

Nonthermal Decontamination of Biological Media by Atmospheric-Pressure Plasmas: Review, Analysis, and Prospects

Mounir Laroussi, *Senior Member, IEEE*

Abstract—Although the use of an electrical discharge to disinfect water was suggested and applied more than a hundred years ago, basic and applied research on the interaction of plasmas with biological media was extensively carried out only relatively recently. In this context, a review of various works on the germicidal effects of atmospheric pressure, “cold” plasmas, is presented. The nonequilibrium discharge devices discussed in this review, which have been used in biological applications by various investigators, are the corona discharge, the diffuse dielectric-barrier discharge, the resistive barrier discharge, and the atmospheric-pressure plasma jet. Analysis of the inactivation kinetics for various bacteria seeded in (or on) various media and exposed to the plasma generated by these devices, showed that three types of survivor curves exist, depending on the type of micro-organism, the type of medium, and the type of exposure (direct versus remote). Insights into the roles of UV radiation, active species, and charged particles has led to the conclusion that chemically reactive species, such as free radicals, play the most important role in the inactivation process. In addition, recent results suggesting that biomanipulation of the cells of micro-organisms with nonequilibrium plasmas is possible are highlighted.

Index Terms—Bacteria, decontamination, discharge, micro-organisms, plasma, sterilization.

I. INTRODUCTION

NONTHERMAL plasmas, or “cold plasmas,” at or near atmospheric pressures, have recently received increased attention because of their use in several emerging novel applications such as excimer-light sources [1], the surface modifications of polymers [2], and the biological and chemical decontamination of media [3]–[6]. Today, nonthermal plasmas can be generated in a wide range of pressures and with various means, such as the use of microwave, RF, pulsed, ac, and dc power sources. Several device geometries, electrode configurations, gas mixtures, and flow rates have been used. In this paper, first an overview of some key devices, operating at or near atmospheric pressure, which have been used to inactivate micro-organisms, is presented. Then the kinetics and mechanisms of the inactivation process are discussed. These are based on the results obtained by several research groups active in this field. It is important to stress to the reader that only experiments carried out at pressures around one atmosphere are the subject of this

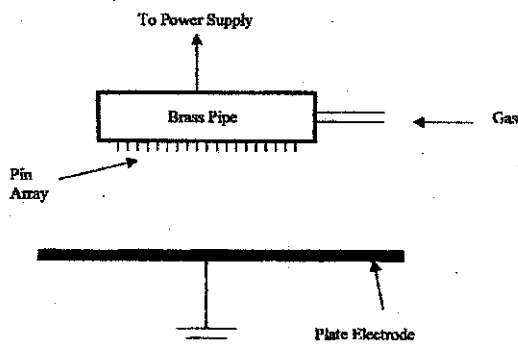


Fig. 1. Basic configuration of the enhanced corona discharge.

analysis (for a comprehensive study conducted at low pressures, the reader is referred to references [7] and [8]). Finally, future prospects and potential uses of nonthermal, atmospheric-pressure plasmas in the medical, food industry, and environmental fields, are presented.

II. COLD-PLASMA GENERATORS

In this section, several methods that have been used to generate relatively large volumes of nonequilibrium cold plasmas, at or near atmospheric pressure (sometimes referred to as “high” pressure) are presented. This is not a comprehensive list of all existing methods. The methods presented here were chosen for two main reasons. 1) They have been used extensively to study the germicidal effects of cold, high-pressure plasmas; and 2) their potential use in various other industrial plasma processing applications (lighting, surface modification, etching, deposition).

A. The Corona Discharge

Siemens [9] was the first to suggest the use of a corona discharge to generate ozone in order to disinfect water supplies. This was the first recorded use of plasma toward the inactivation of micro-organisms. Menashi [10] used a pulsed RF-driven corona discharge to create a plasma at atmospheric pressure. He reported that up to $4 \cdot 10^6$ microbial spores could be inactivated in less than 1 s. Garate *et al.* [5] used an “Enhanced Corona Discharge” [11] to destroy concentrations of up to 10^{10} /ml of *Escherichia coli*, and spores of *Bacillus subtilis* in less than 15 min. A schematic of the enhanced corona discharge is shown

Manuscript received October 24, 2001; revised February 26, 2002. This work was supported in part by Air Force Office of Scientific Research Grant F49620-00-1-0168.

The author is with the Applied Research Center, Old Dominion University, Newport News, Norfolk, VA 23606 USA (e-mail: laroussi@jlab.org).

