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Harnessing Non-Thermal Plasma to Supercharge Recovery in Abdominal Surgeries

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Name of Author:
Shumaila Naseer[1], Muhammad Sohail Arshad[2], Afsheen Khan[3], Mukarram Mustajab[4], Muhammad Ilyas Khan[5], Sidra Abbas[6], Muhammad Siddique Khan[7]

Affiliation: *[1]Senior Registrar, Department of General Surgery, Jinnah Teaching Hospital, Peshawar, Pakistan*
[2]Post Graduate Resident, Department of General Surgery, Bahawal Victotia Hospital, Bahawalpur, Pakistan
[3]Assistant Professor Anatomy, Shaheed Mohtarma Benazir Bhutto Medical College Lyari, Karachi, Pakistan
[4]Consultant General Surgeon, Department of General Surgery, Gajju Khan Medical College. Bacha Khan Medical Complex – MTI, Swabi, Pakistan
[5]Surgical TR, Department of General Surgery, BKMC- MTI, Swabi, Pakistan
6Associate Professor, Department of Surgery, Baqai Medical University, Karachi, Pakistan
[7]Assistant Professor, Department of Surgery, Khyber Teaching Hospital, Peshawar, Pakistan

Corresponding Author:
Dr. Muhammad Siddique Khan,
Email: siddique.khan@kmc.edu.pk

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Abstract: **Background:** Delayed wound healing, surgical site infections (SSI), postoperative ileus, and inflammatory complications remain significant contributors to morbidity after abdominal surgeries. Objective: To evaluate the clinical impact of non-thermal plasma application on wound healing, inflammatory response, gastrointestinal recovery, and postoperative complications in patients undergoing abdominal surgeries. **Methods:** This prospective interventional study was conducted at Jinah teaching hospital Peshawar from May 2024 to May 2025 included 240 patients undergoing abdominal surgery, divided into a control group (standard care, n = 120) and a non-thermal plasma group (standard care plus plasma application, n = 120). Postoperative outcomes assessed included surgical site infection, wound healing scores, time to first flatus and stool, Visual Analog Scale (VAS) pain scores, C-reactive protein (CRP) levels, length of hospital stay, reintervention rates, and 30-day readmission. **Results:** Surgical site infection was significantly reduced in the plasma group (9.2%) compared to controls (20.0%). Wound healing scores on postoperative day 7 were higher with plasma therapy (7.4 ± 1.2 vs 6.1 ± 1.3). Time to first flatus (2.4 ± 0.8 vs 3.2 ± 0.9 days) and first stool (3.2 ± 1.0 vs 4.1 ± 1.2 days) were significantly shorter in the plasma group. Pain scores at 24, 48, and 72 hours were consistently lower. CRP levels were reduced on postoperative days 3 and 7, and hospital stay was shorter (6.9 ± 2.0 vs 8.6 ± 2.3 days). Overall complications (15.8% vs 31.7%), reinterventions (5.0% vs 11.7%), and 30-day readmissions (5.8% vs 13.3%) were significantly decreased with plasma application. **Conclusion:** Non-thermal plasma significantly improves multidimensional postoperative recovery following abdominal surgery, demonstrating reduced infection rates, enhanced wound healing, attenuated inflammation, and improved functional outcomes..

Keywords: Non-thermal plasma; Cold plasma therapy; Abdominal surgery; Surgical site infection; Wound healing.

INTRODUCTION

Surgical operations in the abdomen still constitute one of the most common types of operations in the world and still have high rates of postoperative morbidity with the forms of surgical site infection (SSI), postoperative ileus, and systemic inflammatory complications [1]. Despite improvements in surgical procedures, anesthesia, and perioperative care, variability in recovery persists, even among patients with comorbidities, contaminated wounds, or extended operative time [4]. Surgical site infection remains a significant cause of extended hospital stays, increased healthcare expenditures, and readmission [2]. Postoperative recovery is a complex biological process characterized by inflammation, microbial burden, oxidative stress, angiogenesis, and tissue remodeling [6]. The malfunctioning of this cascade may lead to impaired wound healing, overproduction of the inflammatory response, and delayed functional recovery [3]. The traditional interventions, such as prophylactic antibiotics, optimized glycemic control, and recovery measures, have helped to improve the outcome but have not removed the postoperative complications completely [8]. Non-thermal (cold) plasma has become a new biomedical technology that is able to deliver reactive oxygen and nitrogen species (RONS) at near-physiological temperatures and, therefore, cause antimicrobial, anti-inflammatory and pro-regenerative effects without heating tissue [5]. Preclinical and early clinical evidence suggests that cold plasma may reduce microbial load, regulate inflammatory cytokines, promote fibroblast growth, and induce angiogenesis and epithelialization [9]. The mechanisms are particularly applicable in the context of abdominal surgery, as wound integrity, infection control, and inflammatory modulation directly affect postoperative recovery pathways [7].

