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Effect of Oxygen Gas Plasma Jet on Reactive Oxygen Nitrogen Species Dissolved in Sodium Chloride and Glucose Solutions

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This study investigates the generation and stability of reactive oxygen and nitrogen species (RONS) in medical-grade sodium chloride and glucose infusion solutions following treatment with a non-thermal oxygen gas plasma jet. The plasma system operated at 10 kV and 30 W with an oxygen flow rate of 2.5 L/min and treatment durations of 5, 10, 15, and 20 minutes were applied. Optical emission spectroscopy (OES) confirmed the presence of oxygen and entrained nitrogen species in the plasma discharge, while the concentrations of NO_2^-, NO_3^-, and H_2O_2, as well as pH and temperature, Chemical analyses showed that nitrite (NO_2^-) peaked at 1 ppm after 5 minutes of exposure but became undetectable in contrast nitrate (NO_3^-) concentrations increased and stabilized at 100 ppm, while hydrogen peroxide (H_2O_2) levels rose progressively to 100 ppm by 20 minutes. A notable pH reduction was observed, decreasing from 4.5 in untreated samples to 1.8 after 20 minutes of plasma exposure, indicating pronounced acidification. Storage stability tests conducted over 50 hours revealed that H_2O_2 degraded over time, while NO_3^- remained relatively stable. These findings demonstrate the potential of oxygen plasma jets for the chemical activation of physiologically relevant solutions, highlighting their applicability in sterilization, wound care, and disinfection.

Keywords: Plasma jet; Plasma-activated water; Oxygen plasma; Non-thermal atmospheric plasmas
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1. Introduction

Non-thermal plasma (NTP) is a partially ionized gas capable of producing reactive oxygen and nitrogen species reactive oxygen and nitrogen species, such as NO_2^-, NO_3^-, and H_2O_2, which have demonstrated strong antimicrobial and biochemical effects [1-5]. Plasma-activated water (PAW) has been extensively studied, particularly for its oxidative potential and acidification after plasma exposure [6-8]. However, most research has focused on pure or distilled water. Limited attention has been given to medically relevant solutions like sodium chloride and glucose infusions, which contain salts and organic compounds that may alter RONS generation and stability [9-11]. Understanding these interactions is critical for extending plasma applications to biomedical settings. In this study, we investigated RONS formation in medical infusion solutions (NaCl + glucose, B.P. 2020) treated with a non-thermal oxygen plasma jet. The experimental setup involved an AC high-voltage system operating at 10 kV and 2.5 L/min oxygen flow. Plasma species were characterized using optical emission spectroscopy (OES), and chemical changes, reactive oxygen and nitrogen species concentrations, pH, and temperature, were evaluated during exposure and storage. This research builds upon earlier PAW studies and contributes new insight into plasma-liquid interactions in complex clinical fluids [12,13]. Atmospheric microwave-induced plasma (MIP) has also been widely studied due to its advantages such as no requirement for expensive vacuum systems, low cost, and operational simplicity [14,15]. In this study, we developed an oxygen plasma jet system to investigate its effectiveness in activating sodium chloride and glucose solutions. The variables considered include exposure time, gas type, and flow rate. We measured the concentrations of NO_2^-, NO_3^-, and H_2O_2, as well as the pH and temperature of the treated solutions, aiming to identify optimal conditions for maximizing reactive oxygen and nitrogen species generation.

2. Experimental Part

An oxygen gas plasma jet system was specifically designed to activate medical-grade sodium chloride and glucose solutions (Infusion B.P. 2020). The infusion comprises 0.9% sodium chloride (9 g/L, 154 mmol/L Na^+) and 5% anhydrous glucose (50 g/L, 278 mmol/L), yielding a total osmolarity of approximately 560 mOsmol/L. The absence of additional excipients or buffers is explicitly stated on the commercial label. A schematic representation of the experimental setup is provided in Fig. (1), where an AC high-voltage power supply delivers 10 kV and 30 W, powering a hollow stainless-steel electrode with an inner diameter of 2.4 mm and a length of 10 cm. The electrode is connected to a Teflon tube, regulated for an oxygen gas flow of 2.5 L/min. The grounded electrode is a metal plate situated below the plastic sample container, with 20 mL of the infusion solution placed at the center. The plasma jet nozzle is positioned precisely 1 cm above the liquid surface.