Digital Object Identifier 10.1109/TPS.2002.804220

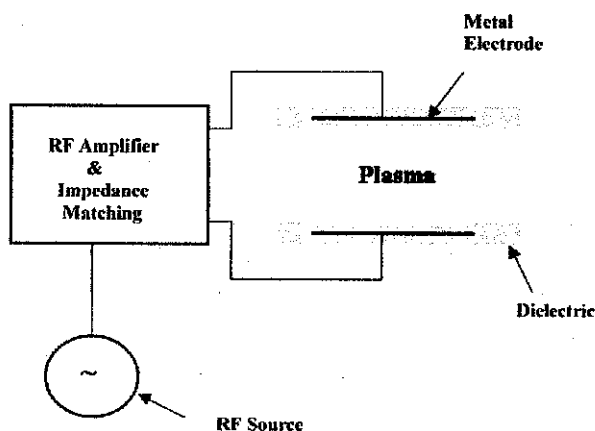


Fig. 2. Configuration of the DBD-based diffuse glow discharge at atmospheric pressure.

in Fig. 1, [12]. This discharge consists of a line of pins fastened to a hollow pipe at one end and protruding from the other end through tiny holes. The feed gas escapes through the holes and provides a local atmosphere around the corona points. The feed gas, a nonelectronegative gas such as helium or argon, replaces the air around the corona points and therefore enhances the discharge by removing the electron-attaching electronegative-oxygen molecules. The pin array can be biased by a dc or ac high-voltage supply, or by a pulsed power supply.

B. The Glow Discharge at Atmospheric Pressure

One of the early developments of diffuse glow discharge plasma at atmospheric pressure was reported by Donohoe [13]. Donohoe used a large gap (cm) pulsed-barrier discharge in a mixture of helium and ethylene to polymerize ethylene [14]. Later, Kanazawa *et al.* [15] reported their development of a stable glow discharge at atmospheric pressure by using a dielectric-barrier discharge (DBD) configuration. They claimed that to obtain a diffuse discharge (as opposed to a filamentary discharge, which is traditionally produced by DBDs), helium had to be the major constituent of the gas mixture, and the frequency of the applied voltage had to be in the kilohertz range. Fig. 2 is a schematic of the DBD-based glow discharge at atmospheric pressure. At least one of the two electrodes must be covered by a dielectric material. After the ignition of the discharge, charged particles are collected on the surface of the dielectric. This charge build-up creates a voltage drop, which counteracts the applied voltage, and therefore chokes the discharge current. The discharge subsequently extinguishes. As the applied voltage increases again (at the second half cycle of the applied voltage) the discharge reignites. This process is repeated over and over during each full cycle of the applied voltage.

Laroussi [3], [4] reported the use of the glow discharge at atmospheric pressure to destroy cells of *Pseudomonas fluorescens*. He used suspensions of the bacteria in Petri dishes placed on a dielectric-covered lower electrode. The electrodes were placed within a chamber containing mostly helium with an admixture of air. He obtained full destruction of concentrations of $4 \cdot 10^6$ /ml in less than 10 min. Using a similar discharge, Kelly-Win-

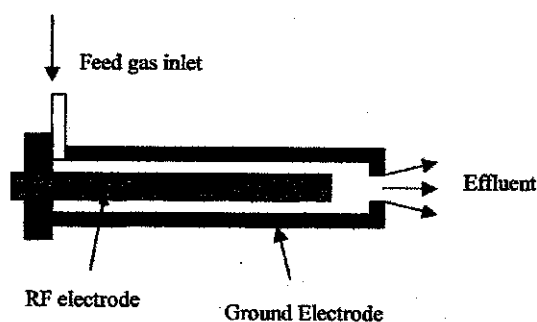


Fig. 3. Configuration of the atmospheric-pressure plasma jet (APPJ) [18].

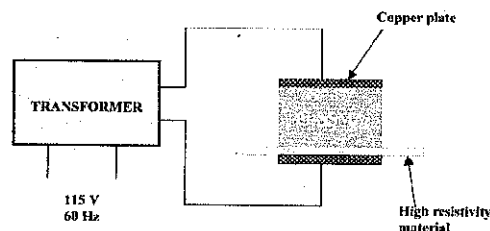


Fig. 4. Configuration of the resistive-barrier discharge (RBD).

tenberg [16] reported the inactivation of *B. subtilis* spores using an air gap. *E. coli*, *B. subtilis*, and a variety of other gram-negative as well as gram-positive bacteria were inactivated successfully by many researchers using the DBD-based diffuse-glow discharge.

C. The Atmospheric-Pressure Plasma Jet

The atmospheric-pressure plasma jet (APPJ) [17] is a capacitively coupled device consisting of two coaxial electrodes between which a gas flows at high rates. Fig. 3 is a schematic of the APPJ. The outer electrode is grounded, while the central electrode is excited by RF power at 13.56 MHz. The free electrons are accelerated by the RF field and enter into collisions with the molecules of the background gas. These inelastic collisions produce various reactive species (excited atoms and molecules, free radicals) that exit the nozzle at high velocity. The reactive species can therefore react with a contaminated surface placed in proximity (cm) of the nozzle [18]. As in the case of the diffuse DBD, the stability of the APPJ plasma (as well as its nonthermal characteristic) depend on using helium as a carrier gas. Herrmann *et al.* [18] used the APPJ to inactivate spores of *Bacillus globigii*, a simulant to Anthrax (*Bacillus anthracis*). Herrmann *et al.* reported the reduction of seven orders of magnitude of the original concentration of *B. globigii* in about 30 s.

