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Generation and Systematic Evacuation Strategies for Surgical Smoke in Laparoscopic Surgery

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Abstract

Laparoscopic surgical smoke, a hazardous aerosol containing toxic chemicals and viable pathogens, poses significant occupational health risks and impairs surgical visibility. This review synthesizes current evidence on smoke evacuation strategies, highlighting the inadequacy of traditional passive dilution and advocating for systematic adoption of active evacuation technologies—such as trocar-integrated, energy device-integrated, or intelligent insufflation-filtration systems—combined with source control measures like power optimization and device maintenance. Tailoring system choice to procedural context is essential to effectively protect operating room personnel, maintain surgical efficiency, ensure patient safety, and optimize resource utilization.

Keywords

Laparoscopic surgery; Surgical smoke; Plume; Occupational exposure; Smoke evacuation; Minimally invasive surgical safety.

1. Introduction

Since its inception in the 1980s, laparoscopic surgery has become a cornerstone of modern minimally invasive surgery, valued for its benefits of reduced trauma, faster recovery, and improved cosmetic outcomes. It is now routinely applied to most general surgical and gynecological procedures. Energy-based devices—including electrosurgical units (ESUs), ultrasonic shears, lasers, and plasma devices—are indispensable in laparoscopy for precise cutting, dissection, and haemostasis. However, the high temperatures (80°C to 400°C) generated by these devices cause cellular fluid vaporization and tissue carbonization, producing substantial aerosols, steam, and particulate matter collectively termed "surgical smoke" or "plume" [1].

In open surgery, smoke can be partially diluted and evacuated by the operating room's laminar airflow systems. In contrast, during laparoscopic procedures, smoke accumulates within the confined abdominal cavity. Secondary heating from the laparoscope's light source or the energy device itself can exacerbate smoke accumulation, significantly impairing visual clarity[2]. Surgeons are often compelled to interrupt procedures repeatedly for smoke evacuation, adversely affecting operational fluency and efficiency. The health implications of laparoscopic smoke have evolved from being perceived as a mere nuisance to a recognized occupational health hazard[3]. This review aims to elaborate on the characteristics, hazards, and systematic management strategies for surgical smoke in laparoscopic surgery..

2. Properties And Health Hazards of Laparoscopic Surgical Smoke

2.1. Physicochemical Properties

Laparoscopic surgical smoke is a complex chemical mixture whose composition depends on the treated tissue type, tissue hydration, and the type and power setting of the energy device used[4, 5] .

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2.2. Physical Properties

Consisting of approximately 95% water vapour and 5% particulate matter, the particles typically range from 0.07 μm to 10 μm in diameter, falling within the respirable range (PM2.5 and smaller)[6]. Smaller particles can deposit deeply in the alveoli and are difficult to clear, posing a greater health risk to operating room personnel.

2.3. Chemical Properties

Over 600 chemical compounds have been identified in surgical smoke. These include: 1) Toxic gases: such as carbon monoxide (CO), hydrogen cyanide (HCN), acrylonitrile, formaldehyde, and benzene—the latter two are recognized carcinogens by the World Health Organization[7]. 2) Viable viruses and bacteria: DNA from viruses like human papilloma virus (HPV), hepatitis B virus (HBV), HIV fragments, and bacteria (e.g., Staphylococcus aureus) has been detected in smoke[8]. Although documented cases of transmission are rare, a theoretical risk remains. 3) Cellular debris and viable material: This includes carbonized particles, blood-borne pathogens, viable cell fragments, and even potentially viable cancer cells, with animal models suggesting a potential implantation risk[9].

2.4. Impact on Operating Room Personnel

2.4.1. Short-term acute effects

Irritating odours can cause ocular irritation (burning, lacrimation). Inhalation may lead to respiratory symptoms such as throat irritation, cough, sneezing, rhinitis, shortness of breath, headache, dizziness, nausea, and fatigue, commonly reported among staff performing lengthy laparoscopic procedures.

2.4.2. Long-term chronic risks

Chronic exposure may increase the risk of respiratory diseases such as chronic bronchitis and emphysema. The mutagenic potential (as indicated by positive Ames test results) and the presence of carcinogenic components (e.g., benzene, formaldehyde) suggest a significantly elevated cancer risk with cumulative exposure[4]. A theoretical risk also exists for the aerosol transmission of blood-borne viruses like HBV and HPV, with case reports linking laryngeal papillomatosis in healthcare workers to laser smoke generated during the treatment of genital warts[9].

2.4.3. Impact on the Patient

While under general anesthesia, patients do not perceive smoke irritation directly. However, absorption of smoke constituents by the peritoneum or intra-abdominal tissues might potentially increase the risk of postoperative complications, such as chemical peritonitis or immune effects, although this requires further investigation.

