatment in addition to pressure relief; they also may require debridement and antibacterial treatment if systemic sepsis, cellulitis, or underlying osteomyelitis is clinically evident.

Electrical stimulation (ES) was proposed as a therapeutic modality for wound healing more than a century ago, and its use has been well documented in clinical studies since the 1960s, especially for wounds not responding to standard forms of treatment. Despite the fact ES has been demonstrated in clinical studies to accelerate wound healing compared to no ES as adjunctive therapy, the understanding of the exact physiological mechanism remains incomplete. Animal models and in vitro preclinical studies provide some indication of the mechanism of ulcer healing enhanced by ES. Endogenous electrical fields (which measure electrical potentials) are known to naturally exist in the human body and are vital for tissue development and repair. The electrical potential at the epidermis (transepithelial potential) is generated by intact skin through directional active ion transport, leading to the concentration of negative chloride ions at the surface and positive sodium and potassium ions in the tissues. The epithelial layer of intact skin acts as an electrical barrier. When a wound occurs, the epithelial barrier is broken, allowing the current to flow out of the wound. The transepithelial potential collapses and ions immediately begin to leak out, establishing a weak but measurable current between the skin and inner tissues (the current of injury). The current is thought to continue until the skin defect is repaired.

Two main types of ES currents commonly noted in the literature are pulsed current (PC) and direct current (DC). Constant, low-intensity DC involves applying continuous, unidirectional flow of current of low intensity (<1 mA) for at least 1 second. PC includes monophasic and biphasic waveforms: monophasic PC involves brief pulses of unidirectional flow of current followed by a finite off period, and biphasic PC consists of brief pulses of bidirectional current that has either a symmetric or asymmetrical biphasic waveform. In symmetric biphasic PC, the bidirectional PC is equal and balanced, whereas asymmetric biphasic PC produces a bidirectional current that is unequal and may or may not be bal-
balanced. Balanced asymmetric biphasic PC has no net positive or negative charge; unbalanced asymmetric biphasic PC creates a net positive or negative charge over time.17

Application of an external electrical current to a wound is believed to mimic the body’s natural bioelectricity and to restart and stimulate endogenous electrical fields and as such, promote wound healing.20-22 ES has been demonstrated in both in vitro23-26 and animal in vivo27 studies to enhance cellular activities such as collagen and DNA synthesis, ATP concentration, and generation of chemotaxic factors.24-27 ES also has been shown in vitro and in vivo studies25,27-31 to increase tissue perfusion, decrease edema, and promote angiogenesis and galvanotaxis compared to no ES stimulation, directing and accelerating the process of endothelial migration in the wound tissue to promote wound healing.

In a clinical study, Baker et al13 assessed 3 different forms of ES current for pressure healing among 192 PrUs in 80 patients with SCI who were treated for 45 minutes/day for 4 weeks. The authors reported ES enhanced PrU healing by measuring percentage changes of wound surface area per week in comparison with no ES in SCI. In addition, the authors identified asymmetric biphasic waveform of electrical current as the optimal wound healing protocol in comparison with microcurrent and without ES. Mittmann et al32 constructed a decision analytic model over a 1-year period to determine the incremental cost effectiveness of ES plus standard wound care (SWC), typically comprised of nonsurgical procedures such as debridement, dressing, nutritional, physical