D. The Resistive Barrier Discharge

The concept of the resistive-barrier discharge (RBD) is based on the DBD configuration. However, instead of a dielectric, a high-resistivity material is used to cover at least one of the electrodes (see Fig. 4). The high-resistivity layer plays the role of a distributed ballast which limits the discharge current and therefore prevents arcing [19]. The advantage of the RBD over the DBD is the possibility to use dc power (or low-frequency ac, 60 Hz) to drive the discharge. Using helium, large-volume diffuse cold plasma at atmospheric pressure can be generated.

Richardson *et al.* [20] and Laroussi *et al.* [21] reported a four-orders-of-magnitude reduction in the original concentration of vegetative *B. subtilis* cells in about 10 min. They also reported that the RBD-inactivated endospores of *B. subtilis*, but not as effectively as the vegetative cells. In these experiments, they used a gas mixture of 97%–3% helium-oxygen, respectively.

III. KINETICS OF THE BACTERIAL-INACTIVATION PROCESS

The concept of inactivation or destruction of a population of micro-organisms is not an absolute one. This is because it is impossible to determine if and when all micro-organisms in a treated sample are destroyed [22]. It is also impossible to provide the ideal conditions that inactivate all micro-organisms. Some cells can always survive under otherwise lethal conditions. Therefore, experimental investigation of the kinetics of cell inactivation is paramount in providing a reliable temporal measure of microbial destruction.

One kinetics measurement parameter, which has been used extensively by researchers studying sterilization by plasma, is what is referred to as the “D” value (Decimal value). This parameter was borrowed from studies on heat sterilization. The D-value is the time required to reduce an original concentration of micro-organisms by 90%. The D-value in this presentation is therefore expressed in the unit of time (this is not always the case: in radiation sterilization the D-value is expressed in unit of dose [22]). Since survivor curves are plotted on semilogarithmic scales, the D-value is determined as the time for a one- \log_{10} reduction. Another parameter, which is of great importance for practical systems, is the inactivation factor (IF). The IF is the percentage kill of a microbial population by a particular treatment [22]. The IF is generally determined for spores (highly resistant micro-organisms) by taking the ratio of the initial count to the final extrapolated count [22]. Since the IF depends on the initial count (before treatment, what is referred to as “the bioburden”), its value reveals the expected number of viable micro-organisms after the treatment. Therefore, the IF of a treatment method directly reflects its sterilizing effectiveness, given a certain bioburden.

To date, the experimental work on the germicidal effects of cold, atmospheric-pressure plasmas has shown that survivor curves take different shapes depending on the type of micro-organism, the type of the medium supporting the micro-organisms, and the method of exposure (*direct exposure*: samples are placed in direct contact with the plasma; *remote exposure*: samples are placed away from the discharge volume or in a second chamber; the reactive species from the plasma, but not the plasma itself, are allowed to diffuse and come in contact with the samples).

Herrmann *et al.* [18] (APPJ, *remote exposure*), Laroussi *et al.* [12] (Diffuse DBD-type discharge, *direct exposure*), and Yamamoto *et al.* [23] (Corona discharge with H_2O_2 , *remote exposure*) reported a “single slope” survivor curve for *B. globigii* on glass coupons (dry samples), for *E. coli* in suspension, and for *E. coli* on glass, respectively. This is illustrated in Fig. 5(a), which shows the number of colony-forming units (CFUs) per milliliter versus treatment time. The D-value ranged from 4.5 s

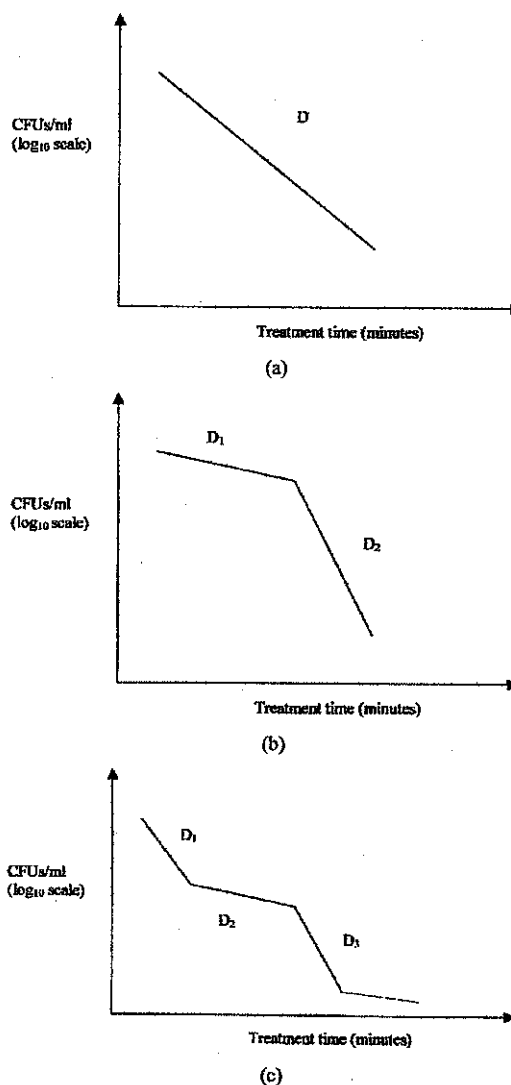


Fig. 5. Kinetics of the inactivation process. (a) Single-slope survivor curve; (b) double-slope survivor curve; and (c) multislope survivor curve.

for the *B. globigii* on glass (APPJ), to 15 s for *E. coli* on glass (Corona with H_2O_2 plasma), to 5 min for *E. coli* in liquid suspensions (DBD-type plasma).

