PLASMA JET INTERACTIONS WITH WET CELLS*

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Treatment of biomedical surfaces and human tissue with atmospheric pressure plasma jets has been shown to:

- Disinfect surfaces by killing bacteria
- Sterilize medical equipment and implants
- Sterilize food and food packaging
- Induce blood coagulation
- Kill cancer cells
- Facilitate healing in chronic wounds
- Sterilize acute wounds

In this poster, I will show the results of a 2-D model that investigated the interaction of the electric field produced by an atmospheric pressure plasma jet and wet cells and the potential for electroporation or intracellular electro-manipulation.
ATMOSPHERIC PRESSURE PLASMA JETS (APPJ)

- Low-temperature non-equilibrium atmospheric pressure plasma jets provide therapeutic and sterilizing effects through:
  - Fluxes of charged and reactive species to surfaces
  - Ion and photon flux to cell structure
  - Intracellular and surface electric fields

Figure from ZIK plasmatis at the INP Greifswald

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Electroporation:
- Transmembrane pore formation resulting from accumulation of electric charge at the cell membrane.
- Threshold – membrane voltage drop of 0.1 – 1 V over pulses of 0.1 – 10 ms with electric fields of a few kV/cm.
- Used for gene delivery and drug delivery.

Intracellular Electro-manipulation (IEM):
- Breaches subcellular vesicular membranes using short (10 – 100 ns) and high E-field pulses (10s of kV/cm) [2].
- Does not reach the charging time of the plasma membrane – no pore formation.
- ns pulsed electric field (nsPEF) induces apoptosis in mammalian cells by targeting intracellular structures.
PLASMA JETS: TOUCHING OR NOT….

- Context – Plasma medicine use of plasma jets in treating tissue with overlying liquid.
- There is intrinsic variability – does the plasma jet “touch” or "not-touch"?
- How important is variability?
- 2D modeling study of He/O₂ plasma jet into humid air onto a thin water layer over tissue.

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[4]
**MODEL:** nonPDPSIM

- 2-D unstructured mesh with spatial dynamic range of $10^4$.
- Fully implicit plasma transport.
- Time slicing algorithms between plasma and fluid timescales.
- Poisson’s equation is solved throughout the computational domain.

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**MODEL GEOMETRY**

- Liquid treated as a "dense plasma".
- Water evaporated above the water layer.
- The tissue acts as the counter electrode.

**Diffusion into water is limited by Henry's law equilibrium at the surface layer. O₂ is naturally dissolved in the liquid before plasma.**

**Components of cell treated as dielectrics with permittivity, conductivity, and dielectric relaxation times listed.**

<table>
<thead>
<tr>
<th></th>
<th>Permittivity (ε/ε₀)</th>
<th>Conductivity (Ω⁻¹ cm⁻¹)</th>
<th>Dielectric Relaxation Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>5.8</td>
<td>8.7 x 10⁻⁸</td>
<td>5.9 x 10⁻⁶</td>
</tr>
<tr>
<td>Cytoplasm</td>
<td>30</td>
<td>4.8 x 10⁻³</td>
<td>5.5 x 10⁻¹⁰</td>
</tr>
<tr>
<td>Nucleus</td>
<td>20</td>
<td>3.0 x 10⁻⁵</td>
<td>5.9 x 10⁻⁸</td>
</tr>
<tr>
<td>Tissue</td>
<td>5</td>
<td>1.0 x 10⁻⁶</td>
<td>4.4 x 10⁻⁷</td>
</tr>
</tbody>
</table>

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Water evaporates from liquid layer at saturated vapor pressure.

He jet displaces the evaporating water vapor.

He/O₂ = 99.8/0.2 (4 slm) with humid air (N₂/O₂/H₂O = 79.5/20/0.5) flowing in the shielding gas (1 slm) for 13 ms to establish flow field.

He jet alone effectively “blocks” the ambient air from the water layer.
-10 kV, 60 ns pulse. Plasma bullet moves as an ionization wave (IW) propagating in He dominated channel at $2 \times 10^7$ cm/s.

- Electrons avalanche at tip of pin electrode, transition to "wall hugging" mode in tube, then transition to axis upon exit.
-10 kV, 60 ns pulse.

Ionization wave does not strike the water layer.

E-fields to cells / tissue are not large enough to induce electroporation or intracellular effects.

No surface charging on the water layer.

E-field at peak voltage and end of the pulse.
15 kV (TOUCHING): e PROPERTIES

-15 kV, 80 ns pulse. Ionization speed $8 \times 10^7$ cm/s, strikes water at 33 ns and continues as surface IW through H$_2$O vapor along the water surface.

- Upon striking the water layer, a restrike, positive IW propagates back up the plasma column.

- Electrons spread onto the water layer, accumulate and solvate.
-15 kV, 80 ns pulse.
- IW strikes water at 33 ns.
- E-field rise from compression of voltage ahead of IW & charging of water surface.
- The E-field penetrates into the cell and tissue producing conduction currents.
- Max E-field at cell membrane produces voltage drop of 0.01 V – too low for pore formation.
-15 kV, 80 ns pulse – end of pulse.

- E-field from surface charging (80 kV/cm) at water layer does not influence cells.

- Max E-field at membrane is too low for pore formation.

- Limited residual E-field in cells in afterglow.

- Intracellular field is below predicted IEM range.
• -20 kV pulse. Plasma bullet moves as an ionization wave (IW) at $1.4 \times 10^8$ cm/s.

• IW strikes water at 20 ns – 13 ns earlier than 15 kV case and with higher electron temperature, and source ionization levels.

• Electron density is 3-5 times higher in conduction channel and at surface than 15 kV case.
-20 kV pulse.

Higher voltage creates higher E-field in all regions.

Max E-field in cytoplasm is 9 kV/cm; membrane 21 kV/cm – still below predicted thresholds.

Dielectric relaxation time for membrane 6 µs; cytoplasm 0.5 ns.

Formation of conduction channel following the IW drops E-field behind the IW in air.
• Plasma jets touching (-15 kV, -20 kV) and not-touching (-10 kV) a 200 µm water layer were computationally investigated.

• The spreading of the plasma over the liquid surface when touching cases enables photolysis, direct charge exchange reactions and direct solvation of the electrons.

• Also creates a surface electric field at a maximum of 80 kV/cm for the -15 kV case.

• Not-touching jet will not produce electroporation or intracellular electro-manipulation as the e-fields are much too low for either.

• The touching cases are influenced by the absence of surface charging effects on the cells which decreases the likelihood of electroporation and intracellular electro-manipulation.

CONCLUDING REMARKS
REFERENCES