2.4.4. Impact on Surgical Operation and Healthcare Costs

Obscured vision due to smoke is a frequent cause of procedural interruption. Cumulative time spent evacuating smoke or re-establishing pneumoperitoneum prolongs operative and anesthesia time, increasing team workload and fatigue. Economically, it reduces operating room turnover efficiency and increases operational costs.

3. Methods For Smoke Evacuation in Laparoscopic Surgery

Strategies for managing laparoscopic smoke can be categorized into source control, active evacuation, and passive dilution, reflecting an evolution from reactive handling to proactive real-time control and prevention.

3.1. Passive Dilution

This traditional, high-risk method relies on intermittently releasing pressurized gas and smoke by opening a trocar valve or removing a seal cap. Although simple and low-cost, it is highly inefficient, requires frequent procedure interruption, and contaminates the operating room environment by releasing unfiltered hazardous smoke, thereby exposing staff to dangerously high particle concentrations.

3.2. Active Evacuation

This approach involves using suction to remove smoke from the abdominal cavity, followed by high-efficiency filtration before release, representing a more effective and safer solution.

3.2.1. Suction via Separate Aspirator

A suction device is introduced through an auxiliary trocar port and connected to wall suction. It allows targeted smoke removal. Intermittent, low-pressure suction is advised to avoid pneumoperitoneum collapse. Advantages include relatively low cost, flexibility, and effectiveness. The main disadvantage is the consumption of an additional port, which can be problematic in single-port or reduced-port surgery.

3.2.2. Trocar-Integrated Continuous Evacuation

Smoke evacuation functionality is built into the trocar itself and connected to suction. This avoids the need for an extra port, making it suitable for most procedures, especially those with limited port numbers. While allowing continuous smoke removal, precise flow control can be challenging; some institutions use IV set regulators for better modulation.

3.2.3. Energy Device-Integrated Evacuation

This approach aims to capture smoke at the very moment of its generation. A miniature suction port is integrated directly into the jaw or shaft of the energy device itself (e.g., electrosurgical hooks, advanced bipolar devices, ultrasonic shears). As the device is used, smoke is immediately aspirated through this port and channeled away. This offers exceptionally high efficiency at the source, minimizing the amount of smoke that ever enters the abdominal cavity, and causes virtually no disruption to the surgical workflow. The primary barrier to adoption is the significantly higher cost of these specialized, often disposable, instruments, which has limited their widespread use outside of specific high-volume or specialized centers[10, 11].

3.2.4. Laparoscope-Integrated Evacuation

This system integrates the smoke evacuation channel within the laparoscope's protective sheath. A common feature combines this with a continuous flow of warm air across the lens to prevent fogging. The system works by creating a constant, gentle airflow from the scope's tip, which effectively pushes debris and smoke particles away from the lens, creating a localized clear visual zone. This elegantly addresses the two main visual impediments in laparoscopy—smoke and fog—simultaneously. The drawbacks are the expense and complexity of the systems, which involve specialized scopes and consoles, and they can have higher maintenance costs[12].

3.2.5. Insufflation System-Integrated Filtration

Representing the most advanced technological solution, these are integrated into the high-flow insufflator unit. They continuously monitor the optical clarity within the pneumoperitoneum using laser particle sensors. Upon detecting a predefined threshold of smoke density, the system automatically initiates a purification cycle: smoke-laden CO_2 is aspirated from the abdomen, passed through a built-in HEPA/ULPA filter (and sometimes an additional activated carbon layer for chemical adsorption), and the cleansed, warmed gas is recirculated back into the abdominal cavity. This closed-loop system maintains a stable pneumoperitoneum pressure and temperature while continuously clearing the visual field. It can also be manually activated. The benefits are profound: near-continuous clear visualization, minimal procedural interruptions, and maximal protection for the OR team. The principal disadvantage is the very high initial capital investment required for these systems[13, 14].

3.3. Source Control

The most effective strategy is to minimize the generation of smoke at its origin. This requires a conscious effort from the surgeon and is a hallmark of proficient laparoscopic technique.

3.3.1. Power Optimization

Using the lowest effective power setting necessary to achieve the desired tissue effect (cutting or coagulation). Excessive power creates unnecessary carbonization and smoke.

3.3.2. Device Selection

Choosing energy devices known to produce less smoke for a given task. For example, ultrasonic shears generally produce less smoke and lower temperatures than monopolar electrocautery for dividing vascular tissue.