Two-slope survivor curves [see Fig. 5(b)] were reported by Kelly-Wintenberg *et al.* [16] (DBD-type, *direct exposure*) for *S. aureus* and *E. coli* on polypropylene samples, and by Laroussi *et al.* [12] for *Pseudomonas aeruginosa* in liquid suspension. The curves show that the D-value of the second line (D_2) was smaller (shorter time) than the D-value of the first line (D_1). Montie *et al.* [24] also reported the same type of survivor curve for *E. coli* and *B. subtilis* on glass, agar, and polypropylene (all under direct exposure to a DBD-type discharge). Montie *et al.* [24] claimed that D_1 was dependent on the species being treated and that D_2 was dependent on the type of surface (or medium) supporting the micro-organisms. Kelly-Wintenberg *et al.* [16] explained the “bi-phasic” nature of the survivor curve by claiming that during the first phase, the active species in the plasma reacts with the outer membrane of the cells, inducing damaging alterations. After this process is advanced enough, the

reactive species can then quickly cause cell death, hence the rapidity of the second phase.

Multi-slope survivor curves [see Fig. 5(c)] were reported by Laroussi *et al.* [12] (diffuse DBD-type, *direct exposure*) for *E. coli* and *P. aeruginosa* on nitrocellulose filter, by Kuzmichev *et al.* [25] (pulsed-barrier discharge, *remote exposure*) for *B. Stearothermophilus* on stainless-steel strips, and by Roth *et al.* [26] for *E. coli* and *S. aureus* on polypropylene fabric (DBD-type discharge, *remote exposure*). Each line has a different D-value. An explanation of this type of curve is lacking at the time of this write-up. However, similar survivor curves (three-phases) were reported in low-pressure studies [7], [8]. Moisan *et al.* [8] claim that the first phase, which exhibits the shortest D-value, is mainly due to the action of UV radiation on isolated spores or on the first layer of stacked spores. The second phase, which has the slowest kinetics, is attributed to a slow erosion process by active species. Finally, the third phase comes into action after spores and debris have been cleared by phase 2, hence, allowing UV to hit the genetic material of the still living spores. The D-value of this phase was observed to be close to the D-value of the first phase. It is important to note that the explanation given earlier is still open to debate, and is not applicable to the case of atmospheric-pressure plasmas, for which it has been shown that UV plays a secondary role in the killing process [4], [18], [23], [25].

IV. INACTIVATION AGENTS

This section presents a discussion on the contributions of the various agents emanating from the plasma to the killing process. These are mainly the UV radiation, reactive species, and charged particles (electrons and ions). The effect of heat is not part of this discussion since it is assumed that the temperature of the samples under treatment is kept close to the ambient temperature or at least below a value known to cause cell damage.

Effect of the UV: UV affects the cells of bacteria by inducing the formation of thymine dimers in the DNA. This inhibits the bacteria's ability to replicate. By comparing the killing kinetics of UV radiation from a low-pressure mercury-vapor lamp and that of atmospheric-pressure cold plasma, Laroussi [4] concluded that UV was not the main killing agent. This claim was later supported by the work of Herrmann *et al.* [18], who exposed *B. globigii* to the APPJ with the plasma effluent being blocked by a quartz window. No substantial reduction in the initial concentration of bacteria was observed. Other researchers [23], [25] carried out various experiments that also supported the claim that UV plays a minor role as a killing mechanism. A possible explanation of these results maybe the following. UV is known to inactivate cells only if its wavelength is within the "germicidal range" (220 nm to 280 nm) and its dose (expressed in watts \cdot s/cm²) is high enough. Therefore, if the UV generated by the plasma does not satisfy these conditions, the UV radiation would be expected to not have a pronounced effect. Most gas mixtures used in atmospheric-pressure cold-plasma experiments simply do not result in the emission of any appreciable dose of UV radiation at the germicidal wavelengths. Shorter wavelengths, which

could be generated, would not have enough propagation lengths or penetration depths to cause lethal damage, especially for remote exposure.