In addition to its antimicrobial activity, non-thermal plasma has been shown to modulate cellular signaling pathways involved in tissue repair and immune regulation [11]. This organized healing may be facilitated by controlled oxidative signaling induced by plasma-generated species and by excessive tissue damage induced by excessive inflammation [10]. Nevertheless, inconsistency in the devices used in plasma, protocols applied and measures in outcome have hindered standardization and general use in surgical practice [13]. Moreover, there is a lack of robust clinical evidence regarding its role in overall postoperative recovery parameters [12]. Non-thermal plasma is a promising innovation in the surgical care pathways as it is necessary to achieve adjunctive measures aimed at increasing the recovery and preserving safety [15]. Past studies have also documented improved wound-healing outcomes and reduced infection rates across a wide range of surgical and chronic wounds [14]. Nevertheless, the impact of the same on multidimensional postoperative outcomes, including gastrointestinal recovery, inflammatory markers, pain management, complication rates, and healthcare use, are currently still developing with big prospective studies [16].

Objective

To evaluate the clinical impact of non-thermal plasma application on wound healing, inflammatory response, gastrointestinal recovery, and postoperative complications in patients undergoing abdominal surgeries.

METHODOLOGY

This was a hospital-based prospective interventional study conducted at Jinah teaching hospital Peshawar from May 2024 to May 2025. A total of 240 patients undergoing elective or emergency abdominal surgeries were included in the study.

Inclusion Criteria

- Patients aged ≥18 years.
- Patients undergoing open or laparoscopic abdominal surgery (including gastrointestinal, hepatobiliary, colorectal, or hernia procedures).
- Clean-contaminated or contaminated surgical wounds.
- Patients who provided written informed consent.

Exclusion Criteria

- Patients with severe immunosuppression or ongoing chemotherapy.
- Patients with uncontrolled diabetes mellitus (HbA1c >9%).
- Patients with known connective tissue disorders affecting wound healing.
- Pregnant patients.
- Patients with pre-existing abdominal wound infection.
- Patients unwilling to participate.

Data collection

After obtaining written informed consent, demographic and baseline clinical data including age, gender, BMI, smoking status, and comorbidities were recorded using a structured proforma. Patients were divided into two groups of 120 each:

Control Group (n = 120): Received standard perioperative surgical care according to institutional protocol.

Non-Thermal Plasma Group (n = 120): Received standard care plus intraoperative and/or immediate postoperative application of non-thermal plasma to the surgical incision site using a certified cold plasma device.

Operative records provided the surgical variables: the nature of the abdominal operation, method of operation (open or laparoscopic), wound type, and the length of operation. Within the non-thermal plasma group, the information on the application of plasma as time and duration was recorded. Prospective outcomes were measured and they were surgical site infection (SSI), time to first flatus and stool, Visual Analog Scale (VAS) pain scores at 24-72 hours, wound healing scores at postoperative days 3 and 7, CRP level at 3 and 7 days, length of hospital stay, reintervention, and 30-day readmission. Trained clinicians assessed wounds in a blinded state, and all laboratory tests were done according to the regular protocols of the institution, the data were checked

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before statistical analysis was conducted.

Statistical Analysis
Data were entered into Microsoft Excel and analyzed using SPSS software version 25. Continuous variables were expressed as mean ± standard deviation (SD), and categorical variables were presented as frequency and percentage. Comparisons between the control and plasma groups were performed using independent-samples t-tests for continuous variables and chi-square tests for categorical variables. A p-value of <0.05 was considered statistically significant.

RESULTS

Baseline characteristics were comparable between the two groups. The mean age was 49.8 ± 12.4 years in the control group and 48.6 ± 13.1 years in the plasma group (p = 0.48). Mean BMI was similar at 26.7 ± 3.8 kg/m² versus 26.2 ± 4.1 kg/m² (p = 0.37). The proportion of males was 60.0% in controls and 58.3% in the plasma group (p = 0.79). Diabetes (30.0% vs 28.3%), hypertension (34.2% vs 32.5%), and smoking (24.2% vs 22.5%) were evenly distributed (all p > 0.70). Operative duration was comparable at 122 ± 34 minutes versus 119 ± 36 minutes (p = 0.53), and the distribution of open (61.7% vs 59.2%) and laparoscopic surgeries (38.3% vs 40.8%) was similar (p = 0.69), indicating well-balanced groups.