Figure 1. Literature search screening flow chart. PU=pressure ulcer; SCI=spinal cord injury; ES=electrical stimulation
<table>
<thead>
<tr>
<th>Author, year, reference, country</th>
<th>Number of patients (PrUs)</th>
<th>Comparison</th>
<th>Type of ES</th>
<th>ES parameters (pulse duration, frequency, intensity)</th>
<th>Electrode characteristics (location, material, size)</th>
<th>Study period</th>
<th>Outcome measures</th>
<th>Methodological quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houghton et al (2010) Canada</td>
<td>40 (34)</td>
<td>I: ES plus SWC program; C: SWC only without ES.</td>
<td>Pulsed current</td>
<td>50 µs, 100Hz and 10Hz, 50–150 V</td>
<td>On wound bed; NR, 4.8 cm x 10.2 cm</td>
<td>3 months</td>
<td>WSA</td>
<td>Low risk of bias Jadad 3, AC yes, ITT yes</td>
</tr>
<tr>
<td>Griffin et al (1991) USA</td>
<td>17 (17)</td>
<td>I: ES plus standard nursing care program; C: Sham ES plus standard nursing care</td>
<td>Pulsed current</td>
<td>75 µs, 100 pps, 200v</td>
<td>On wound bed, aluminium plate; larger than ulcers</td>
<td>20 days</td>
<td>WSA</td>
<td>Low risk of bias Jadad 4, AC yes, ITT no</td>
</tr>
<tr>
<td>Adegoke et al (2001) Nigeria</td>
<td>7 (7)</td>
<td>I: ES plus SWC; C: Sham ES plus SWC</td>
<td>Pulsed current</td>
<td>NR, 30Hz, submotor</td>
<td>On wound bed, aluminium plate; larger than ulcers’ perimeters</td>
<td>4 weeks</td>
<td>WSA</td>
<td>Moderate bias Jadad 2, AC yes, ITT no</td>
</tr>
<tr>
<td>Baker et al (1996) USA</td>
<td>80 (192)</td>
<td>I: asymmetric biphasic ES; II: symmetric biphasic ES; III: microcurrent ES; C: No ES treatment</td>
<td>Pulsed current</td>
<td>I: 100 µs, 50 Hz, submotor II: 300 µs, 60 Hz, submotor III: 10 µs, 1 Hz, 4mA</td>
<td>Edge of ulcer, carbon-rubber, 2.5 cm x 2.5 cm to 5 cm x 10 cm</td>
<td>4 weeks</td>
<td>Healing rate and WSA</td>
<td>Moderate bias Jadad 2, AC no, ITT no</td>
</tr>
<tr>
<td>Jercinovic et al (1994) Slovenia</td>
<td>73 (109)</td>
<td>I: SWC plus ES; C: SWC. Crossover group after 4 weeks</td>
<td>Pulsed current</td>
<td>250us, 40Hz, up to 45mA</td>
<td>Edge of ulcer, self-adhesive, 5 cm x 7.5 cm</td>
<td>4 weeks</td>
<td>Healing rate</td>
<td>Moderate bias Jadad 1, AC no, ITT yes</td>
</tr>
<tr>
<td>Karba et al (1997) Slovenia</td>
<td>50 (50)</td>
<td>I: ES with positive electrode overlaid ulcer and 4 negative electrodes laid around ulcer; II: Same ES program with 2 electrodes laid on intact skin at the ulcer edge across wound; C: Sham ES. All groups received SWC</td>
<td>Constant direct current</td>
<td>NA, NA, 0.6 mA</td>
<td>I: Overlaid the ulcer; rubber electrodes; NR; II: edge of ulcer, self-adhesive electrodes, NR</td>
<td>Not reported</td>
<td>Relative healing rate</td>
<td>Moderate bias Jadad 2, AC no, ITT no</td>
</tr>
</tbody>
</table>

*continued on next page*
ELECTRICAL STIMULATION IN PRESSURE ULCER HEALING

therapies, and surgical procedures for the management of complications in comparison with SWC alone in SCI with Stage III and Stage IV (per the NPUAP) PrUs. The authors assessed PrU healing using healing rates, recurrence rates, and complication rates; ES also reduced the cost of care in the SCI population. Furthermore, the most recent NPUAP/EPUAP clinical guideline recommends the use of ES to facilitate wound healing in recalcitrant Category/Stage II PrUs as well as any Category/Stage III and Stage IV PrUs in patients with SCI. However, the lack of consistency in the use of stimulation mode and parameters, together with the small sample size in the individual published trials, makes it difficult for health professionals and health providers to make clinical decisions on the implementation of ES treatment for PrU.