Effects of the Reactive Species: It has always been recognized that the reactive species, generated in a high-pressure nonequilibrium discharge through electron-impact excitation and dissociation, plays an important role in its germicidal characteristics. Herrmann *et al.* [18], Richardson *et al.* [20], and Kuzmichev *et al.* [25] experimentally showed that discharges containing oxygen have a strong germicidal effect. This is due to the presence, in such discharges, of oxygen-based active species such as atomic oxygen, the metastable singlet state of oxygen, and ozone. In particular, Herrmann *et al.* [18] compared results obtained by the APPJ with and without oxygen. It was found that the D-value in the case of the absence of oxygen assumes a higher value than in the case when oxygen is added and is consistent with that of the case of a heated gas (no plasma). Richardson *et al.* [20] showed that the RBD discharge became more effective in killing *B. subtilis* (vegetative and sporulated) when oxygen was admixed to helium. A mixture containing 3% oxygen was found to produce the best results. After experimenting with various gas mixtures, Kuzmichev *et al.* [25] concluded "the best bactericidal effects are achieved in moistened oxygen and air." In the presence of moisture, the hydroxyl-radical, OH, is also expected to play a significant role by chemically attacking the outer structures of bacterial cells. In the case of air, production of NO and NO_x adds to the lethality of the process. And, of course, the presence of O₂ in air plasmas or in discharges containing an admixture of oxygen leads to the generation of ozone (O₃). Ozone, which interferes with cellular respiration, has been known to have a strong bactericidal effect.

Another method to obtain a plasma rich in active radicals is to add small quantities of hydrogen peroxide, H₂O₂ (in an aerosol form for example) in a discharge volume. Using a corona discharge in argon with an admixture of H₂O₂ in spray form to inactivate *E. coli*, Yamamoto *et al.* [23] reported enhanced inactivation effectiveness with a D-value of 15 s.

Effects of the Charged Particles: The average energy, or kinetic temperature, of the electrons in a nonequilibrium-discharge is in the electron-volt range, and that of the ions is close to room temperature. At high pressures and with relatively low energies, bombardment of bacterial cells by charged particles is expected to play no role in the destruction of micro-organisms. Because of this fact, most researchers in this field have neglected to investigate the role, if any, of the electrons and ions in the inactivation process of bacteria. However, in a technical note to the IEEE TRANSACTIONS ON PLASMA SCIENCE, Mendis *et al.* [27] suggested that charged particles might play a very significant role in the rupture of the outer membrane of bacterial cells. By using a dusty-plasma model, they showed that the electrostatic force caused by charge accumulation on the outer surface of the membrane could overcome the tensile strength of the membrane and cause its rupture. They claim that this scenario is more likely to occur for gram-negative bacteria, the membrane of which possesses an irregular surface. Mendis *et al.* [27] point out that the cellular morphological changes experimentally observed by Laroussi *et al.* [28] (using electron

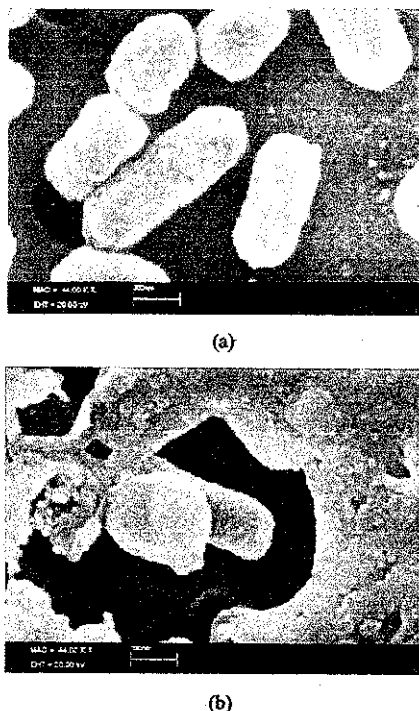


Fig. 6. Scanning-electron microscope (SEM) micrographs of *E. coli* showing damaged cells after treatment. (a) Control and (b) plasma-treated [31].

microscopy) supports their claim. It is also interesting to note that this conclusion is also supported by the observations of Herrmann *et al.*, who did not report any morphological changes after exposing *B. globigii* to the APPJ plasma. In this case (*remote exposure*) no appreciable charge accumulation occurs since it is mostly the noncharged reactive species that interact with the samples under treatment. On the other hand, using a "gas-phase corona reactor" (*direct exposure*) Birmingham *et al.* [29] reported that they observed clear cell lysis after they exposed spores of *B. globigii* to the plasma.

V. MECHANISMS OF CELLULAR DEATH

How death is induced to the cells of micro-organisms is an interesting and complicated question. Several proposals have been suggested for the case of plasma-induced destruction. In the case of low-pressure plasmas Moisan *et al.* [8] suggested that UV, with its known effects on the genetic material, plays a primary role followed by erosion of the cell atom by atom through UV-induced photodesorption, which in turn is followed by etching through reactive-species adsorption. The reactive species then chemically react with the biomaterial of the cells to form volatile compounds. However, this sequence of events is not applicable to the case of high-pressure cold plasmas where the UV has been shown not to play a major role.

