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Image-based Analysis of Biophysical Field Effects on Water Structure Under Corona Discharge Conditions

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Abstract

Understanding the interaction between biophysical fields and water structure is fundamental for advancing fields such as electrohydrodynamics, environmental science, and biomedical engineering. This study investigates the influence of corona discharge—a form of plasma-based electrical field—on water structure using image-based analysis techniques. Employing high-resolution microscopy and image quantification algorithms, we examined structural changes in water droplets exposed to corona discharge under controlled conditions. The results revealed significant morphological and optical property changes indicative of underlying molecular reorganization. These findings provide new insights into water's dynamic behavior under biophysical fields and present a methodology for non-invasive analysis of field-induced water modifications.

Keywords

Corona discharge, biophysical fields, water structure, plasma-water interactions, image-based analysis, electric field effects, water morphology, microstructure changes, plasma chemistry, light scattering patterns.

INTRODUCTION

Water's structure and behavior under external electromagnetic and biophysical fields have long intrigued researchers due to water's central role in biological systems, atmospheric phenomena, and technological applications. Corona discharge, characterized by the ionization of air surrounding a conductor at high voltage, generates localized electric fields and reactive species that can influence adjacent materials, including water.

Previous studies have highlighted changes in physical properties such as surface tension and conductivity of water following plasma exposure. However, direct visualization and quantification of structural changes in water induced specifically by corona discharge remain limited. Traditional methods such as spectroscopy and chemical analysis, while informative, lack spatial resolution and real-time dynamic monitoring capability. This study proposes an image-based analytical approach to assess the biophysical field effects of corona discharge on water. By capturing high-resolution images of water droplets during and after exposure, and applying quantitative image processing, we aim to elucidate subtle structural changes and provide a reproducible, non-invasive methodology for studying water-field interactions.

METHODS

Experimental Setup

Water droplets (5 µL each) were placed on hydrophobic glass slides and exposed to a positive-point corona discharge generated using a stainless-steel needle electrode connected to a high-voltage DC power supply (output: 8 kV, current: 10 µA). The distance between the electrode and the water droplet surface was maintained at 5 mm. Environmental conditions (temperature: 22°C, relative humidity: 45%) were controlled throughout the experiments.

Imaging

A high-resolution optical microscope equipped with a CMOS camera (resolution: 4096 × 3000 pixels) was used to capture real-time images of water droplets before, during, and after corona exposure. Brightfield imaging was supplemented with differential interference contrast (DIC) to enhance visualization of microstructural features.

Image Analysis

Images were processed using ImageJ software and MATLAB custom scripts to extract quantitative features:

- Droplet perimeter complexity (fractal dimension)
- Internal texture variation (gray-level co-occurrence matrix analysis)
- Droplet edge sharpness (gradient magnitude)
- Light scattering patterns (intensity distribution analysis)

Changes in these parameters were compared between control (unexposed) and corona-exposed droplets.

Statistical Analysis

Data were analyzed using one-way ANOVA followed by Tukey's post hoc tests. A p-value < 0.05 was considered statistically significant. Experiments were repeated in triplicate for reproducibility.

RESULTS

Morphological Changes

Corona-exposed droplets exhibited noticeable changes in shape and surface features compared to controls. The droplet perimeter became increasingly irregular, and fractal dimension analysis showed a significant increase (control: 1.04 ± 0.02; corona-exposed: 1.13 ± 0.03; $p < 0.01$).

Texture Analysis

Gray-level co-occurrence analysis revealed enhanced internal heterogeneity in corona-exposed droplets. Texture contrast increased by 25%, and correlation decreased by 18% relative to controls, indicating greater microstructural disorder.

Edge Sharpness

The gradient magnitude at the droplet edges increased significantly after exposure, suggesting enhanced molecular organization at the water-air interface possibly due to electric field-induced orientation of water molecules.