Purpose

The purpose of this quantitative meta-analysis was to increase understanding of how different settings of ES affect PrU healing. Pooled analysis that quantitatively calculates weighted averages of findings across multiple trials can increase the statistical power of the existing small sample size of individual studies, enriching understanding of inconsistent results encountered across individual studies.

The aims of this review were 1) to assess the effect of ES as an adjunctive therapy for PrU on the weekly healing rate in people with SCI when compared to sham stimulation or no ES treatment; 2) to explore whether different types of ES currents and electrode placement have any influence on the healing rate of PrUs; and 3) to examine whether ES treatment worsens PrU in SCI as compared to no ES treatment.

Methods

Literature search. The original systematic review protocol registered in the PROSPERO database in July 2013 (www.crd.york.ac.uk/PROSPERO; registration number CRD42013005088) was updated to include more recent research up to July 3, 2014. Material from the original study plus new findings are analyzed. As before, full reports of randomized, controlled trials (RCTs) and nonrandomized, clinical controlled trials (CCTs) were identified through searches of the Medline, Embase, the Cumulative Index for Nursing and Allied Health Literature (CINAHL), PsycINFO, and the Cochrane Central Register of Controlled Trials without language restrictions. Search terms included spinal cord injury, electrical stimulation, and pressure ulcer. All searched hits were exported to Endnote (Endnote version X7 for Windows, Thomson Reuters). All titles and abstracts were screened for eligibility, and the full text of potentially relevant articles was retrieved and considered for inclusion by the first author. Each stage of the selection process was cross-checked by the second author. Any disagreement was discussed or consulted by the third author.

Literature inclusion/exclusion criteria.

Target population. Persons with SCI and any categorical grade or any number of PrUs irrespective of age, gender, and level and degree of severity of traumatic or nontraumatic injury were included. Studies with a mixed-study population that included individuals with SCI were included if the ulcer outcomes were reported/analyzed separately for SCI participants.

Type of intervention. All types of ES using 2 or more surface electrodes placed on the wound bed or in the edge of wound bed were...
included.

**Type of studies.** RCTs and CCTs that compared any type of ES against SWC consisting of cleansing, dressing, debridement and nutrition without ES or sham ES that were published in an indexed, peer-reviewed journal between January 1985 and July 2014 were included. Conference abstracts and university theses were excluded.

**Outcome.** The publication needed to report ulcer outcome measurement (eg, wound size or average healing rate per day, per week, or during whole study period).

**Data extraction and methodological quality.** The following data were extracted from eligible articles by 1 reviewer (LL) and cross-checked by the second reviewer: year of publication, country of author, and type of study design. All other data, including quality assessment, were assessed independently by 2 reviewers. This included sample size; participant age, gender, and type and level of SCI; the type of ES; the duration and pattern of stimulation; electrode placement; follow-up duration; and adverse events. Additionally, data extraction included outcome measures on the percentage change in wound surface area or changes in ulcer size. Any disagreement in assessed findings between the 2 independent reviewers was resolved by discussion or through consultation with a third reviewer.

