ABSTRACT
A new method, Wireless Micro Current Stimulation, of using electrical stimulation for wound healing has been presented over the last couple of years. Charged air gases are used instead of electrodes to supply the current to the wound. In a model calculation it is shown that the WMCS method compared to the usual method using electrodes does not give qualitatively different physiological effects in tissues.

INTRODUCTION
Electrical stimulation (ES) to encourage wound healing involves the transfer of energy to a wound via an electric current. The usual practice of ES is to transfer the current through surface electrode pads that are in wet, electrolytic contact with both the external skin surface and the wound bed. Two electrodes are required to complete the electrical circuit.\textsuperscript{1,2}

When a wound occurs, there is a weak but measurable current between the skin and inner tissues called the “current of injury”. It is thought that the current continues until the skin defect is repaired and that the healing process is interrupted if the current ceases.\textsuperscript{1,2} ES may mimic the current of injury, restarting or accelerating the wound-healing process.\textsuperscript{1,2}

ES and its effects in healing chronic wounds are well documented. Until now, the current has been introduced into the body with electrodes, but despite the very positive effects on the healing rate of chronic wounds, this method is not often used because of the disadvantages entailed when electrodes are used to transfer the current.\textsuperscript{3,4}

In this paper, we demonstrate by calculating the currents and voltages in tissues with a simple geometry, that there are no qualitative differences between the electrical variables when the current is supplied with the usual method and with WMCS.

METHODS
In the lower atmosphere, the production of $\text{N}_2^+$, $\text{O}_2^-$ and a few free electrons, is primarily caused by radiation from alpha-activities. These so-called primary ions will within a few microseconds gather around themselves a cover of mostly water molecules held together by polarization forces. These processes typically give rise to a concentration of air-borne electrically charged particles in the order of some hundreds per milliliter.\textsuperscript{5}

If a weak direct current electric field is applied to the atmosphere, the naturally produced $\text{N}_2^+$ and $\text{O}_2^-$ will move the former in the direction of the field and the latter in the opposite direction. For a field strength of $10^4$ V m$^{-1}$, the velocity of $\text{N}_2^+$ will be in the order of 1.4 m s$^{-1}$ and that of $\text{O}_2^-$ about 2 m s$^{-1}$.\textsuperscript{5}

If the field strength exceeds a certain value, which at atmospheric pressure is about $3 \times 10^6$ V m$^{-1}$ (3 megavolts per meter; the breakdown field strength), a few free electrons can be accelerated to high velocities and energies, so that they can knock electrons from the oxygen and nitrogen molecules, creating more positive and negative molecules.\textsuperscript{5}

If an $\text{O}_2^-$ ion lands on a conductive surface (like the skin), it gives up its negative charge, ceases to exist as an $\text{O}_2^-$ ion, and turns into an oxygen molecule and a few water molecules. This process is called “plate out”. In other words, the $\text{O}_2^-$ never enters the body. However, the charge on the plated-out $\text{O}_2^-$ will induce a current in the body cells and fluids.\textsuperscript{5}
CALCULATION

Questions have been raised regarding whether the WMCS method and the usual ES method can be expected to produce the same physiological effects. Whatever mechanism underlies the beneficial effects of ES these effects are related to the distribution of currents and voltages in the tissue. Therefore, we calculated these quantities in a simple model to compare the two methodologies.

The electrical potential \( \varphi \) and the current density \( j \) inside the tissue depend on the shape and position of the electrodes, the conductivity \( \sigma \) of the tissue, and the geometry of the body. In each area of tissue where \( \sigma \) is constant, Laplace’s equation \( \Delta \varphi = 0 \) must be met with the appropriate boundary conditions. In general, this can only be calculated with numerical methods, e.g., finite element calculations, etc. However, for simple geometries and constant conductivity over the whole area, analytical solutions can be given.

Because we want to compare the situation when the current is supplied by two small plate electrodes with the WMCS method, where the current is “sprayed” onto a given area at a virtually constant current density, we believe more insight into the problem can be gained by studying these analytical solutions than with a lot of numbers obtained from numerical calculations. Therefore, we will consider a case in which the semi-infinite area of \( z > 0 \), bounded by the plane \( z = 0 \), is filled by a tissue of constant conductivity, \( \sigma \). For \( z \to \infty \), the potential is taken to be 0. The current is supplied through a small disk of radius \( a \), around \((0, 0, 0)\), with the other electrode far away, i.e., at infinity, where \( \varphi = 0 \). In case A, the disk is given a fixed voltage, \( V_0 \), whereas in case B, a current with constant current density, \( j_0 \), is supplied over the disk. Case A models the usual method and case B the WMCS method. Both methods have cylindrical symmetry around the \( z \)-axis, and the solution for \( \varphi \) can therefore be given in cylindrical coordinates \((r, \theta, z)\), where \( r \) is the distance to the \( z \)-axis, \( \theta \) is the polar angle, and \( z \) is the distance from the surface. In both cases A and B, the solution for \( z \geq 0 \) has the form:

\[
\varphi = \int_0^\infty f(s)J_0(sr)e^{-sz} \, ds
\]

(1)

where \( J_0 \) is a Bessel function of order zero, and \( f(s) \) is a function that must be chosen such that \( \varphi \) satisfies the boundary conditions for \( z = 0 \).