Table 1. Baseline Demographic and Clinical Characteristics (n = 240)

Variable	Category	Control (n = 120)	Plasma (n = 120)	Total (n = 240)	p-value
Age (years)	Mean ± SD	49.8 ± 12.4	48.6 ± 13.1	49.2 ± 12.7	0.48
Gender	Male	72 (60.0%)	70 (58.3%)	142 (59.2%)	0.79
Gender	Female	48 (40.0%)	50 (41.7%)	98 (40.8%)	0.79
BMI (kg/m²)	Mean ± SD	26.7 ± 3.8	26.2 ± 4.1	26.5 ± 3.9	0.37
Diabetes Mellitus	Present	36 (30.0%)	34 (28.3%)	70 (29.2%)	0.76
Hypertension	Present	41 (34.2%)	39 (32.5%)	80 (33.3%)	0.77
Smoking	Yes	29 (24.2%)	27 (22.5%)	56 (23.3%)	0.75
Operative Duration (minutes)	Mean ± SD	122 ± 34	119 ± 36	120.5 ± 35	0.53
Open Surgery	Yes	74 (61.7%)	71 (59.2%)	145 (60.4%)	0.69
Laparoscopic Surgery	Yes	46 (38.3%)	49 (40.8%)	95 (39.6%)	0.69

The plasma group demonstrated significantly improved wound outcomes. Surgical site infection occurred in 20.0% of controls compared to 9.2% in the plasma group (p = 0.02). Mean wound healing score on day 7 was higher in the plasma group (7.4 ± 1.2) compared to controls (6.1 ± 1.3), showing statistically superior healing (p < 0.001). Wound dehiscence was reduced from 10.8% in controls to 4.2% in the plasma group (p = 0.04).

Table 2. Postoperative Infection and Wound Healing Outcomes

Variable	Category	Control (n = 120)	Plasma (n = 120)	Total (n = 240)	p-value
Surgical Site Infection	Yes	24 (20.0%)	11 (9.2%)	35 (14.6%)	0.02
Surgical Site Infection	No	96 (80.0%)	109 (90.8%)	205 (85.4%)	0.02
Wound Healing Score (Day 7)	Mean ± SD	6.1 ± 1.3	7.4 ± 1.2	6.8 ± 1.4	<0.001
Wound Dehiscence	Yes	13 (10.8%)	5 (4.2%)	18 (7.5%)	0.04
Need for Secondary Suturing	Yes	9 (7.5%)	3 (2.5%)	12 (5.0%)	0.05

Time to first flatus decreased from 3.2 ± 0.9 days in controls to 2.4 ± 0.8 days (p < 0.001), and time to first stool reduced from 4.1 ± 1.2 days to 3.2 ± 1.0 days (p < 0.001). Postoperative pain was consistently lower in the plasma group, with VAS scores at 24 hours of 5.9 ± 1.3 versus 6.8 ± 1.4, at 48 hours of 4.8 ± 1.1 versus 5.6 ± 1.2, and at 72 hours of 3.9 ± 1.0 versus 4.7 ± 1.1 (all p < 0.001).

Table 3. Gastrointestinal Recovery and Pain Outcomes

Variable	Category	Control (n = 120)	Plasma (n = 120)	Total (n = 240)	p-value
Time to First Flatus (days)	Mean ± SD	3.2 ± 0.9	2.4 ± 0.8	2.8 ± 0.9	<0.001
Time to First Stool (days)	Mean ± SD	4.1 ± 1.2	3.2 ± 1.0	3.6 ± 1.2	<0.001

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VAS Pain Score (24h)	Mean ± SD	6.8 ± 1.4	5.9 ± 1.3	6.4 ± 1.4	<0.001
VAS Pain Score (48h)	Mean ± SD	5.6 ± 1.2	4.8 ± 1.1	5.2 ± 1.2	<0.001
VAS Pain Score (72h)	Mean ± SD	4.7 ± 1.1	3.9 ± 1.0	4.3 ± 1.1	<0.001

CRP levels on postoperative day 3 were lower at 49 ± 16 mg/L compared to 64 ± 18 mg/L in controls ($p < 0.001$), and by day 7 decreased to 18 ± 9 mg/L versus 28 ± 11 mg/L ($p < 0.001$). Mean hospital stay was shortened from 8.6 ± 2.3 days in controls to 6.9 ± 2.0 days in the plasma group ($p < 0.001$). ICU requirement was lower in the plasma group (7.5% vs 14.2%), though this difference did not reach statistical significance ($p = 0.09$).