Each publication was subjected to a quality assessment. For RCTs, a Jadad score (University of Oxford, Oxford, UK) was used together with the item allocation concealment and consideration as to whether the analysis was based on the randomized groups. A modified Downs and Black tool (London School of Hygiene and Tropical Medicine, London, UK) was used for CCTs. Both scales are well-established tools for assessing and reporting the quality of clinical and health-related studies in the literature. The Jadad score independently assesses the methodological quality of a clinical trial and has known reliability and external validity. It contains an assessment — namely, risk of bias (selection bias, performance bias, detection bias, attrition bias) — and is relatively easy to use. The Jadad score addresses items relating to randomization, blinding, and description of withdrawals and dropouts, with scores ranging from 0 to 5 (trials scoring 3 or greater are considered to be of reasonably good quality). In addition to the Jadad score, 2 extra items were added: allocation concealment and intent-to-treat (ITT) analysis, which deal with reporting bias and performance bias for open-label (nonblinded) trials. Allocation concealment was considered adequate if patients and investigators who enrolled patients could not foresee treatment assignment. ITT is defined as an analysis that demonstrates inclusivity of all randomized participants based on specified criteria and includes all randomized patients in the groups to which they were randomly assigned.
assigned, regardless of 1) their adherence with the entry criteria, 2) the treatment they actually received, and 3) subsequent withdrawal from treatment or deviation from the protocol. The Downs and Black tool consists of 27 questions that evaluate the level of 4 domains: reporting, external validity, internal validity (both bias and confounding), and power. Each question was scored as Yes (1) or No/Unknown (0). Because question 5 addressed 2 components (Are the distributions of principal confounders in each group of subjects to be compared clearly described? A list of principal confounders is provided), the full score for the question was 2. Question 27 was modified slightly due to an ambiguity in the first component (Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is <5%? Sample sizes have been calculated?); only the second part of the question was assessed. For example, if the sample size was calculated by a trial, it was scored yes (1). The total score of the 27 questions was calculated by adding up the scores; thus, the highest score any reviewed article could receive was 28. It should be noted that scores increased in line with the methodological quality of the study; higher scores indicated higher methodological quality.

Data analysis. Data were extracted to a spreadsheet. A quantitative pooled analysis was performed to estimate the pooled ES treatment effect on weekly healing rates, the number of ulcers healed, and the incidence of ulcers worsening. All trials included in this review defined ulcer healing in terms of changes in wound surface area either per week, per day, or during the whole study follow-up. Because the daily healing rate has limited clinical relevance, for those trials that reported percentage of ulcer decrease per day or during the whole study period, the weekly healing rate was calculated and used for pooled analysis. Weekly healing rate was defined as the mean percentage change in ulcer size per week. Review Manager (Review Manager (RevMan), Version 5.3. Copenhagen, Denmark), was used for pooling the results. The ES treatment effect was calculated as the mean difference in healing rates between the experimental and control groups. The heterogeneity of the results was assessed using the Cochran’s Q test and the I² statistic. The statistical significance of the pooled effect was determined using the Z test. A forest plot was used to visually represent the results of the pooled analysis.
The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) was used to pool the healing rate per week and the number of ulcers completely healed and ulcers that worsened among the studies. All data irrespective of the length of treatment and follow-up were analyzed. Weekly healing rate was compared between patients who had ES and patients who had no ES treatment. Subgroup analysis was performed for good quality RCTs. The weekly healing rate between PC and constant DC and electrode overlaid versus placed at edge of ulcer were compared. For those trials with more than 2 arms, the ES arm with the largest sample was included for comparison with the control arm (no ES/sham ES). Treatment effect was significant if $P < 0.05$. Heterogeneity between studies was tested with the use of the chi-square test (significant if $P < 0.1$) and $I^2$ test (with substantial heterogeneity defined as values >50%). When studies showed significant heterogeneity ($I^2 > 50\%$), the Mantel–Haenszel random effects model was used to calculate mean difference. Otherwise, the fixed effects model ($I^2 < 50\%$) was used to calculate the pooled effect sizes when studies did not show heterogeneity.

**Results**

**Studies.** The literature search identified a total of 407 unique references; all were exported to Endnote, along with 3 additional articles identified from other sources. Of these 410 articles, 127 were identified as duplicates, resulting 283 abstracts and titles. These were further screened for eligibility, generating 80 potentially relevant abstracts that were retrieved and considered for inclusion in the final review. Of these, 8 (6 RCTs$^{13,38-42}$ and 2 nonrandomized CCTs$^{43,44}$) met the inclusion criteria and were subjected to full-data extraction and quantitative analysis. Figure 1 provides a flow chart of the process and results for screening eligibility and study selection.