In case A, the boundary conditions for \( z = 0 \) are: \( \varphi = V_0 \) for \( 0 \leq r \leq a \), and the current density, \( \dot{j}_z = -\left( \sigma \frac{\partial \varphi}{\partial z} \right)_{z=0} = 0 \), through the plane \( z = 0 \) for \( r > a \). This will be fulfilled when \( f(s) \) is given by:

\[
f_A(s) = \frac{2V_0}{\pi s} \sin(sa)
\]

(2)

For this value of \( f(s) \), the integral (1) can be expressed by the elementary function:
\[ \varphi_A = \frac{2V_0}{\pi} \text{Arc} \sin \left( \frac{2a}{\sqrt{(r-a)^2 + z^2 + \sqrt{(r+a)^2 + z^2}}} \right) \] (3)

The total current, \( I_A \), in case A can now be found by integrating the current density, \( j_z \), over the disk-shaped electrode with voltage \( V_0 \):

\[ I_A = 2\sigma V_0 \int_0^a \int_0^{\infty} \sin(sa) J_0(sr) ds \left( r^2 dr = 4\sigma a V_0 \right) \] (4)

In case B, \( f(s) \) must be: \( f_B(s) = \frac{j_0 a J_1(sa)}{s} \), \( (J_1 \) is the Bessel function of order 1) which gives:

\[ \varphi_B = \frac{j_0 a}{\sigma} \int_0^\infty e^{-sz} J_0(sa) J_1(sa) \frac{ds}{s} \] (5)

The integral in eqn 5 cannot be given in an elementary form when \( z > 0 \), but can be expressed as an infinite sum of hypergeometric functions. For \( z = 0 \), \( \varphi_B \) is given by single hypergeometric functions. We will not give the explicit forms here, but the average value of \( \varphi_B \) over the disk \( r < a \), for \( z = 0 \), is found to be

\[ V_{av} = \frac{8 j_0 a}{3 \pi \sigma} \] and the maximal value \( \varphi_{B,max} = \frac{j_0 a}{\sigma} \). Because the total current is \( I_B = \pi a^2 j_0 \), the ratio of the current to the average voltage is: \( I_B/V_{av} = \frac{3 \pi^2 \sigma a}{8} \), whereas in case A we get: \( I_A/V_0 = 4\sigma a \).

Figs 1–2 show the values for the electrical potential at different values of \( r \) and \( z \) in cases A and B.
Fig. 1: \( \varphi/\varphi_{\text{max}} \) as a function of \( r/a \) for \( z = 0 \) (case A, red; case B, green) and \( z = 2a \) (case A, yellow).

Fig. 2: \( \varphi/\varphi_{\text{max}} \) as a function of \( z/a \) for \( r = 0 \) (case A, red; case B, green).

RESULTS
When we compare the figures for cases A and B, no significant differences can be seen. However, it must be noted that an electrode is usually much smaller than the wound, whereas the current in the WMCS method is supplied over a larger area. This means that \( a \approx 1 \text{ mm} \) in case A, whereas it can easily be 10 mm or more in case B. From the expressions for the total currents, we see that for the same current in cases A and B, the ratio between \( V_0 \) and \( \varphi_{B,\text{max}} \) is \( V_0/\varphi_{B,\text{max}} = \pi a_A/(4a_B) \approx 10 \).

CONCLUSION
The definition on electrical stimulation in wound healing is to transferee a current to the wound in that way to create the current of injury\(^{1,2} \).

In this paper it has been shown that there are no qualitative differences between the electrical variables when the current is supplied with the usual method using electrodes and with WMCS method transferring the current wireless.

Therefore it can be concluded that the WMCS way of transferring the current;
1. can replace the traditional way of transferring the current between electrodes,
2. that it has procedural and patient advantages,
3. that it is able to cover bigger wounds,
4. that it is easy to administrate and
5. that is minimizes the risk of infection.

References:

1. CIGNA Healthcare coverage position: 2008 Electrical Stimulation for Wound healing