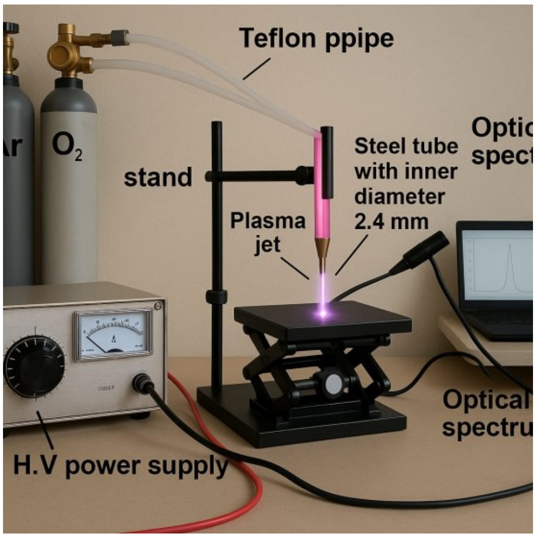

Fig. (1) Schematic diagram of the developed plasma system used for activating aqueous solutions

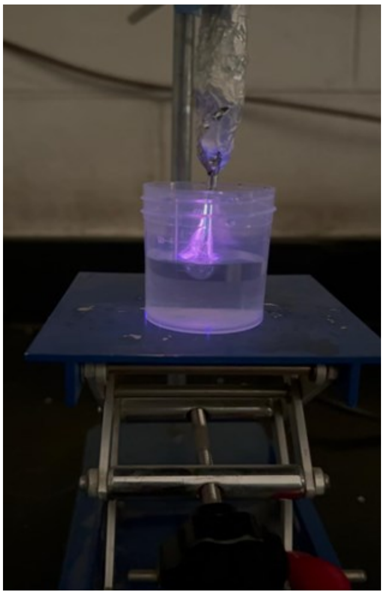

Fig. (2) The plasma jet in operation while activating the sodium chloride and glucose solution at a flow rate of 2.5 L/min, with the nozzle 1 cm above the liquid surface. The grounded electrode is positioned beneath the container

Solutions were subjected to varying plasma exposure durations of 5, 10, 15, and 20 minutes. Chemical analyses of nitrite (NO_2^-), nitrate (NO_3^-), and hydrogen peroxide (H_2O_2) were performed using commercially available test strips (Bartvation, USA). These strips provide semi-quantitative measurements in ppm (mg/L), with a detection range typically spanning 0–500 ppm. While the use of test strips offers rapid and convenient assessments, their precision is inherently limited, and no validation was conducted against more rigorous analytical techniques such as UV-visible spectroscopy, titration, or HPLC, which could improve quantification accuracy. The pH was measured with a calibrated pH meter, and the temperature was recorded using a remote infrared thermometer. The test strips used for detecting nitrite, nitrate, and hydrogen peroxide concentrations are illustrated in Fig. (3).

Fig. (3) (a) Test strips for nitrite and nitrate detection (ppm) (b) Hydrogen peroxide test strips (ppm)

3. Results and discussion

Optical emission spectroscopy (OES) was employed to characterize the plasma species generated by the oxygen gas jet at a flow rate of 2.5 L/min under atmospheric conditions, using a Thorlabs CCS100/M spectrometer. The emission spectra in Fig. (4) revealed strong atomic oxygen lines at 335.13, 355.08, 377.74, 402.63, and 928.05 nm, with 402.63 nm being the most intense. Surprisingly, notable peaks associated with nitrogen species were also observed, including a prominent signal at 589.32 nm. This can be attributed to air entrainment at the nozzle exit, where ambient nitrogen interacts with the plasma, enabling the formation of nitrogen-based RONS. Plasma-liquid interactions led to significant chemical changes in the treated solutions.

