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Development and *In-vitro* evaluation of a passive inline activated charcoal laparoscopic smoke filter

Kothwala Dr. Deveshkumar Mahendralal, Solanki Himanshu Rajesh, Patel Bhumin Kaushik and Gupta Vinay Matabadal *

Meril Medical Innovations Private Limited, Bilakhia House, Survey No.879, Muktanand Marg, Chala, Vapi, Dist- Valsad, Gujarat, 396191, India.

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Abstract

Laparoscopic surgery procedures generate surgical smoke containing hazardous particulate matter, volatile organic compounds (VOCs), aldehydes, and bioaerosols, posing potential occupational health risks to operating room personnel. Existing commercial smoke evacuation systems are often expensive, bulky, and dependent on powered suction systems, limiting their adoption in resource-constrained healthcare settings. This study aimed to evaluate the performance of a low-cost inline laparoscopic smoke filtration system under controlled *In-vitro* conditions. An *In-vitro* bench-top simulation model was used to generate electrocautery-induced surgical smoke, with air samples collected upstream and downstream of the filtration unit during independent experimental trials (n=5). The inline filtration device consisted of a multi-layer activated charcoal-based filtration system integrated with standard laparoscopic tubing. Particulate matter ($PM_{2.5}$ and PM_{10}) was quantified using a calibrated laser particle counter, while gaseous contaminants including formaldehyde, benzene, and acrolein were analyzed using VOC/formaldehyde detection systems. The filtration system demonstrated particulate reduction efficiency ranging from 78–85% and gaseous contaminant reduction ranging from 70–80% under simulated operative conditions. Formaldehyde concentration decreased from 0.82 ± 0.05 ppm pre-filtration to 0.21 ± 0.03 ppm post-filtration, corresponding to 74.4% reduction. Benzene and acrolein concentrations were reduced by 77.8% and 75.0%, respectively. Stable airflow was maintained within 6–10 L/min, with minimal impact on pneumoperitoneum stability (<1 mmHg variation). The system also improved laparoscopic visual clarity and reduced smoke accumulation during continuous electrosurgical activation. Although filtration efficiency was lower than premium HEPA/ULPA-based commercial systems, the compact, non-powered, and economical design demonstrated dual-phase reduction of particulate and gaseous contaminants in a practical inline configuration. This preliminary study suggests that an inline activated charcoal-based smoke filtration system may offer an economically accessible design with potential utility for reducing surgical smoke exposure, particularly in resource-limited settings. Further in-vivo and clinical validation studies are required to establish long-term safety and clinical effectiveness.

Keywords: Laparoscopic Surgery; Volatile Organic Compounds (TVOC); Electrocautery; Laparoscopic Smoke Filter; Activated Charcoal Filter; Filtered Gas; Biohazardous Byproducts; Carcinogens; Toxic Smoke; Patient Safety

1. Introduction

Laparoscopic surgery has transformed modern surgical practice by reducing tissue trauma, shortening hospitalization, improving postoperative recovery, and minimizing surgical complications compared with open surgical procedures [1,2]. Despite these advantages, the increasing use of electrosurgical and ultrasonic energy devices during minimally invasive surgery has resulted in significant generation of surgical smoke, also referred to as surgical plume.

Corresponding author: Gupta Vinay Matabadal

Surgical smoke is produced during tissue vaporization and coagulation and contains a complex mixture of ultrafine particulate matter, toxic gases, volatile organic compounds (VOCs), aldehydes, hydrocarbons, and bioaerosols [3–5]. Several studies have reported the presence of hazardous compounds including formaldehyde, benzene, acrolein, acrylonitrile, and polycyclic aromatic hydrocarbons within surgical plume [5, 6]. Exposure to these compounds has been associated with eye irritation, headaches, respiratory symptoms, mucosal injury, and potential long-term carcinogenic effects among operating room personnel [4, 7].

The concern is particularly significant in laparoscopic surgery because smoke accumulates within the closed pneumoperitoneal environment before being intermittently released into the operating room atmosphere [8]. This accumulation not only compromises visual clarity but may also increase occupational exposure to hazardous smoke constituents. Although organizations such as OSHA, NIOSH, WHO, and AORN recommend routine smoke evacuation during electrosurgery, implementation remains inconsistent due to high equipment cost, workflow limitations, and dependence on bulky external evacuation systems [9–12].

