1 Introduction

One of the few regenerative capabilities of the human body is the healing of lesions inflicted to soft tissue. The process of repair and regeneration following injury represents one of the most fundamental defence mechanisms of an organism against its environment. Wound healing is often viewed as a sequence of events which automatically take course after the injury. However, closer acquaintance with the problems which may arise during the healing quickly dispels the concept of the inevitability of wound healing and brings the process into proper perspective as one of the keystones of modern surgery (Cuono, 1985).

Indeed, wounds which appear on the body without surgical intervention as well as surgical wounds may not heal. Such 'chronic' wounds are difficult and frustrating to manage. They can last for weeks, months or years and represent a major medical, social, and economic problem for the patients, their relatives and the medical community.

The major reason for the appearance of chronic wounds is ischaemia combined with damage to the nervous system and any resultant metabolic abnormalities.

There are three major groups of patients who are susceptible to chronic wounds:

(a) Spinal cord injured patients who develop pressure sores (decubitus ulcers) due to their inability to move and lack of sensibility in areas subjected to prolonged pressure on the skin, and deeper tissues from an external object while sitting or lying. Typical pressure sore locations are bone tuberocities (trochanter, sacrum, heels).

(b) Patients with peripheral vascular disease in whom ischaemic ulcers occur in the lower extremities due to various pathological conditions, the most common being diabetes mellitus. In a large proportion of such patients their condition impairs to such an extent that amputation is required with the usual complication that the wound on the stump resists healing.

(c) Geriatric patients in whom ulcers are due to combinations of immobility and reduced blood circulation.
With these facts in mind it is obvious that any additional treatment modality which might offer hope for accelerated healing of chronic wounds should be amenable to careful investigation. In the following paragraphs we present a survey of several methods which seem to improve wound healing by various applications of electrical and electromagnetic fields. It is our goal to present medical engineers as well as clinicians with adequate evidence about the effects of electricity on wound healing. We hope that additional basic and clinical investigations will be encouraged and that electrical wound healing will soon be generally accepted as a safe, simple and efficient modality for treating chronic wounds.

2 Stimulation modalities

A brief survey of the existing literature exposes a fascinating richness in the application of diverse electrical or electromagnetic fields to different parts of the body to heal chronic wounds. Practically all reports are rather exclusive regarding their specific method, and rarely even attempt to compare their treatment techniques with methods published by authors who used a different method.

Recently some review papers were published which discuss electrical wound healing (DAYTON and PALLADINO, 1989; KLOTH and FEEDAR, 1990; WEISS et al., 1990). However, none of them addressed all current modalities and electrode locations, nor did they discuss possible mechanisms. To present a fairly complete picture regarding the application of electricity in human wound healing is the goal of the present review. In the second part of this paper (STEFANOVSKA et al., 1993) some of our results as well as problems with the evaluation of the healing process will be discussed.

Obviously it is impossible to make a quantitative analysis of the comparative advantages and disadvantages of the different methods because the protocols, quantification and wound aetiologies in the published literature are vastly different. Therefore the aim of the following survey is not to 'grade' and compare the different techniques but only to make the clinician and engineer aware of the fact that there seem to be many truths in electrical wound healing and only time and more research will show if there is something like a single or optimal truth.

2.1 Direct current

It is quite difficult to trace back the history of electrical wound healing. One of its roots was investigations into natural electric fields. DU BOIS-REYMOND (1860) was the first who as early as 1860 described the currents of an injury leaving human skin wounds. The same phenomenon was observed by HERLITZKA (1910). He measured a current of about 1 μA in a skin injury on the hand. Experimental abrasions were made on human skin in research by CUNLIFFE-BARNES (1945) with the purpose of studying the potential difference between intact and injured skin during healing. The abrasions were found to be positive compared with the surrounding intact skin. The potential difference lessened during the healing of the wounds and disappeared when they closed over. The existence of injury currents was confirmed by measuring currents leaving the fingertips in children who had undergone accidental amputation (ILLINGWORTH and BARKER, 1980). On average eight days after the wounding a peak average current of 22 μA cm⁻² was obtained. Thereafter it lessened and reached zero value when the wounds healed completely.

These reports raised three questions: where is the source of injury currents, what is their physiological background, and what is their role in the healing process? Only the first of them was elucidated. In 1982 BARKER et al. presented a map of human 'skin battery' voltages, showing the arrangement of potentials on the surface of the intact skin on different parts of the human body with respect to the reference point in the subdermal layer. The surface of the skin was always negative compared with the deeper skin layers. The transcutaneous voltage was up to 40 mV. JAFFE and VANABLE (1984) finally located the skin battery in the epidermis or 'living layer'.

Human skin thus possesses endogenous electrical properties that may influence wound healing. But can this natural regenerative process be enhanced by applying external electricity? This question gave rise to numerous studies which this review will deal with.

The second historical root of electrical wound healing stems from the seventeenth century when gold leaf was applied to smallpox lesions to prevent scarring (ROBERTSON, 1925). Following this route KANOF (1964) AND WOLF et al. (1966) applied gold leaf directly to skin ulcers. Encouraged by the results and suspecting that the electrochemical influence of the gold may have been responsible for enhancing tissue healing, they conducted the first studies with low intensity direct electrical current.

The rationale for electrical wound healing with direct currents thus originates from two sources: investigations of biopotentials and experiments with gold leaf. Direct currents were consequently applied for wound healing enhancement by several research groups.

Initial studies on animal experimental wound models (CAREY and LEPLEY, 1962; ASSIMACOPOULOS, 1968a) demonstrated faster healing, greater wound tensile strength and intensified inflammatory reaction due to direct electrical current. The first report about human application (ASSIMACOPOULOS, 1968b) deals with only three patients with chronic leg ulcers due to venous insufficiency which resisted conventional treatment for several years. Following the application of up to 0.1 mA of negative-polarity direct current to the ulcers, they healed completely in six weeks.

One year later, the results of an extensive study by WOLCOTT et al. (1969) were published. They comprised 83 ischaemic skin ulcers. Electrical stimulation (ES) treatment consisted of three 2 h segments of 0.2-1 mA direct current applications each day. One copper mesh electrode was placed over the wound and the other proximal to the lesion. The optimum current amplitude was set empirically between visible bleeding (too much current) and copious serious exudate (too little current). Initially the polarity of the electrode in the wound was negative. The polarity was reversed after three days in noninfected wounds, while for infected ulcers the negative electrode was retained in the ulcer until the infection was cleared, plus three additional days. The electrode polarity was changed during the treatment each time the 'growth plateau' was observed. Stimulation was applied for 2 h followed by a 4 h pause. This 2:4 treatment ratio was repeated thrice daily, which totals 6 h of electrotherapy per day. In this study a control group was lacking, but nevertheless the eight participating patients had contralateral wounds of comparable size and aetiology, of which one wound received electrical stimulation and the other served as control. In all such cases significantly faster healing was obtained in stimulated wounds. In addition to accelerated healing, the strong antimicrobial effect of the negative-polarity current was observed in infected wounds.

This study served as an example for many succeeding clinical trials. At the same time it is the most frequently cited work in the history of electrical wound healing.