All 8 studies described the study target population as persons with SCIs who had at least 1 PrU. The number of patients per study ranged from 7 to 150, with the number of ulcers studied ranging from 7 to 192. Four (4) studies ($N = 415$ ulcers) measured mean daily percentage change in ulcer size,$^{41-44}$ 1 study ($N = 192$ ulcers) measured the mean weekly percentage change in ulcer size,$^{13}$ and 3 studies ($N = 58$ ulcers) measured mean percentage change in ulcer size across the entire study period.$^{38-40}$ Six (6) out of 8 trials ($N = 509$ ulcers) compared PC ES to sham/no ES treatment,$^{13,38-41,44}$ 1 trial ($N = 50$ ulcers) compared constant current ES to sham ES treatment,$^{42}$ and 1 ($N = 150$ ulcers) compared PC ES to constant current ES therapy or sham ES.$^{43}$ For stimulus pulse settings, stimulation varied from 40 Hz to 100 Hz in frequency and from 50 V to 150 V (or 4 mA to 45 mA) in intensity.

In terms of electrodes placement, in 3 studies$^{38-40}$ ($N = 58$ ulcers) the electrodes were overlaid on wound bed, in 4 studies ($N = 557$ ulcers) the electrodes were applied to intact skin around the wound,$^{13,41,43,44}$ and in 1 ($N = 50$ ulcers) ES treatment compared electrodes overlaid on the wound bed to electrodes placed on intact skin around the ulcers.$^{42}$ Details of sample characteristics are shown in Table 1.

**Methodological quality.** One (1) of the 6 RCTs described an appropriate method to generate the randomization sequence,$^{40}$ 2 were double-blinded and described the method
of double-blinding. Two (2) RCTs were considered to be of reasonably good methodological quality according to the Jadad score along with 2 other items; hence, they were classified as low risk of bias trials. The remaining 4 RCTs were considered to exhibit moderate risk of bias. Two (2) nonrandomized CCTs were assessed for their reporting quality using the Down and Black tool, scoring 13 and 8, respectively, out of a total achievable score of 28 and subsequently considered relative high risk of bias trials.

Data pooling and meta-analysis.

Effectiveness of ES. ES effectiveness was assessed according to mean weekly healing rate (ie, average percentage change per week in ulcer size), the number of ulcers healed, and the incidence of ulcers worsening (defined as wound size increased during study period), comparing different ES settings and/or how ES performed versus sham or no treatment.

With regard to overall healing rate by ES versus sham/no ES, the pooled analyses of the 7 relevant trials showed people receiving ES treatment in addition to conventional wound treatment (which involved cleansing, dressing, nutrition, and debridement as necessary) reporting a higher weekly healing rate than those without ES treatment by 4.97% (MD 4.97, 95% CI 1.97–7.98, \(P = 0.001\)) (see Figure 2). However, heterogeneity among the studies was substantial (\(I^2 = 83\%\), \(P <0.00001\)). A subgroup analysis of RCTs considered to be of good methodological quality showed a trend toward a higher weekly healing rate in people treated with ES than people without ES treatment, but the pooled effect was not significant (\(P = 0.07\)).

When healing rate by PC ES versus sham/no ES was assessed, the pooled analysis of the 6 trials showed a significantly higher weekly healing rate in people who were treated with PC ES than those without ES treatment (MD 6.27, 95% CI 2.77–9.78, \(P = 0.0005\), \(I^2 = 74\%\)) (see Figure 3). When healing rate by constant DC versus sham/no ES was compared, the pooled analysis of the 2 trials in which constant current ES was applied showed a nonsignificantly higher weekly healing rate in people treated with constant current than those without ES (MD 4.50, 95% CI 1.19–10.18, \(P = 0.12\), \(I^2 = 0\%\)) (see Figure 4).