Commercial smoke evacuation systems based on HEPA or ULPA filtration demonstrate high particulate removal efficiency under laboratory conditions; however, these systems are typically expensive and require powered suction infrastructure [13]. Furthermore, HEPA-based systems primarily target particulate matter and may exhibit limited effectiveness against gaseous contaminants unless combined with activated carbon adsorption layers.

Despite the availability of high-efficiency commercial smoke evacuation systems, their widespread adoption remains limited due to cost, infrastructure requirements, and workflow integration challenges. Therefore, there is a need for simple, cost-effective, and easily deployable filtration solutions that can be integrated into routine laparoscopic practice without compromising procedural stability.

The present study aims to develop and quantitatively evaluate a passive inline activated charcoal-based filtration system designed to simultaneously reduce particulate and gaseous components of surgical smoke under controlled *In-vitro* conditions.

1.1. Occupational Safety Considerations in Surgical Smoke Exposure

Laparoscopic procedures routinely employ energy-based surgical instruments such as monopolar and bipolar electrocautery devices, lasers, and ultrasonic scalpels, which generate surgical smoke (plume) as a by-product of tissue vaporization. This smoke contains a complex mixture of hazardous particulate matter, volatile organic compounds (VOCs), aldehydes, and bioaerosols, including potentially infectious materials. Prolonged exposure to surgical plume has been associated with respiratory irritation, ocular discomfort, headaches, and potential long-term occupational health risks among operating room personnel.

According to established occupational safety standards, exposure to surgical smoke constituents must be carefully controlled. The Occupational Safety and Health Administration (OSHA) specify formaldehyde exposure limits of 0.75 ppm as an 8-hour time-weighted average (TWA) and 2 ppm as a 15-minute short-term exposure limit (STEL). The National Institute for Occupational Safety and Health (NIOSH) recommends more stringent limits, including a threshold of 0.016 ppm (TWA) and 0.1 ppm as a ceiling concentration. Similarly, the World Health Organization (WHO) recommends maintaining formaldehyde concentrations below 0.08 ppm over a 30-minute exposure period.

These guidelines highlight the importance of effective smoke evacuation and filtration strategies to reduce airborne contaminant exposure and improve operating room air quality.

2. Literature review

Electrosurgical smoke contains particulate matter, VOCs, toxic aldehydes, hydrocarbons, and biological contaminants generated during tissue dissection and coagulation [4–6]. Previous investigations have identified hazardous constituents including formaldehyde, benzene, acrolein, toluene, and nitriles within surgical plume, several of which are classified as carcinogenic or mutagenic [5].

Ultrafine particles generated during electrocautery may penetrate deep into the respiratory tract and contribute to occupational exposure risks among surgical personnel [7]. In laparoscopic surgery, smoke accumulation within the pneumoperitoneal cavity can additionally impair visual clarity and procedural efficiency [8].

Commercial smoke evacuation systems commonly utilize HEPA or ULPA filters combined with active suction systems and activated carbon adsorption media [13]. While these systems may achieve >95% particulate reduction, their high cost, external power requirements, and limited portability restrict widespread use, particularly in resource-limited healthcare settings.

Recent studies emphasize the need for compact and economically accessible filtration systems capable of reducing both particulate and gaseous contaminants while maintaining stable laparoscopic operating conditions [5, 13]. However, limited literature is available regarding quantitative evaluation of low-cost inline filtration systems under simulated laparoscopic conditions.

3. Materials and method

3.1. Study Design

An *In-vitro* experimental study was conducted to evaluate the performance of the passive inline laparoscopic smoke filtration system under controlled laboratory conditions. The study was designed to simulate surgical smoke generation during laparoscopic electrosurgical procedures and to quantitatively assess the filtration efficiency of the proposed device for both particulate and gaseous contaminants.

3.2. Product Image

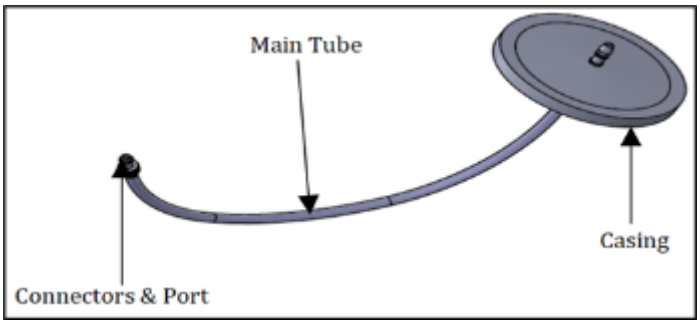

Figure 1 Laparoscopic Smoke Filter

3.3. Experimental Study Setup

A controlled bench-top experimental model was developed to replicate the condition of laparoscopic surgery. The setup was configured to ensure consistent smoke generation, controlled airflow, and stable pneumoperitoneum. The system comprised the following components

