Article

Novel Gas-Liquid Drainage Tube for Electrosurgery: Safeguarding Health by Evacuating Toxic Gases and Improving Surgical Field Clarity

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AIM: Surgical smoke generated during electrosurgery contains various toxic substances, including carbon monoxide (CO), hydrogen sulfide (H_2S), formaldehyde (HCHO), total volatile organic compounds (TVOC), and particulate matter 2.5 (PM2.5), which pose a significant health threat to both surgical staff and patients. This study investigates the effectiveness of a novel gas-liquid drainage tube in removing surgical smoke and improving the safety of the surgical environment.

METHODS: A gas detector and an air quality monitor were used to measure the concentrations of CO, carbon dioxide (CO_2), PM2.5, HCHO, TVOC, and H_2S in the rat model during electrosurgery. Animals were divided into two groups (n = 3 each): an experimental group employing a novel gas-liquid drainage tube and a control group using a traditional drainage tube. Measurements were taken at various time points (1, 5, 10, 15, 30, 60, and 120 min) and fixed distances from the surgical site (0, 10, 30, 50, 100, and 150 cm). Additionally, the effectiveness of the drainage tube in maintaining surgical field clarity during the procedure was evaluated using an image subtraction algorithm.

RESULTS: Compared to the control group, the novel gas-liquid drainage tube significantly reduced the concentrations of CO, CO_2, PM2.5, HCHO, TVOC, and H_2S in the experimental group ($p < 0.05$). Furthermore, the drainage tube effectively reduced hazards and cleared smoke, thus improving the clarity of the surgical field.

CONCLUSIONS: This device effectively reduces the concentration of harmful gases and particulate matter generated during electrosurgical procedures. These findings suggest that it may contribute to creating a cleaner, safer surgical environment.

Keywords: gas-liquid drainage tube; toxic gases; electrosurgery; surgical smoke clearance; surgical safety

Introduction

Electrosurgical knives are widely used in surgical procedures to deliver high-frequency electrical currents that heat the electrode tip, producing controlled thermal effects for tissue cutting or coagulation [1,2]. These devices are integral to many procedures, including skin excisions, tumor resections, and vascular hemostasis. During tumor resections, electrosurgical knives enable effective tissue division while minimizing bleeding [3,4]. In dermatologic surgery, they allow for precise excision while simultaneously providing local hemostasis [5]. In vascular procedures, they are used to rapidly coagulate the ends of blood vessels to prevent bleeding [6].

However, electrosurgical knives have notable limitations, particularly the generation of significant surgical smoke. This smoke contains more than 600 hazardous chemical components, active viruses, viable and nonviable particulates, and mutagenic substances [7]. Prolonged exposure poses potential risks, such as chronic toxicity, respiratory irritation, infection transmission, and carbon monoxide-related toxicity [8]. These hazards may have long-term health effects on surgeons and nurses, particularly with persistent or repeated exposure [9,10]. Rapid smoke removal is therefore crucial to mitigate the accumulation of hazards and their potential health risks. Dedicated smoke evacuation systems that provide continuous suction during surgical procedures can reduce particulate matter 2.5 (PM2.5) levels in the operating room [11]. Nevertheless, their high cost and maintenance requirements limit widespread adoption.

Our hospital developed and patented a novel gas-liquid drainage tube in 2020 (Patent No. ZL201920534902.1) [12]. This device significantly improves the structure of traditional drainage systems, aiming to more effectively clear surgical smoke and maintain the visual field during electrosurgeries. By integrating both gas and liquid drainage channels, the tube is suitable for complex surgeries that involve simultaneous smoke generation and fluid accumulation. Compared with traditional drainage tubes, it incurs only a modest increase in cost while offering significantly

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Fig. 1. A schematic diagram of the experimental setup.

better smoke removal. Despite these advantages, its specific efficiency and effectiveness still need to be assessed and validated through further investigations.

In this study, we experimentally evaluated the impact of the gas-liquid drainage tube on air quality during electrosurgery. Specifically, we assessed concentrations of carbon monoxide (CO), hydrogen sulfide (H_2S), carbon dioxide (CO_2), particulate matter 2.5 (PM2.5), formaldehyde (HCHO), and total volatile organic compound (TVOC) to examine whether the surgical device improves surgical smoke management in the operating room.