Montie *et al.* [30] proposed three killing mechanisms in the case of high-pressure cold plasmas: 1) lipid peroxidation resulting from the susceptibility of unsaturated fatty acids to attacks by hydroxyl radicals; and 2) protein oxidation resulting from the susceptibility of amino acids to oxidation; and 3) DNA oxidation resulting from the formation of base adducts, which

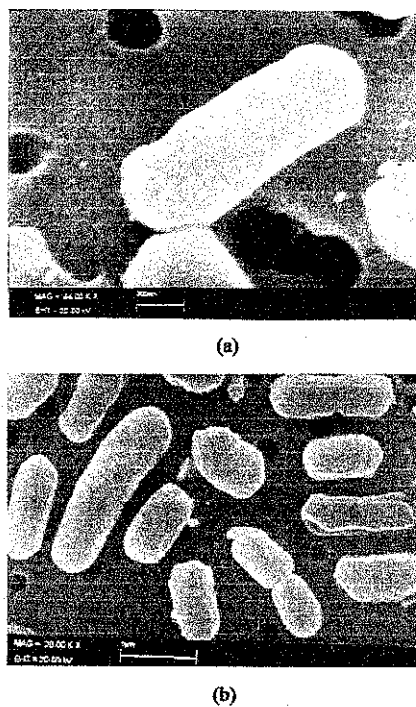


Fig. 7. SEM micrographs of *B. subtilis* showing no visible morphological changes after treatment. (a) Control and (b) plasma treated.

are generated through reactions with oxygen radicals. The previously mentioned mechanisms assume the presence of oxygen and moisture in the gas mixture.

Laroussi *et al.* [28] and Montie *et al.* [30] reported that for *E. coli*, a gram negative bacterium, the outer membrane ruptures after short exposures (10–30 s) to plasma, followed by leakage of their cytoplasm (see Fig. 6). In addition, for longer exposure times, total cell fragmentation was observed. Montie *et al.* [30] claim that the rapid rupture of the membrane of gram-negative bacteria is due to alterations to the membrane lipids caused by the fatty-acid peroxide formation. As discussed earlier, Mendis *et al.* [27] suggested that the membrane rupture of gram-negative bacteria is caused by charge accumulation on the outer surface of the membrane. One way to resolve this question is to compare the time scales of both mechanisms. Mendis *et al.* [27] give a typical charging time constant in the tens of milliseconds (less than 500 ms), a time much shorter than the reported "killing" times. Montie *et al.* [30] on the other hand do not mention a time scale for their proposed mechanism. No clear answer is available at the time of this write-up.

Gram-positive bacteria do not undergo visible morphological changes [21] (see Fig. 7). However, reduction in cell viability was achieved on various types of such bacteria. One possible explanation is that some reactive species generated by the plasma can diffuse through an otherwise chemically and physically robust outer membrane, and directly react with the biomaterials inside the cell. These reactions could either compromise the integrity of the whole cell, leading to its death, or could simply render the cell unculturable but not necessarily dead.

Another interesting recent development was reported by Laroussi and coworkers [21], [31]: Carrying out "sub-lethal"

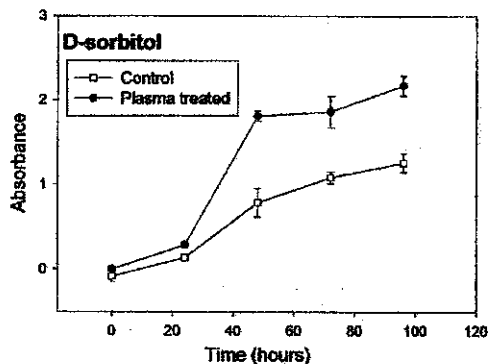


Fig. 8. Heterotrophic-pathway changes after treatment: increased utilization of substrate by *E. coli* exposed to plasma [31].

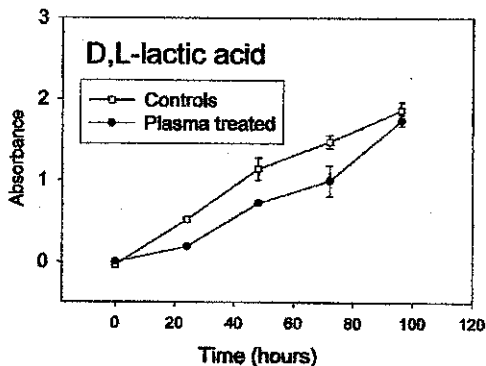


Fig. 9. Heterotrophic-pathway changes after treatment: decreased utilization of substrate by *E. coli* exposed to plasma [31].

experiments, they reported that short exposures to plasmas can affect the metabolic functions of cells without necessarily killing them. This was achieved by exposing *E. coli* cells to small doses of plasma and monitoring changes in their heterotrophic pathways, relative to those of unexposed cells (controls). A change in these pathways is indicative of changes in enzyme activities. Figs. 8 and 9 show cases of increased and decreased use of certain nutrients by exposed cells relative to control cells, respectively. These results indicate that plasma could be used just to alter the metabolic behavior of micro-organisms, in applications where killing is not the desired result. This newly discovered "bio-manipulation" effect of cold plasmas could potentially lead to novel and interesting biological applications.

