Dynamics of Dielectric Barrier Discharges Over Wounded Skin

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***Abstract*—The intersection of plasma filaments in a dielectric barrier discharge with a small wound in the human skin in the context of plasma medicine is investigated with results from a computer model. The relative location of the filament with respect to the wound determines the symmetry of treatment.**

***Index Terms*—Dielectric barrier discharge (DBD), plasma medicine.**

ATMOSPHERIC-PRESSURE plasmas in direct contact with living tissue have therapeutic effects for wound healing and sterilization [1]. These effects are attributed to production of beneficial radicals intersecting with biological reaction chains, ions delivering activation energy to the tissue, and intracellular production of electric fields. A typical plasma source is a multifilamentary dielectric barrier discharge (DBD) where the tissue serves as a counter electrode (Fig. 1). Individual filaments are a few nanoseconds in duration and are distributed randomly. Repetition rates are a few to tens of kilohertz.

To provide insights to filaments in DBDs intersecting with wounded human skin, we computationally investigated the dynamics of a single filament at different locations near the wound. The model *nonPDPSIM* [2] is a 2-D simulation performed on an unstructured numerical mesh in which Poisson's equation and transport equations for charged and neutral species are solved. The skin consists of a thin outer layer, the epidermis, and an inner layer, the dermis. Four layers of cells are resolved in the epidermis. The wound is a small slice in the skin to the dermis, which exposes live cells to the plasma. This type of wound is dry and shallow and may represent later stages of wound healing. Cellular structures are represented as lossy dielectrics with conductivities and permittivities appropriate for biological tissue. Cell membranes have low conductivity ($10^{-7}\ \Omega^{-1} \cdot \mathrm{cm}^{-1}$); cytoplasm and nucleoplasm have high conductivity (10^{-3}–$10^{-4}\ \Omega^{-1} \cdot \mathrm{cm}^{-1}$). The model geometry shown in Fig. 1 has a 0.8-mm-thick dielectric covering a powered electrode positioned over the thumb.

Filaments are launched in humid air from the dielectric to intersect to the left, directly over, and to the right of the wound. The skin is initially uncharged, and the DBD voltage is

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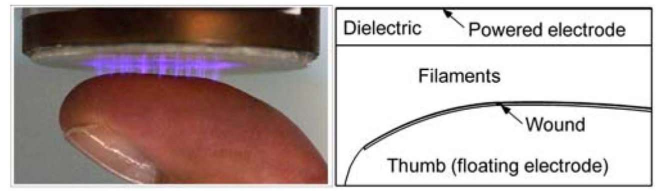

Fig. 1. DBD treatment of the human skin. (Left) Plasma applied to a thumb acting as a floating electrode (from [1]). (Right) Model geometry. The computational domain extends many millimeters further. The electrical ground is on the edge of the larger domain.

-30 kV. The plasma properties after the streamer intersects with the wound, 0.5 ns after initiation at the dielectric, are shown in Fig. 2. Upon intersecting the skin, the filaments charge the surface, producing lateral electric fields which spread the filament over the tissue to many times its diameter. The electron densities reach $10^{15}\ \mathrm{cm}^{-3}$, increasing near the surface due to the large capacitance of the exposed features. The Debye length of a few micrometers is comparable to the dimensions of the wound, which enables penetration of the plasma into the wound. As the filaments on either side of the wound spread along and charge the surface, they penetrate into the wound and asymmetrically charge the exposed cells. This results in the charged particle densities in contact with the cells to be highest opposite the entry point of the plasma. When the filament is directly over the wound, the plasma is symmetric but concentrated at the top of the wound where the view angle to the plasma is largest. Surface charge densities up to $10^{16}\ \mathrm{cm}^{-3}$ are sufficient to produce electroporation within the epidermis layer [2].

Electron impact produces radicals in direct contact with the cells, such as O ($10^{15}\ \mathrm{cm}^{-3}$) and NO ($5 \times 10^{12}\ \mathrm{cm}^{-3}$), while attachment produces antimicrobial active species, such as O_2^- ($7 \times 10^{12}\ \mathrm{cm}^{-3}$). At this short time, the locations of radicals reflect the location of their creation by either electron impact (O) or reactions of radicals with feedstock gases (NO). The locations also reflect the track of the streamer as it spreads along the surface and enters the wound. During the time between pulses, diffusion will spatially homogenize these initial densities. As such, the largest densities of radicals, such as O, inside the wound are these initial values.