With regard to healing rate by PC versus DC ES treatment, 1 CCT compared PC ES treatment versus DC for PrU healing. A higher weekly healing rate was achieved by PC ES: 5.43% to 4.40% per day versus 3.11% to 3.83% per day, respectively (\(P = 0.03\)).

Healing rate by electrode placement also was assessed (ie, active electrode overlaid the wound bed versus sham/no ES). A meta-analysis of the 4 trials that applied the active electrodes directly on the wound found a significantly higher rate with ES irrespective of current type than without ES (MD 9.01, 95% CI 2.02–16.00, \(P = 0.01\), \(I^2 = 90\%\)) (see Figure 5).

When electrode placement on intact skin was analyzed, the pooled analysis of the healing rate for the 4 trials where both electrodes were placed on intact skin/the edge of wound versus sham/no ES showed a significantly higher weekly healing rate in people who received ES than those who received no ES (MD 7.71, 95% CI 1.59–13.83; \(P = 0.01\), \(I^2 = 79\%\)) (see Figure 6).

The healing rate when the active electrode overlaid the wound bed was compared to electrodes placed on intact skin/the edge of wound. One (1) study compared the effect of ES delivered by applying the electrodes either directly on the wound bed or on the edge/intact skin around the ulcer versus sham ES treatment. In group 1, the positive electrode overlaid the ulcer and 4 negative electrodes were laid around the ulcer; in group 2, 2 electrodes were laid on intact skin at the ulcer edge across the wound; and in group 3, 2 electrodes were laid on intact skin at the ulcer edge across the wound without ES delivery. The authors reported electrodes that overlaid wound bed achieved a higher healing rate than electrodes placed on intact skin around the ulcer or sham ES group (1.6%/day overlaid versus 4.8±1.5%/day versus 4.2±11%/day).

Two (2) trials addressed the number of ulcers completely healed by ES versus sham/no ES. Both trials reported a higher number of ulcers completely healed in the ES treatment group (52% and 37%, respectively) compared to sham/no ES treatment (24% and 28%, respectively). Pooled analysis of these 2 trials showed significantly higher numbers of ulcers (N = 226 ulcers) healed with ES treatment (OR 2.68, 95% CI 1.17–6.14, \(P = 0.02\), \(F = 0\%\)) (see Figure 7).

Two (2) studies reported the incidence of ulcers that worsened during the study period compared to sham/no treatment. Both trials reported lower number of ulcers worsened in individuals who had ES treatment (N = 143 ulcers). However, the pooled analysis of these 2 trials showed the difference was nonsignificant (OR 0.38, 95% CI 0.12–1.24, \(P = 0.11\), \(F = 18\%\)) (see Figure 8).

Adverse events. Only 1 of the 8 studies reported adverse events. The authors indicated some patients experienced minor adverse reactions related to ES, which included red, raised, itchy skin beneath the large dispersive electrode. One (1) patient had a persistent (>24 hour) redness or burn under the active electrode, presumably from too high a stimulus intensity, which resolved within 48 hours.

Discussion

ES has been recommended for use in the treatment of PrUs in recent (2014) NPUAP/EPUAP guidelines, yet the specifics for ES are not clear. The comparison of ES current types and placement of electrodes reported in the present review should provide new insights for clinicians who treat PrU in the SCI population. Of the 8 studies that met inclusion criteria and were included in this review, 6 were RCTs and 2 were CCTs.

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2 were nonrandomized CCTs.\textsuperscript{43,44} Two (2) of the 6 RCTs\textsuperscript{39,40} were classified as having good quality of evidence according to the Jadad scale; they used allocation concealment and ITT analysis. The other 4 RCTs\textsuperscript{13,38,41,42} were classified as moderate quality, and the remaining 2 nonrandomized\textsuperscript{3,44} CCTs provided a relatively low level of evidence. As a whole, the 8 trials provided a moderate level of evidence.