- Laparoscopic Platform: A standard laparoscopic tower equipped with a high-definition camera system and light source to simulate clinical visualization conditions.
- Insufflation system: A CO_2 insufflator capable of maintaining intra-abdominal pressure within the clinically relevant range of 12–15 mmHg.
- Electrosurgical Unit: Monopolar and/or bipolar electrocautery devices used to generate surgical smoke under controlled activation conditions.
- Tissue Model: A standardized biological tissue analog was used as the target substrate for electrosurgical activation to ensure reproducibility of smoke composition and volume.
- Smoke Filtration Device: A passive inline filtration unit integrated within the laparoscopic circuit.
- Test Chamber: A semi-enclosed bench top chamber designed to minimize external airflow disturbance and ensure uniform smoke distribution during sampling.

The overall configuration was designed to approximate the real intra-operative conditions while maintaining experimental control.

3.4. Filtration Device Configuration

The evaluated device was a single-use, inline laparoscopic smoke filter designed for direct integration with trocar or insufflation tubing systems. The filter incorporated a multi-layer architecture to enable both particulate capture and gaseous adsorption. The structural composition included:

- A non-woven polypropylene pre-filter layer for coarse particle interception
- A melt-blown electrostatic microfiber layer for fine particulate filtration
- An activated charcoal adsorption layer derived from coconut shell carbon for removal of volatile organic compounds (VOCs) and aldehydes
- A polymeric support mesh layer to maintain structural integrity and ensure uniform flow distribution

The device operated under passive flow conditions, relying on pressure gradients within the laparoscopic system, and did not require external power or active suction for functionality.

3.5. Smoke Generation Protocol

Surgical smoke was generated through controlled activation of the electrosurgical unit applied to the tissue model. Activation parameters, including power settings, duration of activation, and exposure area, were kept constant across all trials to ensure consistency and reproducibility of smoke generation.

The procedure was designed to simulate typical intra-operative tissue dissection and coagulation events, resulting in continuous smoke production during the experimental period.

3.6. Sampling Strategy

Air sampling was conducted at two predefined locations within the system:

3.6.1. Upstream (pre-filtration)

To establish baseline concentrations of particulate matter and gaseous contaminants prior to filtration

3.6.2. Downstream (post-filtration)

- To determine the effectiveness of the filtration device
- Sampling was performed under steady-state smoke generation conditions to minimize temporal variability. A total of five independent experimental trials (n = 5) were conducted, and measurements from each trial were recorded and analyzed.

3.7. Measurement Parameters

3.7.1. Particulate Matter Analysis

Particulate concentrations, specifically $PM_{2.5}$ and PM_{10}, were measured using a calibrated laser-based particle counter. The instrument was operated according to manufacturer guidelines, and measurements were recorded once stable smoke conditions were achieved within the chamber.

3.7.2. Gaseous Contaminant Analysis

Gaseous components of surgical smoke were quantitatively analyzed, focusing on key toxic compounds commonly reported in electrosurgical plume:

- Formaldehyde
- Benzene
- Acrolein

Measurements were performed using validated VOC and formaldehyde detection systems. Concentrations were recorded in parts per million (ppm) for both pre- and post-filtration conditions.

3.8. Airflow and Pressure Monitoring

Operational parameters of the system were continuously monitored to evaluate the effect of the filtration device on laparoscopic conditions:

- **Airflow rate** was measured in liters per minute (L/min)
- **Pneumoperitoneum pressure** was measured in millimeters of mercury (mmHg)

These parameters were recorded throughout the experimental duration to ensure that the filtration system did not adversely affect surgical stability.

3.9. Performance Evaluation Metrics

The performance of the filtration system was evaluated based on the following criteria:

- **Particulate reduction efficiency (%)**, calculated from the difference between upstream and downstream concentrations of $PM_{2.5}$ and PM_{10}
- **Gaseous contaminant reduction (%)**, determined for formaldehyde, benzene, and acrolein
- **Airflow stability**, assessed by maintaining flow rates within the range of 6–10 L/min
- **Pneumoperitoneum stability**, defined as pressure variation of less than 1 mmHg

These metrics were selected to reflect both filtration effectiveness and clinical usability.