Materials and Methods

In Vivo Experiments and Animal Ethics

Six male Sprague-Dawley (SD) rats (n = 6; 8-week-old; weighing 250–300 g) were obtained from Hangzhou Medical College, China. All procedures were conducted in accordance with the guidelines for the care and use of laboratory animals and were approved by the Institutional Animal Care and Use Committee (IACUC) of Zhejiang Center of Laboratory Animals (ZJCLA) (Approval No. ZJCLA-IACUC-20010910). Before experiments, rats were housed under a controlled environment (22 ± 2 °C, 55 ± 10% humidity, 12-hour light/dark cycle), with free access to standard chow and water.

Gas-Liquid Drainage Device Setup

An experimental chamber was established to model a laparoscopic operating environment (Fig. 1). The gas-liquid drainage tube (Patent No. ZL201920534902.1) is a smoke evacuation system developed by our hospital in 2020 that improves the traditional drainage tube design [12]. The primary tube connects to the laparoscopic suction line to remove blood, body fluids, secretions, and irrigation effluent from the surgical field. Additionally, a secondary tube connects to the Trocar valve and utilizes the wall-mounted negative pressure suction system to continuously and effectively evacuate electrosurgical smoke.

The experiment was conducted in a polymethyl methacrylate (PMMA) chamber (CY-46, Caiyi Crafts Processing Factory, Guangzhou, China; 30 × 48 × 30 cm). The chamber featured an inlet valve at one end of the long axis, an exhaust valve at the opposite end, and a sealed operating port. An observation window was made on one short axis of the back side, with a background window on the opposite short axis, for clarity evaluations. A removable lid on the top of the chamber allowed placement of experimental tissue samples inside.

Grouping of Rats and Measurement of Parameters

Two study groups of rats were established based on experimental design (n = 3 per group): a control group and an experimental group, to isolate and evaluate the effect of the intervention against a standard baseline. The sample size was sufficient to obtain interpretable data while adhering to the Replacement, Reduction and Refinement (3Rs) principles in animal research. Rats were anesthetized with sodium pentobarbital (80 mg/kg; P3761, Sigma-Aldrich, St. Louis, MO, USA), and hair was removed using a disposable shaver (SL-3013, GoodMax, Wuhan, China). Electrosurgery was performed on the skin and adipose tissue for 15 min to generate surgical smoke within the experimental chamber. The experimental group used the novel gas-liquid drainage