In terms of effectiveness, the quantitative pooled analysis of the 7 controlled trials showed an average higher weekly healing rate during the treatment period when patients received ES in addition to SWC of cleansing, dressing, nutrition, and debridement as necessary. Of the 8 trials included in the review, 2 studies\textsuperscript{13,40} (N = 226 ulcers) reported the number of ulcers completely healed during the study period (OR 2.68, 95% CI 1.17–6.14); significantly more PrUs healed with ES treatment in comparison to sham ES or no ES treatment (P = 0.02). Two (2) trials\textsuperscript{39,41} reported fewer ulcers worsening when patients received ES treatment. These 2 trials also showed a trend toward higher weekly healing in the ES group, although the difference was not significant between ES treatment and control groups.

In addition to supporting the recommendations of the most recent NPUAP/EPUAP clinical guidelines\textsuperscript{5} regarding the application of ES for recalcitrant PrU healing in persons with SCI, the current findings are also in agreement with previous studies demonstrating ES enhances PrU healing in the SCI population\textsuperscript{45} and chronic wound healing in the non-SCI population.\textsuperscript{11-16} A systematic review conducted by Lala et al\textsuperscript{45} reported the risk of PrU healing during the study period (20 days to 3 months) together with daily healing rate (percentage decrease per day) in SCI. The authors concluded ES seems to be an effective adjunctive therapy to accelerate and increase PrU closure in individuals with SCI. In the current review, the calculated weekly healing rate was anecdotally suggested by clinicians and tissue viability specialists to be more clinically relevant than simply describing the positive outcomes of previous research. In addition, the types of ES current and placements of electrodes, presented along with the incidence of worsening PrUs, should be of interest to clinicians.

The constant DC that involves unidirectional continuous flow of current for longer than 1 second has been associated with an antibacterial effect in PrU healing, but it can cause chemical and thermal burns.\textsuperscript{46} This type of ES was employed in 2 of the studies\textsuperscript{43,44} reviewed. The most commonly used ES for PrU healing in the review was PC that involved no sinusoidal, interrupted current flow for a brief period of time. It is suggested that PC ES more closely mimics the “current of injury” necessary for triggering tissue healing by sustained activation of the voltage-gated sodium channels in the surrounding tissues.\textsuperscript{24} As compared with continuous DC stimulation, PC ES may carry a lower risk of possible skin burns and a greater depth of penetration.\textsuperscript{39,24,46,47} PC ES was utilized in 6 out of 8 studies (N = 465 ulcers)\textsuperscript{13,38-42} Pooled analysis of 6 trials showed PC ES significantly improved weekly healing rate compared with no ES.

Three (3) studies involved placing the active electrode directly on the wound bed and the negative electrode on the intact skin around the edge of the ulcer.\textsuperscript{38-40} Four (4) studies reported the negative and positive electrodes were placed on opposite sides of the PrU on intact skin.\textsuperscript{13,41,43,44} One (1) study\textsuperscript{45} compared electrode placement (1 group of participants received ES by applying the ES with positive electrode overlaid on the ulcer and 4 negative electrodes laid around ulcer, while the other group received ES by applying same ES program with 2 electrodes laid on the intact skin at the ulcer edge across wound; the participants in the control group received sham ES treatment with 2 electrodes laid on the intact skin at the ulcer edge across wound). The authors found participants who received ES by electrodes overlaid on the wound bed had a higher healing rate than the participants who received ES by electrode placed surrounding the wound.