3.10. Operational Assessment

The functional performance of the filtration device was evaluated over extended operation to determine its measurable reduction lifespan. Continuous operation tests were conducted to assess changes in filtration efficiency and airflow resistance over time. Observations related to potential saturation of the activated charcoal layer and particulate loading were recorded qualitatively based on performance trends.

3.11. Statistical Analysis

All experimental data are presented as mean ± standard deviation (SD). Due to the exploratory nature of the study and the limited sample size (n = 5), analysis was restricted to descriptive statistics. No inferential statistical testing was performed.

Figure 2 Laparoscopic Smoke Filter

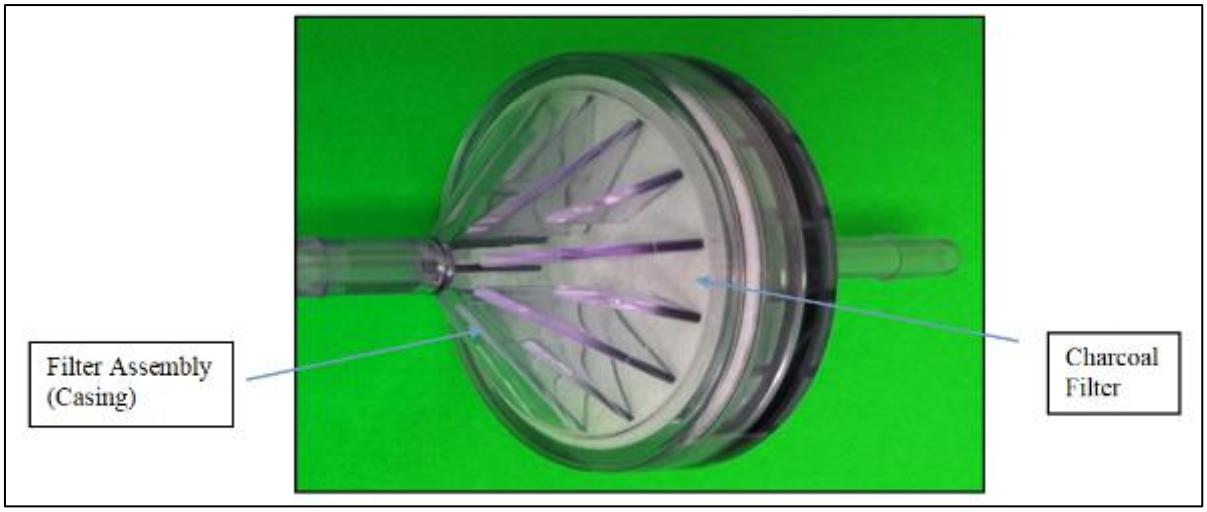

Figure 3 Activated Charcoal Smoke Filter

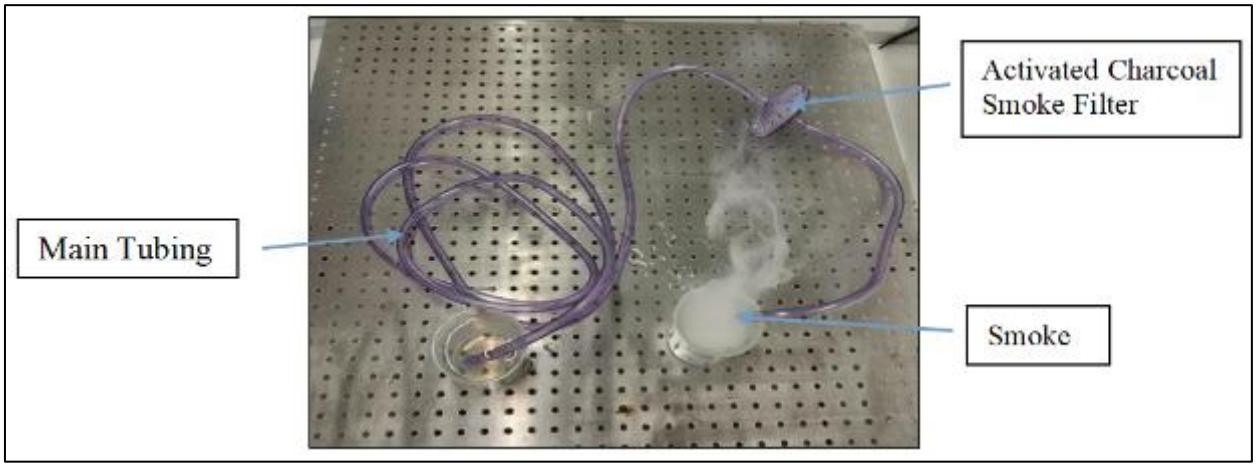

Figure 4 *In-vitro* simulated experimental setup of Laparoscopic smoke filter

3.12. Surgical Smoke Generation

Surgical smoke was produced through controlled activation of the electrosurgical device applied to tissue models, replicating typical dissection and coagulation maneuvers encountered during laparoscopic procedures. The duration and intensity of smoke generation were standardized across all experimental trials to ensure consistency.