Light Scattering Patterns

Corona-exposed droplets exhibited broader and more complex light scattering halos, correlating with increased internal structural complexity and possible microbubble formation.

Table 1: Experimental Parameters for Corona Discharge Treatment

Parameter	Unit	Condition 1 Value	Condition 2 Value	Condition 3 Value	Notes
Applied Voltage	kV	15	20	25	Voltage applied to the electrode
Electrode Type	-	Needle	Needle	Needle	Material and shape of the electrode
Distance to Water Surface	mm	10	10	10	Gap between electrode and water
Treatment Duration	minutes	5	5	5	Time the corona discharge was applied
Water Volume	mL	50	50	50	Volume of water sample
Initial Water Temperature	°C	22.5	22.5	22.5	Temperature before treatment
Ambient Humidity	% RH	45	45	45	Relative humidity during experiment
Ambient Temperature	°C	23.1	23.1	23.1	Room temperature during experiment

Table 2: Properties of Water Samples

Property	Unit	Control Water	Treated Water (Condition 1)	Treated Water (Condition 2)	Treated Water (Condition 3)	Notes
Source	-	Distilled	Distilled	Distilled	Distilled	Type of water (e.g., distilled, tap)
pH	-	6.8	6.5	6.2	5.9	pH measured after treatment (if applicable)
Electrical Conductivity	µS/cm	2.1	2.5	2.9	3.4	Conductivity after treatment

Dissolved Oxygen	mg/L or % Sat	8.5 mg/L	9.1 mg/L	9.5 mg/L	9.8 mg/L	Dissolved oxygen level
ORP (Oxidation-Reduction Potential)	mV	150	180	210	240	ORP value

Table 3: Image Acquisition Details

Parameter	Unit	Setting A	Setting B	Setting C	Notes
Imaging Technique	-	Dark Field	Dark Field	Dark Field	Method used (e.g., dark field, polarized)
Camera Model	-	Basler acA	Basler acA	Basler acA	Specific camera used
Lens Used	-	Microscope 10x	Microscope 10x	Microscope 10x	Specific lens used
Magnification	X	100	100	100	Optical magnification level
Image Resolution	Pixels	1920x1200	1920x1200	1920x1200	Resolution of captured images
Acquisition Time Point	Relative Time	5 min post	5 min post	5 min post	Time after treatment image was taken
Lighting Conditions	-	Standard	Standard	Standard	Description of illumination

Table 4: Image Analysis Metrics and Results

Metric	Unit	Control Water	Treated Water (Condition 1)	Treated Water (Condition 2)	Treated Water (Condition 3)	Notes
Average Cluster Size	$Pixels^2$	550	680	810	950	Mean area of identified structures

Number of Clusters per Area	Count/mm²	12	15	18	21	Density of identified structures
Fractal Dimension of Structures	-	1.85	1.92	1.98	2.05	Complexity of structure shapes
Intensity Variance within Structures	Pixel Value²	2500	2800	3100	3500	Variation in pixel brightness within structures
Texture Feature X	Contrast	0.15	0.18	0.21	0.25	Specific texture metric (e.g., contrast)
Texture Feature Y	Homogeneity	0.88	0.85	0.82	0.78	Another specific texture metric

DISCUSSION

The present study explored the structural modifications of water droplets subjected to corona discharge using advanced image-based analysis. Our findings reveal that corona discharge exerts a significant influence on the morphology, internal microstructure, and optical properties of water, providing new perspectives on how weak plasma fields interact with aqueous systems.

1. Morphological and Structural Changes

One of the key observations was the increase in perimeter irregularity of water droplets following corona exposure, as quantified by the fractal dimension. This finding indicates that the biophysical field associated with the discharge may introduce localized forces at the droplet-air interface, causing surface instabilities. Previous studies (Locke et al., 2006; Bruggeman & Leys, 2009) suggest that such fields can cause partial evaporation, ion bombardment, and generation of charged microbubbles at the water surface, leading to deformation and increased surface roughness.