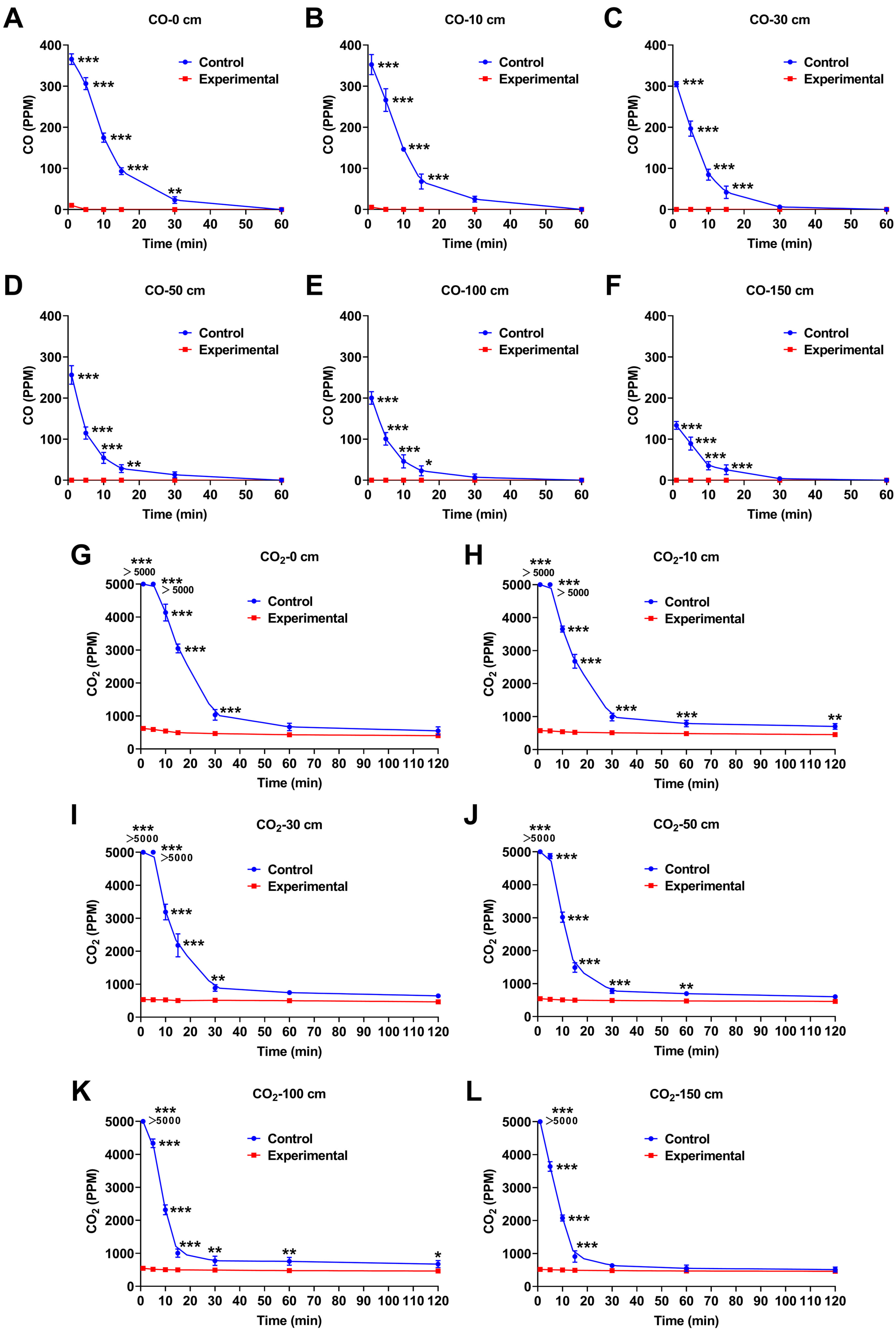

Fig. 2. Effect of the gas-liquid drainage tube on the removal of carbon monoxide (CO) and carbon dioxide (CO_2) generated by the electrosurgical knife. A four-in-one gas detector was used to measure the CO and CO_2 levels in the control and experimental groups during electrosurgery. Measurements were taken at fixed distances of 0 cm (A,G), 10 cm (B,H), 30 cm (C,I), 50 cm (D,J), 100 cm (E,K), and 150 cm (F,L) from the source, at designated time points (1, 5, 10, 15, 30, 60, and 120 min (CO_2)). n = 3 rats per group. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, vs. Control.

