2020

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Original Publication Citation
Laroussi, M. (2020). Low temperature plasma jets: Characterization and biomedical applications. *Plasma*, *3*(2), 54-58. https://doi.org/10.3390/plasma3020006

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Editorial

Low Temperature Plasma Jets: Characterization and Biomedical Applications †

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† This editorial is for the upcoming ebook 'Cold Plasma: Characteristics and Applications in Medicine'.

Received: 14 March 2020; Accepted: 14 March 2020; Published: 3 April 2020

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For many decades non-equilibrium plasmas (NEPs) that can be generated at atmospheric pressure have played important roles in various material and surface processing applications. Although there are many methods to generate NEPs, one of the simplest and most practical ways is to use the dielectric barrier discharge (DBD) configuration. This discharge uses a dielectric to cover at least one of two electrodes. The plasma generated in the gap between electrodes is generally filamentary, but under some conditions can be uniformly diffuse. Extensive research work has been done on DBD, and one of its earliest applications was to generate ozone for the cleaning of water supplies [1–4]. DBD has also gained widespread use in biomedical applications since the mid 1990s, when it was demonstrated that the plasma produced by DBD possesses strong germicidal properties [5]. However, because the plasma is confined to the gap between electrodes, the use of the conventional DBD setup in biomedical applications has remained limited. This situation changed when investigators reported that with proper design the plasma can be "blown" out of the discharge gap and into the ambient air [6,7]. This development has opened up all kind of possibilities to use this plasma arrangement for medical applications. This is because the plasma can be made available completely out of the ignition region and launched via a nozzle into ambient air. Therefore, it can be aimed at a specific location (such as a wound) and applied for a certain length of time to achieve a biological outcome. Since all this can be done at atmospheric pressure and in ambient air it has become possible to treat actual patients with such plasma generation schemes. These devices have come to be known as non-equilibrium atmospheric pressure plasma jets (N-APPJ).

The first applications of N-APPJs were in material processing. Using various operating conditions and gases, they were found to increase the wettability of polypropylene (PP) and polyethylene terephthalate (PET) films [8]; to degrade aromatic rings of dies such methyl violet [9]; to etch silicon and Si (100); to ash photoresist at a rate greater than 1.2 µm/min [10]; to deposit silicon dioxide, SiO_2, and films on various substrates at deposition rates greater than 10 nm/s; and so on. However, the biomedical applications of N-APPJs only surged after the first "bio-tolerant" plasma jets were reported in the mid-2000s [6,7,11]. Today these plasma jets and other plasma sources are being extensively researched for medical applications ranging from wound healing to dentistry and cancer therapy [12–27].

Around 2005, investigators at Old Dominion University, USA, and the University of Wuppertal, Germany, independently discovered that the plasma plumes of N-APPJs were in fact not continuous but made of fast-propagating discrete small volumes of plasma (known as "plasma bullets") [28,29]. This has led to numerous experimental and modeling works aimed at elucidating the mechanisms of ignition and propagation of N-APPJs [30–34]. Recently it was well established that these jets are enabled by guided ionization waves where photoionization and the electric field at the head of the ionization front play important roles [35]. The magnitude of the electric field was measured by several investigators and was found to be in the 10–30 kV/cm range [36–38].

Various power-driving methods have been used to ignite and sustain N-APPJs. These include DC, pulsed DC, RF, and microwave power [7]. Because they provide interesting reactive chemistry, N-APPJs play an ever-increasing role in biomedicine. Reactive oxygen species (ROSs) and reactive nitrogen species (RNSs) such as O, OH, O_2^-, $^1O_2$, H_2O_2, NO, and NO_2, which are generated by these plasma jets, have been shown to play a central role in their interactions with liquids and soft matter, including cells and tissues [39–42]. Based on these results it has been concluded that the biological effects of these plasmas are mostly mediated by the ROSs and RNSs they produce. These reactive molecules (radical and non-radical) can oxidize membranes' lipids and proteins and can trigger and/or modulate cell signaling. Depending on the type and concentration of ROS and RNS, proliferation or destruction of cells can occur. Many investigators have reported that low temperature plasma can be tailored to induce apoptosis in cancer cells without causing damage to healthy cells [43–45]. It is also suspected that the high electric field at the head of plasma plumes can cause electroporation, letting ROS and RNS molecules into the interior of the cells. These can then cause various deleterious effects including DNA strand breaks and mitochondrial damage.

This book is a compilation of two special issues guest edited by Dr. Mounir Laroussi for the journal *Plasma*. The two special issues are: (1) Low Temperature Plasma Jets: Physics, Diagnostics, and Applications; (2) Plasma Medicine. This book is therefore organized into two parts. The first part is a collection of six papers published in the special issues on plasma jets that discuss the design of plasma jets such the Cooperation in Science and Technology (COST) plasma jets [46], the interaction of plasma jets with various targets [47–49], characterizations of plasma jets, treatments of water by a plasma jet [50], and the use of a plasma jet as a source of guided ionization waves to ignite a large volume plasma in an electrodeless chamber [51]. The second part of the book is a collection of 8 papers published in the special issue on plasma medicine. The first paper is an introductory review of the field of plasma medicine [52]; some of the following papers discuss the applications of various plasma jets for cancer treatment, including triple-negative breast cancer cells, ovarian cancer cells, and the manner in which plasma can decrease the viability of malignant solid tumors cells [53–55]. One paper presents a performance evaluation of three plasma sources/jets [56], while two other papers discuss how plasma modulates the responsiveness of human macrophages and cellular glucose uptake [57,58]. Finally, the issue concludes with a review paper discussing how low temperature plasma offers a new hope for cancer treatment [59].

Conflicts of Interest: The author declares no conflict of interest.

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