In conclusion, images of charged and neutral species from a plasma filament in a DBD treating wounded skin have been presented. The plasma penetrates into the wound limited only by the Debye length and charging of the wound's surface.

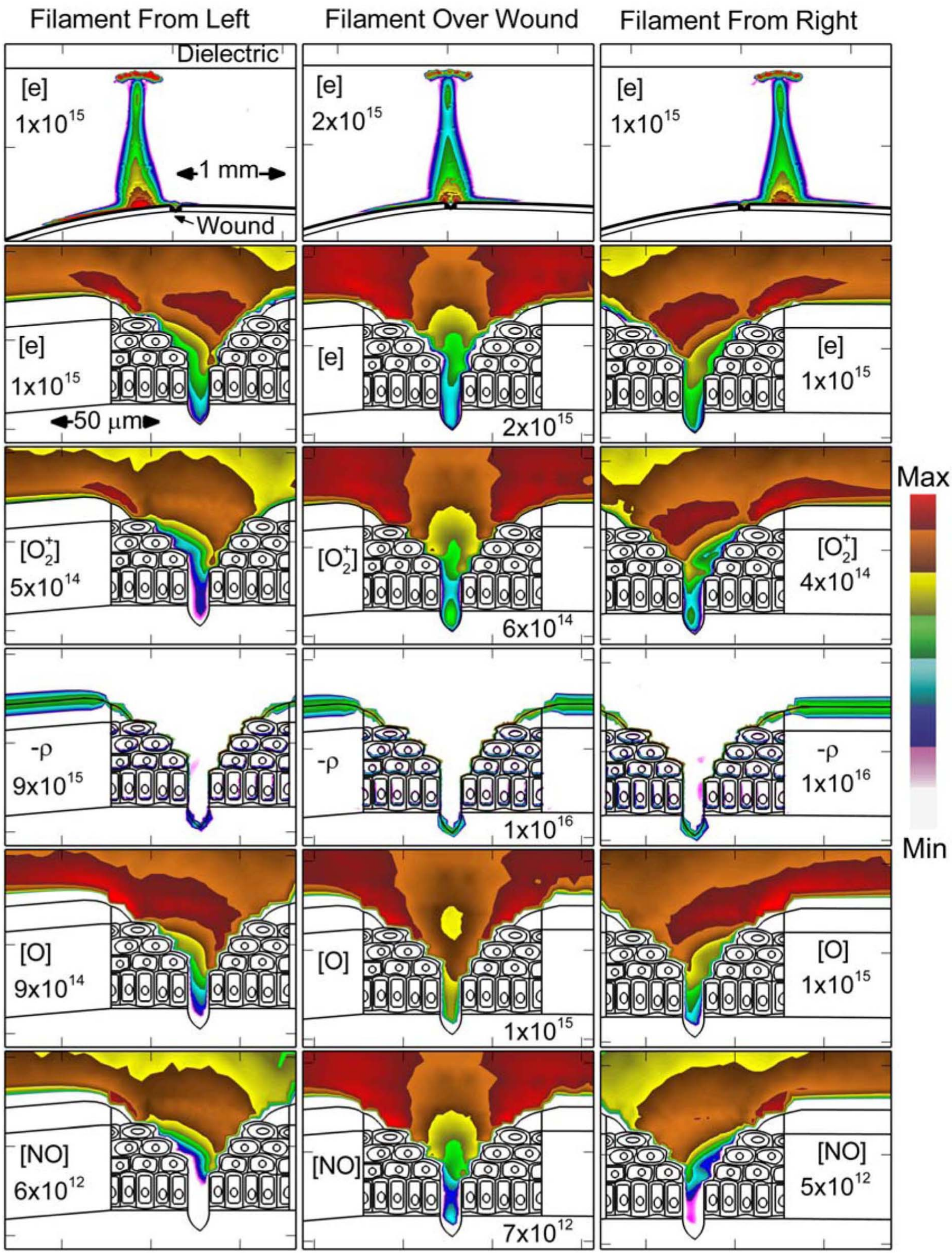

Fig. 2. Plasma characteristics near and inside slightly wounded skin when plasma filaments strike the skin (left) to the left, (center) directly over, and (right) to the right of the wound. The species are (top to bottom) electrons, O_2^+, negative charge density, O, and NO. The maximum values (densities have units of cm^{-3}) are shown in each frame. Contours are plotted on a three-decade log scale.

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