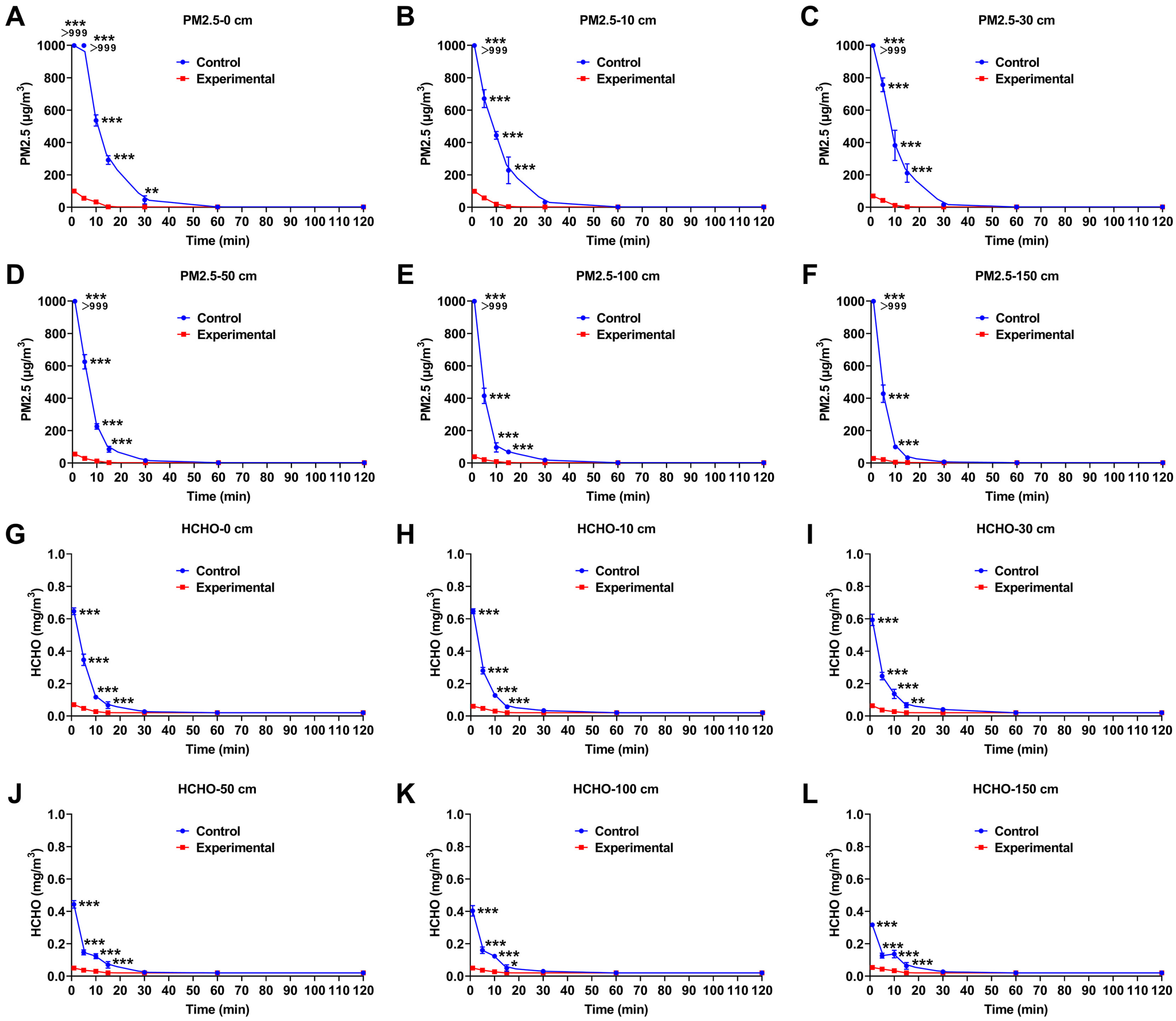

Fig. 3. Effect of the gas-liquid drainage tube on the removal of particulate matter 2.5 (PM2.5) and formaldehyde (HCHO) generated by the electrosurgical knife. An air quality monitor was used to measure the PM2.5 and HCHO levels in the control and experimental groups during electrosurgery. Measurements were taken at fixed distances of 0 cm (A,G), 10 cm (B,H), 30 cm (C,I), 50 cm (D,J), 100 cm (E,K), and 150 cm (F,L) from the source, at designated time points (1, 5, 10, 15, 30, 60, and 120 min). n = 3 rats per group. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, vs. Control.

tube, and the control group used a traditional drainage tube (WPNT-B1-12, Weipu Medical, Changzhou, China).

The start time of electrosurgery was recorded as 0 outside the chamber. At predetermined time points, such as 1, 5, 10, 15, 30, 60 min, and 120 min, and fixed distances from the source (10, 30, 50, 100, and 150 cm), concentrations of CO, H_2S, CO_2, PM2.5, HCHO, and TVOC were measured. CO and H_2S levels were quantified using a four-in-one gas detector (Nanyang Explosion-Proof Electrical Research Institute, Nanyang, China). CO_2, PM2.5, HCHO, and TVOC were evaluated with a BR-Smart126 air quality tester (Browantong, Shenzhen, China). After measurements, rats were euthanized by cervical dislocation.