Electrode polarity has long been thought a complex issue in the literature. For instance, anodal stimulation was shown to increase fibroblast migration,\textsuperscript{31,48} while cathode stimulation enhanced keratinocyte migration\textsuperscript{22} and increased fibroblast proliferation.\textsuperscript{49} Both anodal and cathode stimulation have an antibacterial effect, with cathode stimulation seeming to have greater antibacterial effects.\textsuperscript{46,49} In the current endeavor, only 1 study\textsuperscript{47} compared electrode configuration by either placing the active electrode in the wound and the dispersive electrode at a distance from the ulcer versus placing both electrodes on the edge of ulcer. Although the average weekly healing rate was significantly higher when active electrodes overlaid the wound surface than when electrodes were placed surrounding the wound, this study was not a RCT and was classified as low level of evidence with high risk of bias. Such results should be interpreted with caution. Thus, the assessment of the different effects between 2 types of electrodes placement for PrU healing is inconclusive. Future preclinical, in vivo models and clinical trials examining the impact of electrode configuration on PrU healing are warranted.

Limitations

Although systematic reviews and meta-analyses have their own merits in terms of increasing the statistical power of the small sample size of individual studies, conducting such analyses often presents a number of limitations. These include publication bias (particularly against negative findings), language restrictions, heterogeneity across each studies, and coding of keywords. The small number of relevant trials, together with substantial heterogeneity in this review, made it difficult to interpret some findings and draw firm conclusions. Higher heterogeneities evident across the trials in this review can be explained by the variation of study design and stimulation parameters (stimulation frequency, intensity, waveform) and stimulation device used.

Another limitation of the study was the use of the Jadad
scale for assessing methodology quality of RCTs. Although the Jadad scale is a well-established tool and is widely used for assessing and reporting the quality of clinical and health-related studies in the literature, it has shortcomings. The Jadad scale is criticized for being oversimplistic, placing too much emphasis on blinding and exhibiting low consistency between different raters. Furthermore, it does not take into account allocation concealment. However, in this review, 2 assessment items (allocation concealment and ITT analysis) were added. The methodological quality of CCTs was assessed using the Downs and Black tool, a well-established assessment tool used in SCI literature; however, it features no cut-off point for definition of good or poor CCTs. Future reviews should consider using 1 assessment tool for both RCTs and CCTs. Nevertheless, the methodology for each article also was assessed independently by 2 authors, and consensus was achieved and disagreement was discussed between them.

A further limitation is the exclusion of non-English language literature. Although adding non-English articles may have strengthened the current review, the language restriction cannot be avoided due to lack of interpretation resources. To minimize the limitation, the authors adopted a well-structured search strategy that was approved by a clinical librarian, supplemented all “explode” functions, and utilized hand searches as well as contacting specialists to minimize the potential bias.

In addition to types of ES current and electrode placement, other parameters (such as material, size of electrodes, level of injury, quality of life, hospital stay, pain, and cost to patients and carers) also may have an impact on PrU healing. Unfortunately, incomplete reporting of such data was identified in the current review — for instance, only 1 trial in this review reported the level of injury and the majority of trials failed to report the size or material of electrodes used for ES treatment. Such data should be reported in future clinical studies.

Conclusion

ES appears to help facilitate PrU healing in the SCI population. Pulsed DC ES confers better benefits for PrU healing than constant DC. PrUs in people who had ES treatment seem more likely to completely close and less likely to worsen than ulcers in people who had no ES treatment. ES has been recommended for Stage III and Stage IV ulcers and for recalcitrant Stage II PrU healing by the NPUAP/EPF/AUP, yet the NICE guideline recommends not to use ES for PrU healing. Health professionals and the health service need well-designed clinical studies involving large sample populations to determine the optimal stimulation parameters and stimulation location with the most beneficial effect on the enhancement of PrU healing in SCI. Although an electrode directly placed on the wound bed may be more efficient than all electrodes placed on intact skin around the wound, more rigorous preclinical studies and clinical trials on determining the optimal stimulation parameters (eg, type of ES current — in particular, constant DC versus PC that were commonly used for PrU healing in SCI), locations of electrodes, material, and size of electrodes are warranted. To better understand the exact physiological basis of ES for enhancing PrU healing, research is urgently needed in the form of more preclinical in vivo models to identify the optimal mode of ES current and electrode placement (polarity).

References