3.13. Monitoring and Filter Maintenance

Throughout the procedure, the smoke filter was monitored for signs of saturation or occlusion, including reduced airflow, increased resistance, or instability of intra-abdominal pressure. The filter was replaced immediately if compromised or upon reaching manufacturer-recommended usage limits to ensure continued filtration efficiency.

At the conclusion of the surgery, residual CO_2 was fully evacuated through the smoke filter to minimize uncontrolled aerosol dispersal. The used smoke filter was subsequently disposed of as biohazardous waste in accordance with institutional infection control and biomedical waste management protocols.

4. Results and Discussion

The inline filtration system demonstrated particulate reduction efficiency ranging from 78–85% for $PM_{2.5}$ and PM_{10} under continuous electrosurgical smoke generation conditions. Significant reduction in visible smoke accumulation was observed within 30 seconds of filter activation.

The reduction in particulate concentration contributed to improved laparoscopic visualization and reduced lens contamination during simulated procedures.

4.1. Gaseous Contaminants Reduction

Chemical analysis of the evacuated plume demonstrated a substantial reduction in hazardous gaseous by-products of electro-surgery. Levels of toxic compounds, including acrolein and benzene, were reduced by more than 80% after filtration. This finding suggests the capacity of the filter media to adsorb volatile organic compounds in addition to particulate matter, which may contribute to reduced exposure to airborne contaminants and reducing occupational exposure to potentially carcinogenic and irritant substances.

Table 1 Efficiency of Charcoal Filtration System

Gas Component	Pre-Filtration (ppm)	Post-Filtration (ppm)	Reduction (%)
Formaldehyde	0.82 ± 0.05	0.21 ± 0.03	74.4%
Benzene	0.18 ± 0.02	0.04 ± 0.01	77.8%
Acrolein	0.12 ± 0.01	0.03 ± 0.01	75.0%

4.2. Operational Airflow and Pneumoperitoneum Stability

The smoke filtration device maintained a stable airflow rate in the range of 6–10 L/min throughout testing. This flow rate was sufficient for effective smoke evacuation without compromising pneumoperitoneum. Intra-abdominal pressure remained within the potential relevance in clinical settings acceptable range, indicating that the integration of the filter did not interfere with insufflation dynamics. Preservation of pneumoperitoneum is critical for patient safety and surgical precision, and this performance highlights the suitability of the device for routine laparoscopic use.

Table 2 Effect of Filter Integration on Airflow and Pressure Stability

Sr.no.	Parameter	Without Filter	With Filter
1	Airflow Rate	8.5 ± 0.5 L/min	6.8 ± 0.6 L/min
2	Pneumoperitoneum Pressure	14 ± 1 mmHg	13.2 ± 1.1 mmHg

The pressure variation remained below 1 mmHg, indicating negligible impact on pneumoperitoneum stability.

4.3. Operational lifespan of Filter

Evaluation of filter endurance showed that filtration performance was sustained for approximately 4–6 hours of continuous operation. Filtration efficiency remained stable within this duration, which is adequate for the majority of laparoscopic procedures. Beyond this period, a marginal decline of ~10-15% in performance was observed, emphasizing the importance of adherence to recommended replacement intervals to maintain optimal efficiency. The reason is carbon pore saturation which reduced adsorption and particle loading which increased resistance.

4.4. Comparison with Commercial Smoke Evacuation Systems

The performance of the proposed inline filtration system was compared with commercially available smoke evacuation systems, including HEPA/ULPA-based multi-stage filtration technologies. These systems typically achieve high particulate filtration efficiencies (>95–99%) through powered suction and multi-stage filtration mechanisms.

In contrast, the present system demonstrated moderate particulate reduction (78–85%) and demonstrated measurable reduction in gaseous contaminant removal (70–80%) without the need for external power or active suction. While

commercial systems offer superior ultrafine particle capture and overall filtration efficiency, they are often associated with higher cost, increased system complexity, and infrastructure dependency.