Table 4. Inflammatory Markers and Hospital Course

Variable	Category	Control (n = 120)	Plasma (n = 120)	Total (n = 240)	p-value
CRP Day 3 (mg/L)	Mean ± SD	64 ± 18	49 ± 16	56.5 ± 19	<0.001
CRP Day 7 (mg/L)	Mean ± SD	28 ± 11	18 ± 9	23 ± 12	<0.001
Hospital Stay (days)	Mean ± SD	8.6 ± 2.3	6.9 ± 2.0	7.8 ± 2.3	<0.001
ICU Requirement	Yes	17 (14.2%)	9 (7.5%)	26 (10.8%)	0.09

Overall complication rates were significantly lower in the plasma group, with any postoperative complication occurring in 31.7% of controls versus 15.8% of plasma-treated patients ($p = 0.004$). Reintervention was required in 11.7% of controls compared to 5.0% in the plasma group ($p = 0.05$). Thirty-day readmission rates were reduced from 13.3% in controls to 5.8% with plasma therapy ($p = 0.04$).

Table 5. Complications, Reintervention, and Readmission

Variable	Category	Control (n = 120)	Plasma (n = 120)	Total (n = 240)	p-value
Any Postoperative Complication	Yes	38 (31.7%)	19 (15.8%)	57 (23.8%)	0.004
Reintervention Required	Yes	14 (11.7%)	6 (5.0%)	20 (8.3%)	0.05
30-Day Readmission	Yes	16 (13.3%)	7 (5.8%)	23 (9.6%)	0.04
30-Day Readmission	No	104 (86.7%)	113 (94.2%)	217 (90.4%)	0.04

DISCUSSION

The current study shows that the application of adjunctive non-thermal plasma is a significant improvement of the postoperative recovery after abdominal surgeries in various clinical areas of relevance. There was no significant difference in terms of baseline features in the study, which means that the observed differences can be explained by the intervention and not by the demographic characteristics or even operative factors [17]. There was a significant decrease in surgical site infections (9.2% vs 20.0%), there was also better wound healing scores (7.4 ± 1.2 vs 6.1 ± 1.3) and low wound dehiscence rates (4.2 vs 10.8). These results are consistent with the earlier studies that have established cold plasma to have antimicrobial effects due to the presence of reactive oxygen and nitrogen species coupled with the fact that it enhances fibroblast activation and angiogenesis. Other studies on the effects of plasma-assisted wound care have also demonstrated similar decreases in SSI rates and epithelialization [18]. Gastrointestinal recovery was also speeded up, bowel recovery (first flatus: 2.4 +/- 0.8 vs 3.2 +/- 0.9 days; first stool: 3.2 +/- 1.0 vs 4.1 +/- 1.2 days) was earlier. It was also found that postoperative pain was significantly reduced at all time measurements in the plasma group. According to the previous studies, non-thermal plasma can affect inflammatory mediators and microcirculation and this may be the reason as to why the duration of postoperative ileus and intensity of pain in the current report were lower in the case of non-thermal plasma as opposed to the control group [19].

The inflammatory reaction was also significantly reduced, and the level of the CRP activity was lower on the 3rd and 7th days of the operation (49 ± 16 vs 64 ± 18 mg/L and 18 ± 9 vs 28 ± 11 mg/L, respectively). These biochemical observations are in line with the previous experimental and clinical studies that have shown the modulation of pro-inflammatory cytokines and oxidative balance by plasma induction, which leads to the tightened healing cascade [20]. Notably, these biological and functional advantages were converted into clinical outcomes, such as a decrease in the overall complication rates (15.8% vs 31.7%), the number of reinterventions (5.0 vs 11.7), 30-day readmissions (5.8 vs 13.3), and the number of hospital days (6.9 +2.0 vs 8.6 +2.3). Similar decreases in burden of complications, and length of stay in hospital have been reported in earlier studies that assessed the efficacy of plasma-assisted protocols of surgical recovery [21]. Generally, the results validate the assumption that non-thermal plasma is not only an

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adjunctive antimicrobial but also a multimodal postoperative recovery enhancer. Although promising, further standardization of plasma dosing parameters and larger multicenter studies is needed to establish reproducibility and determine the best clinical guidelines as has been highlighted in the research.

CONCLUSION

It is concluded that the integration of non-thermal plasma into perioperative care for abdominal surgeries significantly enhances postoperative recovery by reducing surgical site infections, accelerating wound healing, attenuating inflammatory response, shortening time to bowel function recovery, decreasing pain scores, and lowering overall complication and readmission rates. These findings suggest that non-thermal plasma functions as a multimodal therapeutic adjunct that not only improves local wound biology but also translates into measurable clinical and healthcare utilization benefits. Further large-scale, standardized studies are warranted to optimize application protocols and confirm long-term safety and reproducibility across diverse surgical settings.

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