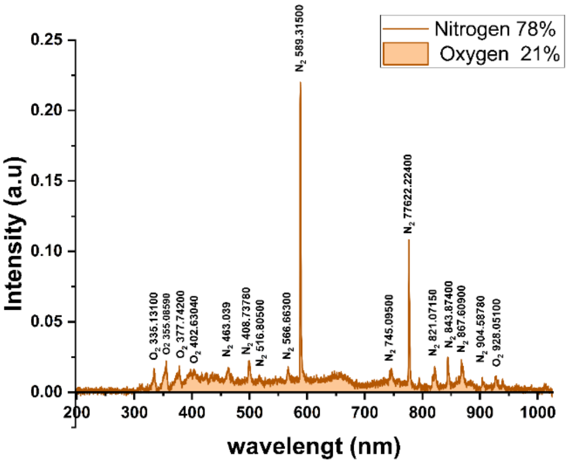

Fig. (4) Optical emission spectra of oxygen plasma jet at 2.5 L/min flow rate under atmospheric pressure

As shown in Fig. (5) and table (1), nitrite (NO_2^-) appeared only after 5 minutes of exposure (1 ppm), then rapidly declined to undetectable levels, likely due to oxidation into nitrate (NO_3^-). Nitrate concentrations reached 100 ppm and remained stable with extended exposure. Hydrogen peroxide H_2O_2 levels increased steadily, peaking at 100 ppm after 20 minutes. H_2O_2 formation likely results from the recombination of oxygen radicals or electron-induced reactions, such as: $O_2 + 2e^- \rightarrow 2O^- \rightarrow H_2O_2$ (in liquid phase via OH• mediation) NO_2^- degradation may occur through several pathways, including: $NO_2^- + H_2O_2 \rightarrow NO_3^- + H_2O$ oxidation by hydroxyl radicals •OH, ozone O_3, or nitrogen pentoxide N_2O_5. The observed conversion suggests interplay between reactive species, but no strict stoichiometric balance was established.

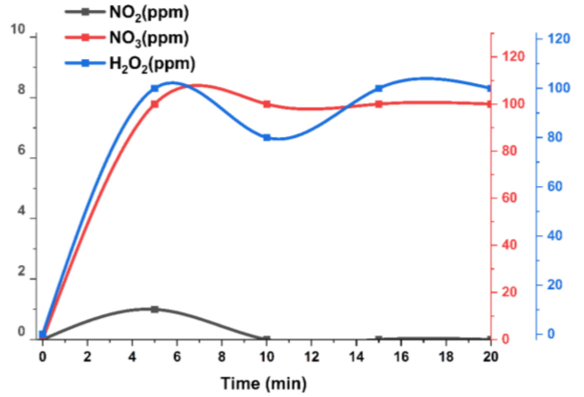

Fig. (5) The concentrations of NO_2^-, NO_3^-, and H_2O_2 (in ppm) as a function of plasma exposure time. (5, 10, 15, and 20) minutes using oxygen plasma jet at 2.5 L/min

Table (1) Concentrations of reactive oxygen and nitrogen species, pH, and temperature for different exposure times

Time (min)	NO_2 (ppm)	NO_3 (ppm)	H_2O_2 (ppm)	Total (RONS)	pH	Temp. (°C)
0	0	0	0	0	4.5	25
5	1	100	100	201	2.5	37.8
10	0	100	80	180	2.2	31.8
15	0	100	100	200	2.0	32.2
20	0	100	100	200	1.8	38.8

Post-treatment stability was assessed at 26, 38, and 50 hours. As shown in Fig. (6) and table (2), NO_2^- remained undetectable, confirming its complete conversion or instability. NO_3^- concentrations increased from 100 ppm at 26 h to 250 ppm by 38 h and remained constant thereafter. H_2O_2, however, degraded over time, dropping from 40 ppm at 26 h to 7 ppm by 50 h, suggesting its vulnerability to decomposition. Likely degradation mechanisms include disproportionation $2H_2O_2 \rightarrow 2H_2O + O_2$, reactions with residual reactive oxygen and nitrogen species (e.g., NO, •OH), or catalytic decomposition via metal traces. The "Total reactive oxygen and nitrogen species column in tables (1) and (2) represents the arithmetic sum of NO_2^-, NO_3^-, and H_2O_2 concentrations (in ppm). However, it should be noted that this value does not reflect the cumulative oxidative potential or reaction kinetics, as each species contributes differently to chemical reactivity and biological impact.

