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The Invisible Killer of the Operating Room: How Surgical Smoke Acts as a Toxic Airborne Threat to the Respiratory Fitness, Oncogenic Risk Profile and Occupational Safety of the Surgical Team

Martyna Szepietowska

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0000-2423-4563>

mszepietowska@gmail.com

Dominika Janik

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0000-8527-7428>

dominika.janik121@gmail.com

Zuzanna Zapart

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0007-0466-4508>

pczuzanna@gmail.com

Agata Sochocka

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0004-5384-2014>

agatasochocka@gmail.com

Nina Nowicka

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0004-1942-0045>

nina.en@autograf.pl

Oliwia Zuzanna Gańska

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0007-9024-0209>

oliwiaganska12@gmail.com

Alicja Sikorska

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0009-6274-6944>

alicja.sikorska@gmail.com

Jakub Bundyra

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0008-7042-1990>

kubabundyra4@gmail.com

Emil Mian

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0006-1538-7190>

emilmian@icloud.com

Julia Parda

Medical University of Warsaw, Żwirki i Wigury 61, 02-091 Warsaw, Poland

<https://orcid.org/0009-0006-9079-5936>

parda.julka@gmail.com

Corresponding Author: Martyna Szepietowska

E-mail: mszepietowska@gmail.com

Abstract

Background. Surgical smoke is a hazardous byproduct generated by energy-based devices such as electrocautery, lasers, and ultrasonic scalpels during thermal tissue ablation. While water vapor accounts for most of the plume, the remaining portion contains chemical pollutants, particulate matter, and infectious biological agents that may affect the physical health of the surgical team. Operating room personnel are frequently exposed to these substances due to inconsistent safety standards.

Aim. This review analyses the chemical, physical, and biological hazards associated with surgical smoke and evaluates documented health outcomes among surgical personnel and the efficacy of modern protective and evacuation measures.

Material and methods. A review of literature was conducted using PubMed and Google Scholar, with a focus on English-language publications that addressed the chemical and biological composition of the smoke, clinical health outcomes, and the technological efficiency of various filtration and evacuation systems.

Results. Research consistently indicates that surgical plume contains carcinogenic and toxic substances, such as benzene and formaldehyde in concentrations that can exceed occupational exposure limits. Significant evidence shows the potential aerosolization of pathogens such as HPV, Hepatitis B, and coronaviruses. Chronic exposure is associated with a higher risk of

severe persistent asthma and various acute symptoms, as well as specific head and neck cancers. While standard surgical masks provide inadequate filtration for submicron particles, N95 respirators and integrated smoke evacuation systems show high capture efficiency.

Conclusions. Surgical smoke represents a substantial oncogenic and infectious risk to operating room staff. To mitigate these hazards, institutional mandates for the use of smoke evacuation technology are necessary, alongside targeted education to improve staff compliance and safety behaviours.

Keywords: occupational hazards, surgical smoke, electrosurgery, HPV, workplace safety, smoke evacuation, energy-based devices

1. Introduction

The landscape of modern surgery is defined by the widespread use of energy-based devices (EBDs), including advanced electrosurgery, lasers, and ultrasonic scalpels, which are essential for achieving precise tissue dissection and effective haemostasis [1-5]. These instruments allow for shorter operative times and reduced blood loss; however, the thermal destruction of biological tissue produces a gaseous byproduct known as surgical smoke or plume [2, 3, 5]. Recent investigations emphasize that while much of this plume consists of water vapor, the remaining portion contains a concentrated mixture of toxic non-condensable gases and hazardous particulate matter (PM) that directly affects the breathing zone of the surgical team [2-4, 6]. As surgical techniques become increasingly complex, the volume of smoke generated per procedure has risen, making it a critical focus of modern occupational health studies [3, 5]. Still, organizational factors like staff shortages and insufficient rest periods between surgeries contribute to an environment where safety priorities are frequently compromised [7].

Contemporary research underscores that surgical smoke is a complex chemical aerosol containing over 80 distinct toxic substances, including recognized carcinogens like benzene, ethylbenzene, and formaldehyde [5, 8, 9]. The health implications of such pollutants are part of a broader global crisis where poor air quality, both ambient and household, is associated with millions of premature deaths and the escalation of chronic respiratory diseases – specifically pollutants such as particulate matter, nitrogen dioxide, and sulphur dioxide have been shown to trigger pro-inflammatory responses and oxidative stress, significantly increasing the risk of developing asthma and exacerbating symptoms in vulnerable populations [10]. Experimental data suggest that the particulate matter generated during procedures, specifically PM_{2.5} and ultrafine particles, often reaches levels that significantly exceed the safety thresholds established by international labour and health organizations [3, 11, 12]. The physical threat is further contextualized by the small size of these particles, which allows them to bypass the mechanical filtration layers of standard surgical masks and penetrate deep into the pulmonary alveoli, potentially inducing systemic oxidative stress and inflammatory responses [3, 12, 13]. Furthermore, the latest studies suggest that even in minimally invasive procedures, the concentrated accumulation of these particles within the pneumoperitoneum can impair surgical visibility and lead to high-velocity exposure during gas venting [2, 14].