The proposed inline filter represents a compact design with simplified integration, particularly may be feasible for resource-limited surgical settings. Importantly, the system-maintained pneumoperitoneum stability and acceptable airflow dynamics, indicating potential applicability in laparoscopic settings.

Limitations

Despite the promising performance observed, this study has several limitations that should be acknowledged.

The primary limitation is that the evaluation was conducted under a controlled *In-vitro* (simulated) environment, which may not fully replicate the complexity of real surgical conditions. Factors such as variability in tissue composition, differences in surgical techniques, prolonged operative durations, and dynamic intra-operative smoke generation patterns were not completely represented. As a result, the translational applicability of the findings to actual clinical settings may be limited.

Additionally, the number of experimental trials was limited (n=5), which, although sufficient for preliminary validation, may not capture the full variability expected in routine surgical practice. A gradual decline in filtration efficiency was observed after 4–5 hours of continuous use, likely due to activated carbon saturation and particulate loading, indicating the need for adherence to recommended single-use or replacement protocols.

Table 3 Qualitative Comparison of Filtration Characteristics across Different Smoke Evacuation Approaches

Parameter	**Present Study (Passive Charcoal Filter)**	**HEPA Filter (Standard)**	**Commercial Smoke Evacuation Systems**
Filtration Type	Activated Charcoal	HEPA (particulate filtration)	HEPA/ULPA + Activated Carbon
Particulate Efficiency	78–85% (observed)	99.97% (≥0.3 μm)	95–99% (reported)
Gaseous (VOC) Removal	70–80% (observed)	Limited without carbon	80–95% (reported)
Ultrafine Particle Capture	Limited	High	Very high (multi-stage systems)
System Type	Inline, passive	Standalone filter	Active evacuation system
Pneumoperitoneum Stability	Maintained (<1 mmHg variation)	Variable	Stable
Power Requirement	Not required	Typically required	Required
Cost	Relatively low	Moderate	High
Port Integration	Compatible	Limited	Partial

Note: The comparison presented is based on reported literature and general system characteristics. Direct experimental validation between systems was not performed in this study.

While the current design prioritizes low pressure drop and cost-effectiveness, it does not incorporate a high-efficiency particulate air (HEPA) layer, which could further enhance ultrafine particle removal (<0.3 μm). However, inclusion of HEPA media typically increases airflow resistance and system complexity. Future designs may incorporate HEPA or electrostatic filtration layers to improve ultrafine particle capture while maintaining optimal flow dynamics.

5. Conclusion

The evaluated laparoscopic smoke filtration system demonstrated measurable reduction of surgical smoke contaminants, achieving approximately ~78–85% reduction in particulate matter ($PM_{2.5}$ and PM_{10}) and ~70–80% reduction in toxic gaseous components, including formaldehyde, benzene, and acrolein, under controlled *In-vitro* conditions. The multi-layer filter design, combining mechanical particle capture and activated carbon adsorption,

enabled efficient smoke clearance while maintaining stable pneumoperitoneum (12–15 mmHg) and acceptable airflow dynamics, with only minimal pressure variation (<1 mmHg). The use of the filtration system resulted in a marked improvement in laparoscopic visual clarity, thereby supporting uninterrupted surgical workflow and reducing procedural interruptions. The device demonstrated a functional operational duration of approximately 4–5 hours, consistent with typical laparoscopic procedure times. Importantly, the system offers a balanced trade-off between filtration efficiency and airflow resistance, making it feasible for integration into standard laparoscopic setups without compromising procedural stability. In comparison to high-cost commercial smoke evacuation systems, the present design provides a economically accessible design and compact alternative, particularly relevant for resource-limited healthcare settings. However, while the present study provides an initial *In-vitro* evaluation of the laparoscopic smoke filtration system, further pre-clinical and clinical investigations are required to validate its performance under real surgical conditions. Future studies should focus on confirming long-term safety, filtration efficiency across diverse surgical scenarios, and consistent maintenance of pneumoperitoneum and airflow dynamics during prolonged procedures. Upon successful clinical validation, laparoscopic smoke filtration systems are expected to may contribute in reducing occupational exposure to surgical smoke, improving intra-operative visibility, and enhancing overall operating room safety and procedural efficiency in minimally invasive surgery.

Compliance with ethical standards

Disclosure of conflict of interest

All the authors are an employee of Meril Medical Innovations Private Limited, Vapi, Gujarat – India and declare no competing interests related to this study.

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