VI. PROSPECTS AND CONCLUSIONS

Research on the interaction of both low-pressure and high-pressure nonequilibrium plasmas with biological media has reached a stage of maturity, which indicates that this emerging field promises to yield valuable technological novelty. The establishment of conferences and symposia discussing the basic and applied research underway in this field is an indication of the interest of a scientific community cutting across several disciplines. In the medical field, the use of plasma to sterilize heat-sensitive reusable tools in a rapid, safe, and effective way is bound to replace the present method, which relies on the use of ethylene oxide, a toxic gas. In the food

industry, the use of plasmas to sterilize packaging will lead to a safer food with longer shelf life. In space applications, plasma is considered as a potential method to decontaminate spacecraft on planetary missions. The goal in this application is to avoid transporting micro-organisms from Earth to the destination planet (or moon). Plasma is also being seriously considered for the decontamination of the air intake of buildings. This is extremely important in biological-warfare situations, where harmful biological agents are released in the air and can quickly contaminate the atmosphere inside buildings via their ventilation systems.

Extensive research on the use of high-pressure cold plasmas to inactivate micro-organisms is a relatively recent event. Certainly, there are a lot of basic issues that need more in-depth investigation. Among these are the effects of plasma on the biochemical pathways of bacteria. A clear understanding of these will lead to new applications other than sterilization/decontamination. However, for practical devices intended for the destruction of pathogens, all the available results indicate that the presence of small amounts of oxygen, humidity, or hydrogen peroxide in the decontamination chamber leads to a rapid and effective process. In addition, it appears that direct exposure and remote exposure are both equally effective. This leads to the conclusion that it is the reactive species generated by the plasma that play the major role in the destruction of micro-organisms.

REFERENCES

- [1] B. Eliasson and U. Kogelschatz, "Non-equilibrium volume plasma chemistry," *IEEE Trans. Plasma Sci.*, vol. 19, pp. 1063-1077, Dec. 1991.
- [2] F. Massines, C. Mayoux, R. Messaoudi, A. Rabei, and P. Segur, "Experimental study of an atmospheric pressure glow discharge: Application to polymers surface treatment," in *Proc. Int. Conf. Gas Discharges and Their Applications*, Swansea, U.K., 1992, pp. 730-733.
- [3] M. Laroussi, "Sterilization of tools and infectious waste by plasmas," *Bull. Amer. Phys. Soc. Div. Plasma Phys.*, vol. 40, no. 11, pp. 1685-1686, 1995.
- [4] —, "Sterilization of contaminated matter with an atmospheric pressure plasma," *IEEE Trans. Plasma Sci.*, vol. 24, pp. 1188-1191, June 1996.
- [5] E. Garate, K. Evans, O. Gornostaeva, I. Alexeff, W. Kang, M. Rader, and T. K. Wood, "Atmospheric plasma induced sterilization and chemical neutralization," *Proc. IEEE Int. Conf. Plasma Science*, p. 183, June 1998.
- [6] J. G. Birmingham and P. Irving, "Corona discharge plasma reactor for decontamination," *Proc. IEEE Int. Conf. Plasma Science*, p. 183, 1998.
- [7] S. Moreau, M. Moisan, J. Barbeau, J. Pelletier, and A. Ricard, "Using the flowing afterglow of a plasma to inactivate bacillus subtilis spores: Influence of the operating conditions," *J. Appl. Phys.*, vol. 88, pp. 1166-1174, 2000.
- [8] M. Moisan, J. Barbeau, S. Moreau, J. Pelletier, M. Tabrizian, and L. H. Yabia, "Low temperature sterilization using gas plasmas: A review of the experiments, and an analysis of the inactivation mechanisms," *Int. J. Pharmaceut.*, vol. 226, pp. 1-21, 2001.
- [9] W. Siemens, *Poggendorfs Ann. Phys. Chem.*, vol. 12, pp. 66-122, 1857.
- [10] W. P. Menashi, "Treatment of surfaces," U. S. Patent 3 383 163, 1968.
- [11] M. Rader, I. Alexeff, P. P. Tsai, and L. C. Wadsworth, "Electrostatic charging apparatus and method," U. S. Patent 5 592 357, 1997.
- [12] M. Laroussi, I. Alexeff, and W. Kang, "Biological decontamination by nonthermal plasmas," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 184-188, Feb. 2000.
- [13] K. G. Donohoe, "The development and characterization of an atmospheric pressure non-equilibrium plasma chemical reactor," Ph.D. dissertation, Calif. Inst. Technol., Pasadena, CA, 1976.
- [14] K. G. Donohoe and T. Wydeven, "Plasma polymerization of ethylene in an atmospheric pressure discharge," *J. Appl. Polymer Sci.*, vol. 23, pp. 2591-2601, 1979.