The biological hazards associated with the plume have entered a new era of scrutiny following the global COVID-19 pandemic. Scientific evidence now confirms that surgical smoke can serve as a vehicle for the aerosolization of infectious pathogens, ranging from bacteria and fungi to high-risk viruses such as human papillomavirus (HPV), hepatitis B, and human coronaviruses [15-17]. The viability of these pathogens within the plume is a verified concern, with documented clinical cases of surgeons developing oropharyngeal and laryngeal cancers that correspond exactly to the viral strains found in their patients [18-21]. Beyond acute infections, the cumulative inhalation of these chemical and biological aerosols has been epidemiologically linked to a substantial increase in chronic respiratory pathologies, such as severe persistent asthma among perioperative nurses [18, 22, 23]. This mirrors findings in environmental studies where long-term or early-life exposure to traffic-related air pollution and industrial emissions consistently correlates with higher rates of asthma-related hospital admissions and emergency room visits [10].

Despite this growing evidence of severe physical harm, a persistent "prevention gap" remains in daily clinical practice. This gap is driven by various factors, including ergonomic barriers such as the noise generated by evacuation units, a perceived lack of convenience, and an absence of mandatory national legislative standards for air quality in many jurisdictions [5, 6, 24, 25]. Consequently, many operating room workers continue to rely on standard masks that do not provide adequate protection against the submicron constituents of the smoke [11, 26]. Therefore, this narrative review aims to synthesize the latest evidence to provide a comprehensive analysis of the physical health impacts of surgical smoke on healthcare workers and the necessity for integrated evacuation and high-filtration technologies.

2. Chemical and Physical Characteristics of Surgical Smoke

Surgical smoke, the byproduct resulting from the thermal interaction between energy-based devices and biological tissue, is a complex aerosolized plume whose specific composition is dictated by the surgical modality, the energy settings of the instrument, and the biological properties of the target tissue [2-4]. While approximately 95% of this plume consists of water vapor, it serves as a carrier for the remaining 5% of hazardous components, which include a diverse array of more than 80 toxic chemicals, cellular debris, and infectious agents [2, 4, 27]. The process of thermal destruction of cells involves the rapid heating of intracellular fluids to the point of boiling and subsequent membrane rupture, which ejects a mixture of non-condensable gases and particulate matter into the immediate operating environment [5, 27].

Chemical analysis using gas chromatography-mass spectrometry has identified numerous volatile organic compounds (VOCs) that present both acute and chronic health risks to healthcare providers [8, 9, 28]. Recent prospective randomized studies have observed that irritating, toxic, and carcinogenic VOCs are consistently present in operating room air, with concentrations of certain compounds sometimes exceeding the permissible exposure limits [4, 8]. Key pollutants identified in the plume include benzene, toluene, ethylbenzene, xylene, and formaldehyde [8, 29, 30]. Research indicates that smoke produced during specific procedures, such as breast reduction surgery, contains organic compounds that are definitively mutagenic in biological assays [23]. Furthermore, the cauterization of specialized tissues, such as mammary glands, produces significantly higher concentrations of carcinogens like 1,3-butadiene compared to adipose or skin tissues [2, 31]. Similarly, during burn operations, the

excision of necrotic tissue releases complex hydrocarbon derivatives, with benzene and its derivatives accounting for a significant portion of the total compounds identified [32]. High concentrations of formaldehyde and methanol are also prevalent [18, 30, 33].

The physical characteristics of the particulate matter (PM) further exacerbate the health risk to surgical personnel. The hazard risk is primarily a function of particle size. Most particles in the surgical plume are submicron in size, typically ranging from 0.07 μm for electrocautery to 0.31 μm for laser-based procedures [3, 5, 13]. Ultrafine particles ($<0.1 \mu\text{m}$) exhibit gas-like diffusion and remain airborne for extended periods, possessing the capacity for deep alveolar penetration and systemic absorption. The physical behaviour and distribution of these particles depend heavily on the energy modality used. Electrosurgery generates the smallest particles, averaging approximately 0.07 μm . These ultrafine particles are particularly hazardous because their small size allows them to bypass the upper respiratory defenses and standard medical masks, settling deep within the alveolar region where they can induce local oxidative stress and systemic inflammatory responses [3, 12, 23]. Laser ablation produces particles with an average diameter of 0.31 μm that remain in aerosolized suspension and can serve as a vector for viral transmission. Ultrasonic scalpels generate larger, heavier droplets ranging from 0.35 μm to 6.5 μm , which are more likely to preserve biological viability within the plume. In contrast, high-speed drills produce particles exceeding 10.0 μm that follow a mechanical trajectory, primarily resulting in localized mechanical irritation rather than deep pulmonary penetration [4]. Real-time monitoring suggests that surgical teams experience intense "short bursts" of extreme particle concentrations – exceeding $100,000/\text{cm}^3$ – immediately upon tool activation, even if the overall room air quality appears within normal limits [8, 13].