3.3.3. Tip Maintenance

Regularly cleaning the active electrode tip of eschar (charred tissue) buildup during the procedure. A charred tip increases electrical impedance, requiring higher power to achieve the same effect and generating significantly more smoke.

3.3.4. Technique Modification

Employing techniques like "pre-coagulation" before cutting vascular tissue can reduce bleeding and the subsequent smoke generated from coagulating that bleeding. Using a "small bites" technique with frequent, short activation bursts rather than prolonged, continuous activation also reduces cumulative smoke production.

4. Smoke Evacuation Strategies in Special Surgical Situations

4.1. Single-Incision Laparoscopic Surgery (SILS)

The single port limits options. Integrated insufflation/filtration systems or energy device-integrated suction are ideal, avoiding instrument changes and maintaining pneumoperitoneum. If unavailable, careful intermittent manual suction at key moments is necessary.

4.2. Robotic-Assisted Laparoscopic Surgery

Instrument arm positioning makes instrument switching cumbersome. Insufflation system-integrated filtration is preferred for automated, assistant-independent smoke control. Alternatively, the assistant must strategically position a suction device, avoiding robotic arms. Some bipolar robotic instruments incorporate irrigation/suction[15, 16].

4.3. High-Volume Smoke Procedures (e.g., liver resection, surgery in obese patients)

Smoke generation often exceeds evacuation capacity. Source control is critical: optimize power settings, favor coagulation over cutting when possible, and use a "small bites" technique. An assistant dedicated to smoke evacuation with a suction device is highly beneficial.

4.4. Procedures in Complex Anatomic Locations (e.g., prostatectomy, rectal resection)

Poor visibility in confined spaces can lead to serious errors. Proactive, intermittent suction by the assistant during energy device use is essential to prevent visual contamination.

5. Discussion

The pervasive use of laparoscopic surgery has heightened concerns regarding surgical smoke. This review confirms that surgical smoke is not merely an obstruction but a serious occupational health hazard containing toxic chemicals, viable pathogens, and cellular debris, which is linked to acute and potential chronic health effects for operating room staff. Furthermore, smoke-induced visual impairment disrupts surgical flow, increases operative time, anesthesia exposure, and overall healthcare costs.

Traditional passive dilution is inadequate and unsafe due to its inefficiency and environmental contamination. Active evacuation technologies, which employ suction coupled with high-efficiency filtration, represent the standard for safe and effective smoke management. These systems reduce exposure risks, maintain visual clarity, and enhance procedural efficiency and safety. Multiple options exist, each with specific advantages: suction via a separate aspirator (flexible, cost-effective), trocar-integrated systems (port-saving), energy device-integrated systems (high efficiency at source), laparoscope-integrated systems (dual fog/smoke control), and intelligent insufflation systems (continuous operation, stable pneumoperitoneum).

The choice of system depends on the procedural context. Integrated systems like intelligent insufflators are particularly advantageous in challenging scenarios such as SILS, robotic surgery, high-smoke-generation procedures, and complex anatomies, as they enable continuous smoke control without compromising workflow or pneumoperitoneum stability. Complementing evacuation with source control strategies—prudent energy device use, power optimization, and instrument maintenance—is equally vital for minimizing smoke generation at its origin.

While this review summarizes the current evidence, it is limited by the heterogeneity of existing studies and the lack of large-scale randomized trials directly comparing the long-term health outcomes or cost-effectiveness of different evacuation systems. Future research should focus on these areas.

This review is limited by the inherent heterogeneity of the available literature, which consists largely of in vitro studies, case reports, and observational studies. A significant gap exists in the form of large-scale, randomized controlled trials that directly compare the long-term health outcomes (e.g., respiratory function, cancer incidence) among OR staff using different protection strategies. Furthermore, high-quality health economic analyses comparing the cost-effectiveness of these various evacuation technologies are scarce. Future research should prioritize these areas to provide Level I evidence that can guide policy and purchasing decisions. Additionally, more studies are needed to quantify the specific risk to patients from intra-abdominal smoke exposure and to establish evidence-based safety standards for permissible smoke levels in the OR environment. Adopting advanced smoke evacuation systems constitutes an imperative investment in operating room personnel health, patient safety, surgical efficiency, and optimal resource utilization.

6. Conclusion

Surgical smoke generated during laparoscopic procedures constitutes a significant occupational health risk and operational hindrance. A systematic approach encompassing the adoption of advanced active smoke evacuation technologies, particularly integrated filtration systems, combined with diligent source control measures, is essential for effective mitigation. This strategy safeguards the wellbeing of healthcare workers, ensures patient safety, enhances surgical efficiency, and contributes to the optimization of healthcare resources.

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