Image Subtraction Algorithm

During electrosurgery, background images of the chamber were captured every 1 min using a Nikon camera (D850, Nikon, Sendai, Japan). The image subtraction algorithm was then applied for evaluation [13]. Visual clarity of the simulated surgical field was quantified by measuring the spatial resolution in Line Widths per Picture Height (LW/PH). An ISO 12233 resolution test chart was placed in the chamber as the surgical background. Images were captured under three conditions: a baseline image without smoke and at predetermined time points after smoke generation, using either the experimental or the control drainage setup. All images were analyzed in Imatest version 5.2 (Imatest LLC, Boulder, CO, USA) to calculate LW/PH values. Higher LW/PH values indicate greater clarity and higher resolving power.

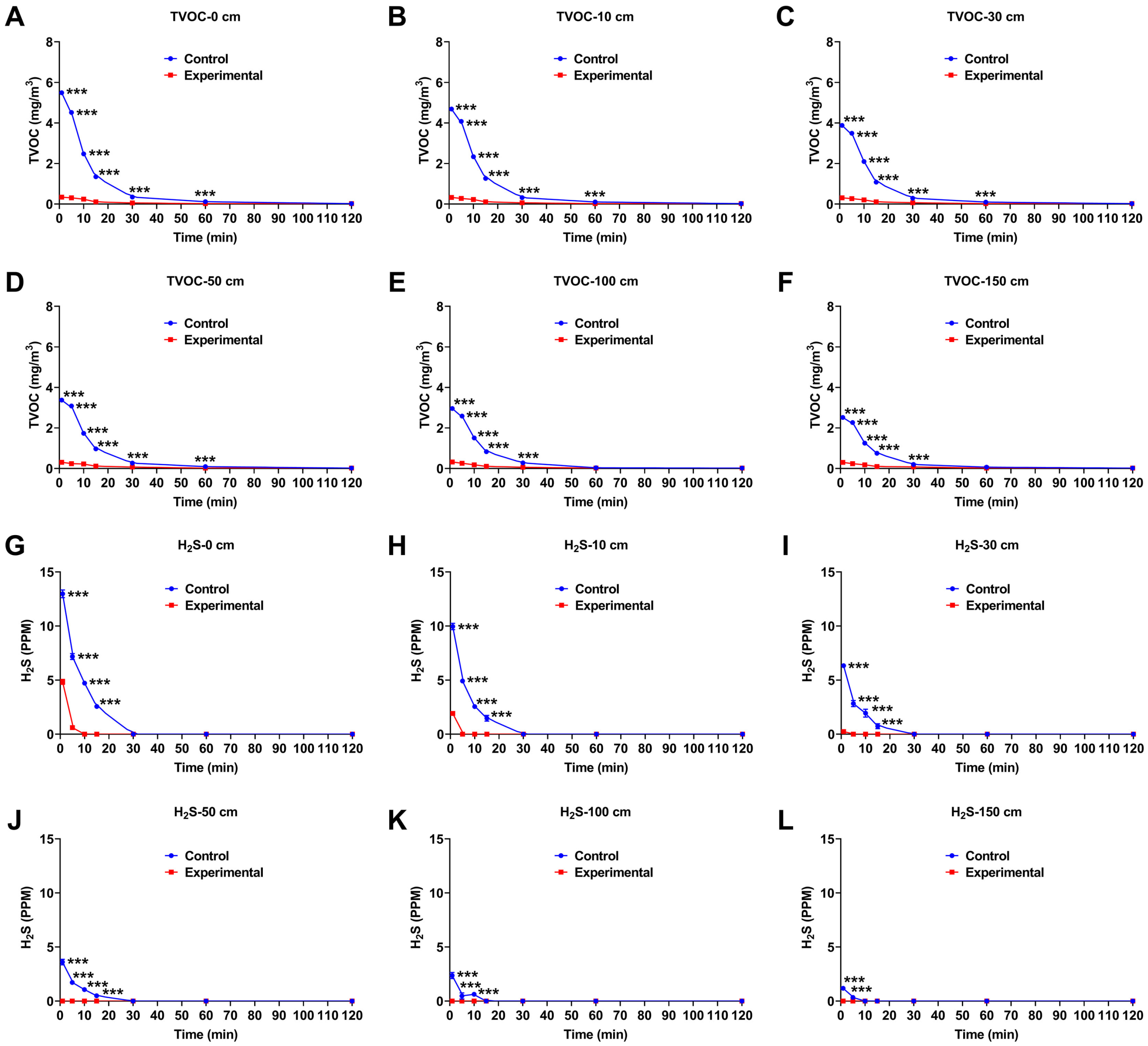

Fig. 4. Effect of the gas-liquid drainage tube on the removal of total volatile organic compound (TVOC) and hydrogen sulfide (H_2S) generated by the electrosurgical knife. An air quality monitor was used to assess the TVOC and H_2S levels in the control and experimental groups during electrosurgery. Measurements were taken at fixed distances of 0 cm (A,G), 10 cm (B,H), 30 cm (C,I), 50 cm (D,J), 100 cm (E,K), and 150 cm (F,L) from the source, at designated time points (1, 5, 10, 15, 30, 60, and 120 min). n = 3 rats per group. ***$p < 0.001$, vs. Control.