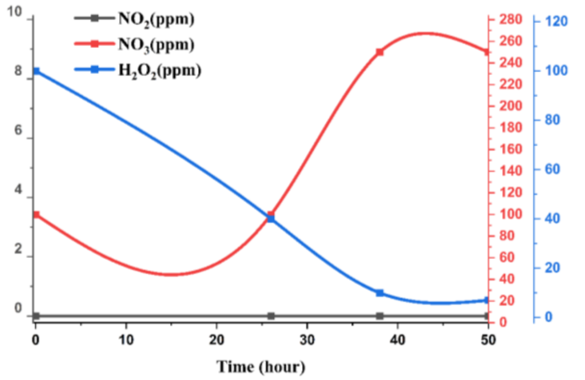

Fig. (6) The effect of storage time on the concentration of reactive oxygen and nitrogen species

Table (2) the effect of storage time on the concentration of reactive oxygen and nitrogen species and the pH

Time (hour)	NO_2 (ppm)	NO_3 (ppm)	H_2O_2 (ppm)	Total (RONS)	pH	Temp. (°C)
0h	0	100	100	200	1.8	38.8
26h	0	100	40	140	1.9	32.6
38h	0	250	10	260	1.9	30.8
50h	0	250	7	257	2.1	30.4

Figure (7) illustrates the pH changes in the sodium chloride and glucose solutions both during plasma exposure and post-treatment storage. The pH dropped progressively from 4.5 in untreated samples to 1.8 after 20 minutes, indicating strong acidification. This is likely due to the formation of nitric acid (HNO_3), but other acidic compounds such as peroxynitrous acid ONOOH and nitrous acid HNO_2, or products from glucose degradation under plasma-induced oxidative stress, may also contribute.

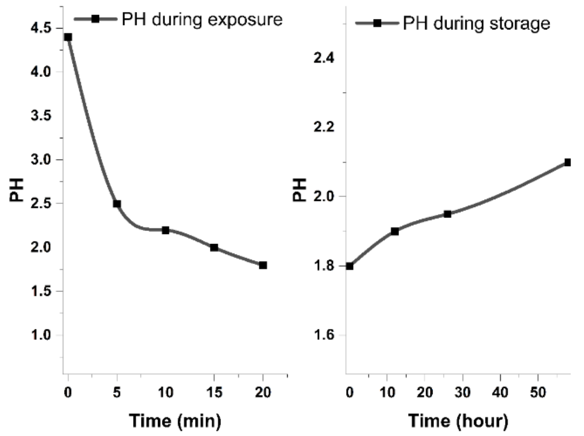

Fig. (7) pH variation of plasma-treated sodium chloride and glucose solutions during exposure and storage (oxygen flow rate: 2.5 L/min)

The pH initially remained acidic 1.9 at 26-38 h, but slightly increased to 2.1 by 50 h. This minor rise may be due to neutralization reactions or the breakdown of intermediate acidic species formed during or after plasma exposure.

4. Conclusion

This study demonstrated that an oxygen gas plasma jet effectively generates reactive oxygen and nitrogen species in medical sodium chloride and glucose solutions. Plasma exposure resulted in the formation of stable nitrate (NO_3^-) and transient hydrogen peroxide H_2O_2, while nitrite (NO_2^-) was short-lived and rapidly converted. A significant pH reduction from 4.5 to 1.8 confirmed acidification due to plasma-induced reactions. Optical emission spectroscopy verified the presence of reactive species, including nitrogen-derived peaks attributed to air entrainment. Storage analysis showed nitrate stability and gradual H_2O_2 degradation, highlighting time-sensitive reactivity. These findings confirm the chemical activation potential of oxygen plasma for physiologically relevant fluids.

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