- [15] S. Kanazawa, M. Kogoma, T. Moriwaki, and S. Okazaki, "Stable glow plasma at atmospheric pressure," *J. Appl. Phys. D, Appl. Phys.*, vol. 21, pp. 838-840, 1988.
- [16] K. Kelly-Wintenberg, T. C. Montie, C. Brickman, J. R. Roth, A. K. Carr, K. Sor ge, L. C. Wadworth, and P. P. Y. Tsai, "Room temperature sterilization of surfaces and fabrics with a one atmosphere uniform glow discharge plasma," *J. Indust. Microbiol. Biotechnol.*, vol. 20, pp. 69-74, 1998.
- [17] A. Scutze, J. Y. Jeong, S. E. Babyan, J. park, G. S. Selwyn, and R. F. Hicks, "The atmospheric pressure plasma jet: A review and comparison to other plasma sources," *IEEE Trans. Plasma Sci.*, vol. 26, pp. 1685-1694, Dec. 1998.
- [18] H. W. Herrmann, I. Henins, J. Park, and G. S. Selwyn, "Decontamination of chemical and biological warfare (CBW) agents using an atmospheric pressure plasma jet," *Phys. Plasmas*, vol. 6, no. 5, pp. 2284-2289, 1999.
- [19] M. Laroussi and I. Alexeff, "The resistive barrier discharge," in *Proc. IEEE Int. Conf. Plasma Science*, Las Vegas, NV, 2001, p. 169.
- [20] J. P. Richardson, F. F. Dyer, F. C. Dobbs, I. Alexeff, and M. Laroussi, "On the use of the resistive barrier discharge to kill bacteria: Recent results," *Proc. IEEE Int. Conf. Plasma Science*, p. 109, 2000.
- [21] M. Laroussi, J. P. Richardson, and F. C. Dobbs, "Biochemical pathways in the interaction of nonequilibrium plasmas with bacteria," in *Proc. Electromed.*, Portsmouth, VA, 2001, pp. 33-34.
- [22] S. S. Block, "Sterilization," in *Encyclopedia of Microbiology*. New York: Academic, 1992, vol. 4, pp. 87-103.
- [23] M. Yamamoto, M. Nishioka, and M. Sadakata, "Sterilization using a corona discharge with H₂O₂ droplets and examination of effective species," in *Proc. 15th Int. Symp. Plasma Chemistry*, vol. II, Orleans, France, 2001, pp. 743-751.
- [24] T. C. Montie, K. Kelly-Wintenberg, and J. R. Roth, "An overview of research using a one-atmosphere glow discharge plasma for sterilization of surfaces and materials," in *Proc. Electromed.*, Norfolk, VA, 1999, p. 27.
- [25] A. I. Kuzmichev, I. A. Soloshenko, V. V. Tsiolko, V. I. Kryzhanovsky, V. Yu. Bazhenov, I. L. Mikhno, and V. A. Khomich, "Feature of sterilization by different type of atmospheric pressure discharges," in *Proc. Int. Symp. High Pressure Low Temperature Plasma Chemistry*, Greifswald, Germany, 2001, pp. 402-406.
- [26] J. R. Roth, D. M. Sherman, R. Bengadri, F. Karakaya, Z. Chen, T. C. Montie, K. Kelly-Wintenberg, and P. P. Y. Tsai, "A remote exposure reactor (RER) for plasma processing and sterilization by plasma active species at one atmosphere," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 56-63, Feb. 2000.
- [27] D. A. Mendis, M. Rosenberg, and F. Azam, "A note on the possible electrostatic disruption of bacteria," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 1304-1306, Aug. 2000.
- [28] M. laroussi, G. Saylor, B. Galscock, B. McCurdy, M. Pearce, N. Bright, and C. Malott, "Images of biological samples undergoing sterilization by a glow discharge at atmospheric pressure," *IEEE Trans. Plasma Sci.*, vol. 27, pp. 34-35, Feb. 1999.
- [29] J. G. Birmingham and D. J. Hammerstrom, "Bacterial decontamination using ambient pressure nonthermal discharges," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 51-55, Feb. 2000.
- [30] T. C. Montie, K. Kelly-Wintenberg, and J. R. Roth, "An overview of research using the one atmosphere uniform glow discharge plasma (OAugDP) for sterilization of surfaces and materials," *IEEE Trans. Plasma Sci.*, vol. 28, pp. 41-50, Feb. 2000.
- [31] M. Laroussi, J. P. Richardson, and F. C. Dobbs, "Effects of Non-Equilibrium Atmospheric Pressure Plasmas on the Heterotrophic Pathways of Bacteria and on their Cell Morphology," *Appl. Phys. Lett.*, vol. 81, no. 4, pp. 772-774, 2002.



Mounir Laroussi (SM'96) is a Research Associate Professor with the Electrical and Computer Engineering Department, Old Dominion University (ODU), Norfolk, VA, and with the Applied Research Center, ODU, Newport News, VA, where he directs the research activities of the Applied Plasma Technology Laboratory.

His research interests are the physics of plasmas, the industrial applications of nonthermal atmospheric-pressure plasmas, and the interaction of EM waves with plasmas. He has authored or coauthored

more than 50 papers and holds three patents in the field of plasmas and applications.

Dr. Laroussi is an elected member of IEEE NPSS Administrative Committee.