Statistical Analysis

Statistical analysis was performed using GraphPad Prism 8.0 (GraphPad Software LLC, San Diego, CA, USA). Data were presented as means ± standard deviation. For Figs. 2,3,4, a two-way analysis of variance (ANOVA) was applied, followed by a Bonferroni-adjusted post-hoc comparison. Assumptions were verified using the Shapiro-Wilk test for normality and Levene's test for homogeneity of variance, both confirmed normality and homogeneity of variance. A p-value of <0.05 was considered statistically significant. The Type I error rate (α) was set to 0.05, with Bonferroni correction applied to prevent false inflation.

Results

Gas-Liquid Drainage Tube Clears CO and CO_2 Produced During Electrosurgery

At 0 cm, the experimental group exhibited a reduction in CO levels compared to the control group at all time points from 1 to 30 minutes (Fig. 2A, $p < 0.01$). At 10, 30, 50, 100, and 150 cm, CO levels were also reduced across 1 to 15 minutes (Fig. 2B–F, $p < 0.05$).

At 0 and 30 cm, the experimental group showed reduced CO_2 levels across all time points from 1 to 30 minutes compared to the control group (Fig. 2G,I, $p < 0.01$). At 10 and 100 cm, the reduction in CO_2 levels persisted through 120 minutes (Fig. 2H,K, $p < 0.05$). At 50 cm, CO_2 levels were