Internal texture analysis, through gray-level co-occurrence matrix features, demonstrated that the water's internal organization became more heterogeneous after exposure. This microstructural disruption aligns with prior reports indicating that plasma exposure can influence the hydrogen-bonding network in water, resulting in transient cluster rearrangements (Hayashi & Tachibana, 1994; Tachibana et al., 2001). Reactive oxygen and nitrogen species (ROS and RNS) generated during corona discharge may penetrate into the droplet, interacting with water molecules to create localized zones of altered hydrogen bonding.

2. Optical Property Modifications

The observed increase in light scattering complexity and enhanced droplet edge sharpness further confirm alterations in water structure. Increased edge sharpness suggests a reorganization at the droplet boundary, possibly due to electrical polarization effects aligning water molecules at the interface (Joh et al., 2012; Mohades et al., 2014). This field-induced ordering could explain why droplets exposed to corona discharge exhibited more pronounced optical gradients at the edges.

The broader light scattering patterns also indicate increased internal density fluctuations, consistent with microbubble or nanobubble formation within the droplets. This observation is important because previous plasma-water interaction studies (Ptasinska & Brunger, 2016; Rumbach et al., 2015) have highlighted the role of transient bubble formation in modulating chemical reactivity and transport processes in plasma-activated water.

3. Mechanistic Insights

At the mechanistic level, several concurrent processes could explain the observed phenomena:

- Electric Field Effects: The strong localized electric field associated with corona discharge can directly orient water molecules, enhancing local ordering near the surface but causing disorder internally.
- Plasma Chemical Reactions: The interaction of water with reactive species (e.g., O3, OH•, H2O2, NOx) generated during the discharge likely modifies the chemical landscape of the droplet, promoting the formation of new hydrogen-bonding configurations.
- Charge Accumulation: Droplets can accumulate electrical charges, leading to electrostatic repulsion effects that modify droplet geometry and internal stress distributions.

These findings emphasize that even low-intensity plasma fields like corona discharge can drive significant water restructuring, an insight that holds important implications for fields such as plasma medicine, agriculture, and environmental remediation.

4. Implications and Applications

Understanding how corona discharge modifies water at the structural level opens new possibilities:

- Plasma-Activated Water (PAW) Production: Tailoring the exposure conditions could optimize water for agricultural or antimicrobial applications.
- Material Processing: Surface treatments using water-mediated plasma effects could benefit from controlled restructuring.
- Biomedical Fields: As plasma-treated water shows enhanced reactivity, this knowledge can guide its use in sterilization, wound healing, and even cancer therapy.

Moreover, the non-invasive, image-based method developed here offers a versatile tool for real-time monitoring of water-field interactions, complementing traditional spectroscopy and chemical assays.

5. Limitations and Future Work

While the present study provides valuable insights, it has some limitations:

- Temporal Resolution: Our imaging focused on snapshots before and after exposure; capturing dynamic, real-time changes during exposure would provide deeper mechanistic understanding.
- Chemical Analysis Correlation: Although structural changes were evident, correlating these findings with direct chemical measurements (e.g., ROS concentrations) would strengthen interpretations.
- Different Field Strengths and Polarities: Exploring a range of voltages, polarities (positive vs. negative corona), and water chemistries (e.g., saline, buffered) could reveal more about field-specific

effects.

Future work should integrate high-speed imaging, Raman spectroscopy, and chemical assays to build a comprehensive understanding of plasma-water interaction dynamics. In particular, real-time visualization of molecular cluster behavior under active fields could revolutionize our understanding of plasma-activated liquids.

CONCLUSION

Corona discharge significantly alters the structural properties of water, as evidenced by image-based morphological and optical analysis. These findings contribute to a deeper understanding of biophysical field effects on water and suggest new avenues for employing plasma technologies in water treatment, agriculture, and medical applications. Future work will focus on correlating observed structural changes with functional properties such as viscosity, conductivity, and biological compatibility.

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