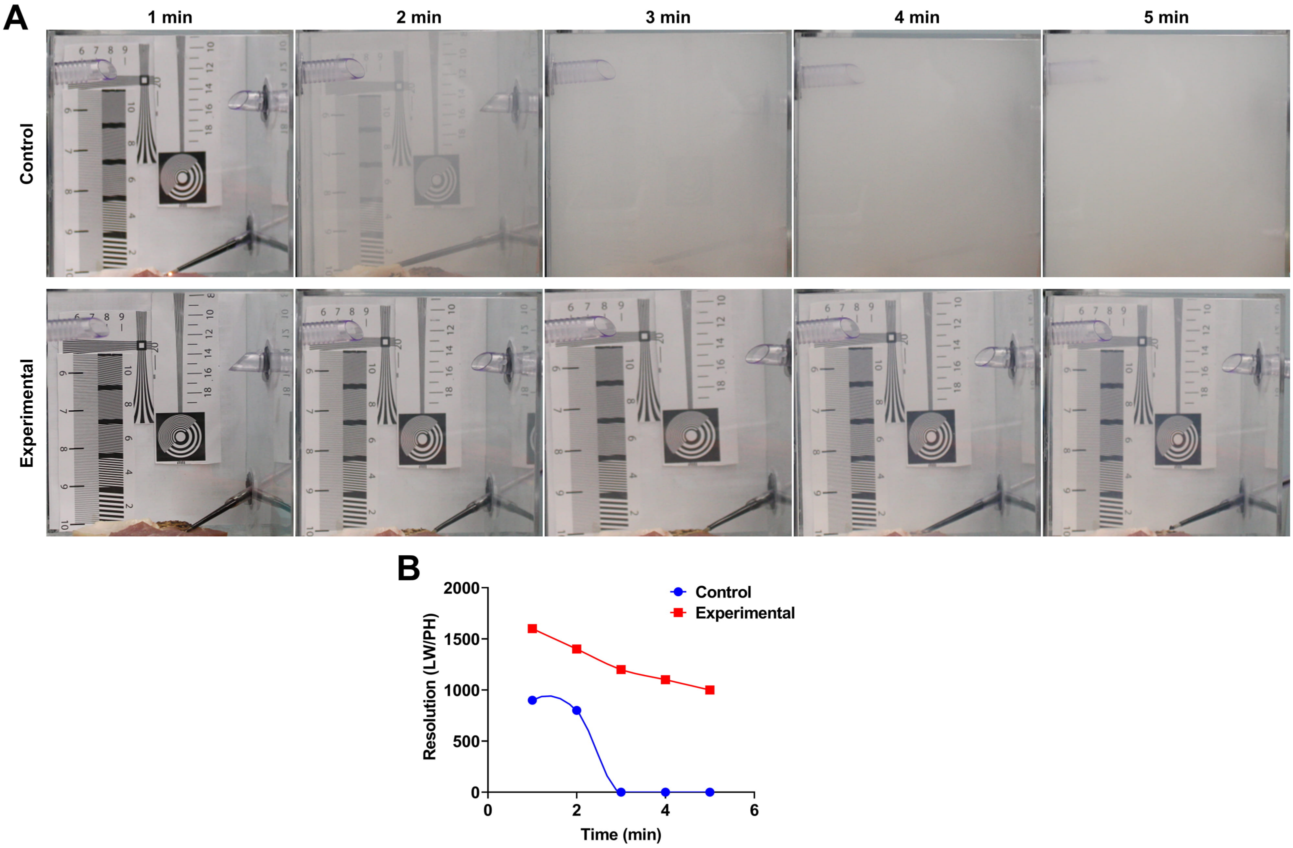

Fig. 5. Effect of the gas-liquid drainage tube on the clearance of smoke produced by the electrosurgical knife. (A) The smoke clearance recorded in the control and experimental groups during electrosurgery at 1, 2, 3, 4, and 5 min intervals. (B) An image subtraction algorithm was used to assess the smoke clearance in the control and experimental groups during electrosurgery.

reduced between 1 and 60 minutes (Fig. 2J, $p < 0.01$). At 150 cm, a decrease was significantly evident at 1–15 minutes (Fig. 2L, $p < 0.001$).

Gas-Liquid Drainage Tube Clears PM2.5, HCHO, TVOC, H_2S, and Smoke Produced During Electrosurgery

At 0 cm, the experimental group showed a reduction in PM2.5 levels at each time point from 1 to 30 minutes compared to the control group (Fig. 3A, $p < 0.01$). At 10, 30, 50 and 100 cm, PM2.5 was significantly decreased within 1–15 minutes (Fig. 3B–E, $p < 0.001$), and at 150 cm within 1–10 minutes (Fig. 3F, $p < 0.001$). The experimental group had lower HCHO levels at 0, 10, 30, 50, 100, and 150 cm between 1 and 15 minutes (Fig. 3G–L, $p < 0.05$). TVOC levels decreased at 0, 10, 30, and 50 cm over 1–60 minutes (Fig. 4A–D, $p < 0.001$), and reduced significantly at 100 and 150 cm across 1–30 minutes (Fig. 4E,F, $p < 0.001$). H_2S was lower at 0, 10, 30, and 50 cm from 1 to 15 minutes (Fig. 4G–J, $p < 0.001$), at 100 cm during 1 to 10 minutes (Fig. 4K, $p < 0.001$), and at 150 cm across 1–5 minutes (Fig. 4L, $p < 0.001$). Image-based evaluations confirmed better smoke clearance in the experimental group across all measured time points than in the control group (Fig. 5A,B).

Discussion

Surgical smoke contains various toxic substances, including CO, H_2S, HCHO, and TVOC, which pose significant health risks to the operator and potentially to patients. CO is a colorless, odorless gas that binds hemoglobin and reduces oxygen-carrying capacity, leading to hypoxic injury [14,15]. H_2S is a highly toxic gas; exposure can cause headaches, nausea, and at high levels, respiratory arrest [16,17]. HCHO is a known carcinogen that irritates the upper respiratory tract and eyes, with long-term exposure linked to increased cancer risk [18,19]. TVOC is a mixture of toxic, volatile compounds that, when inhaled over prolonged periods, can induce headaches, nausea, and airway inflammation [20,21]. These hazards pose significant health risks to surgical staff and may also affect patients in the operating room [22,23].

In this study, we found that the gas-liquid drainage tube significantly reduced the levels of toxic substances, such as CO, H_2S, HCHO, and TVOC, generated during electrosurgery, thereby reducing the risks of olfactory fatigue and respiratory irritation and ensuring a safer occupational environment. These findings highlight the significance of active smoke evacuation not only for protecting healthcare workers and medical personnel but also for substantially reducing postoperative complications and supporting better patient recovery.

Previous studies have revealed that surgical smoke contains fine particles, with particle sizes ranging from 10 nm to 1 µm and an average diameter of approximately 70 nm [24,25]. Particles smaller than 1.1 µm account for about 77% of the total [25]. However, standard surgical masks do not effectively filter particles smaller than 5 µm, allowing most particles to be inhaled and deposited in the alveoli, where they can cause long-term harm [26]. Although N95 masks can filter 95% of these particles, prolonged wear is associated with pressure injuries on the nasal bridge, cheeks, and ears [27].

In this study, the gas-liquid drainage tube effectively reduced PM2.5 concentration during electrosurgery. Surgical smoke produced during electrosurgery significantly affects the visualization of the surgical field [28]. The resulting white or grayish-white smoke can obscure fine anatomical details as its concentration increases, making it challenging in the confined surgical field [29]. This effect is even more pronounced in the closed environment of laparoscopic surgeries. When smoke accumulates, surgeons need additional time to distinguish anatomical structures, and reduced visibility may require waiting for the smoke to dissipate. Applying a 5-point Likert scale for surgical field clarity, the median smoke level during total hysterectomy reached 3.9, significantly hindering tissue recognition [30]. In this study, continuous evacuation using the gas-liquid drainage tube effectively cleared smoke produced during electrosurgery, maintaining clarity of the surgical view. By continuously suctioning and clearing surgical smoke, the drainage tube significantly reduced the accumulation of harmful products in the air, thereby providing a safer surgical environment for both the surgical staff and patients.

We acknowledge some limitations to this study. First, the study focused solely on smoke evacuation efficiency during electrosurgery and did not evaluate the drainage tube's impact on other potential environmental contaminants, including viruses or viable cells. Second, although the animal model provided valuable insights into the efficacy of the gas-liquid drainage tube, its generalizability to human surgical settings is uncertain. Prospective clinical trials are needed to validate these findings in human patients.

Conclusions

The compelling evidence presented in this study supports the gas-liquid drainage tube as a promising solution to surgical smoke in operating rooms. By effectively evacuating toxic gases and particulate matter, its clinical implementation could enhance occupational safety standards for surgical teams. Widespread adoption of this technology would not only mitigate long-term health risks for surgeons and nurses but also maintain surgical field clarity, thereby improving surgical precision. Integrating this system into routine practice represents a feasible step toward protecting the healthcare professionals and improving the standard of patient care.

Availability of Data and Materials

The data used and analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

KH: Conceptualization, Formal analysis, Validation, Funding acquisition. LLW: Conceptualization, Formal analysis, Methodology. XWL: Data curation, Formal analysis, Validation. KZ: Data curation, Methodology, Visualization, Supervision. All authors drafted the manuscript. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

All procedures were conducted in accordance with the guidelines for the care and use of laboratory animals and were approved by the Institutional Animal Care and Use Committee (IACUC) of Zhejiang Center of Laboratory Animals (ZJCLA) (Approval No. ZJCLA-IACUC-20010910). The sample size was sufficient to obtain interpretable data while adhering to the 3Rs principles in animal research.

Acknowledgment

Not applicable.

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Conflict of Interest

Kui Hu is the inventor of the novel gas-liquid drainage tube patented under ZL201920534902.1 at this research institute. Other authors declare that there is no conflict of interest.

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