The operative environment and access modality, meaning the choice between open and laparoscopic techniques, also significantly alter the exposure profile of the surgical team. In traditional open surgery, smoke emission is constant but dispersed throughout the room air [34, 35]. In laparoscopic procedures, smoke is trapped within the pneumoperitoneum under high pressure, which can severely impair surgical visibility and lead to the "chimney effect". This phenomenon occurs when high-velocity jets of concentrated pollutants and halocarbons are released toward the surgical team during trocar manipulation or periodic gas venting [14, 36, 28]. Furthermore, the lack of oxygen in a pneumoperitoneum can lead to incomplete combustion, potentially increasing the production of certain toxic hydrocarbons [36].

Tissue type also plays a critical role in the smoke's chemical profile. For instance, orthopaedic procedures involving the cutting of muscle and meniscus tissue have been associated with high levels of toluene and styrene, while bone debridement produces significant particulate counts [37]. Even in training environments, the use of porcine models or synthetic materials can expose trainees to hazardous gases, although recent innovations in training tissues aim to produce smoke comprised mainly of water and carbon dioxide [38]. Collectively, these findings underscore that surgical smoke is a potent chemical and physical hazard requiring rigorous occupational safety standards [9, 39].

3. Biological Hazards and Viral Transmission

While the chemical toxicity of surgical smoke is a primary concern, the potential for biological transmission of pathogens presents a distinct and arguably more acute risk to operating room personnel [27, 39]. Surgical smoke functions as a significant biological vector, capable of transporting and potentially preserving various infectious pathogens, including bacteria, viruses, and viable malignant cells [4, 18]. Recent systematic reviews emphasize that the water vapor within the plume provides a protective medium that facilitates the survival of these biological components even when subjected to the intense thermal energy of electrosurgical or laser devices [15, 27].

Human papillomavirus (HPV) remains the most extensively documented biological threat in this context, with evidence confirming that medical personnel are at risk of inhaling infectious HPV particles during procedures such as laser ablation or loop electrosurgical excision (LEEP) [17, 19, 40]. Surgeons and gynaecologists performing these high-energy treatments demonstrate a significantly higher prevalence of HPV DNA with a positivity rate of 10.11%, specifically high-risk types 16 and 18, in their nasal mucosa compared to 2.91% in unexposed healthcare workers [40, 41]. This presence of viral material is not merely environmental contamination, but it correlates directly with the frequency and duration of procedures performed and the lack of specialized respiratory protection [40, 41].

The clinical consequences of this exposure have moved beyond theoretical risk into documented occupational disease. There are landmark case reports of laser surgeons developing laryngeal papillomatosis with the exact HPV DNA types found in their patients' lesions [20].

Furthermore, more recent evidence identifies oropharyngeal squamous cell carcinoma and base-of-tongue cancers in non-smoking surgeons who had long histories of performing LEEP and laser procedures on dysplastic cervical lesions [19, 21]. These findings suggest that the inhalation of surgical smoke is a viable pathway for the development of head and neck cancers among medical professionals [18, 21]. Beyond HPV, the risk profile includes a broad spectrum of viral pathogens such as Hepatitis B (HBV), Polio, and Varicella-Zoster [15, 39]. Laboratory stability tests have shown that HBV, in particular, can survive thermal energy exposure and remain viable within the smoke [39].

The emergence of the COVID-19 pandemic introduced intense scrutiny regarding the aerosolization of the SARS-CoV-2 virus during surgical interventions. Research has confirmed that human coronavirus RNA can be detected in abdominal fluids and within the smoke generated by both electric and ultrasonic scalpels [16, 17, 42]. Importantly, the actual infectivity of SARS-CoV-2 through this route remains a subject of debate [16, 17, 42]. Some researchers suggest that the heat from electrocautery may degrade the viral envelope, reducing its ability to cause infection, though the presence of viral genetic material remains a valid indicator of potential exposure [16, 42].

In addition to viral risks, surgical smoke acts as a vehicle for bacterial and fungal contamination. Pathogens such as *Staphylococcus aureus* and *Pseudomonas aeruginosa* can be aerosolized during the treatment of infected tissues [27]. This dispersal poses a dual risk, potentially leading to occupational infections for the staff and increasing the risk of surgical site infections for the patient. The use of N95 respirators is essential in these scenarios, as they are specifically validated to prevent the penetration of these hazardous biological aerosols into the respiratory tract of the provider [16, 26, 40].

4. Acute and Chronic Health Effects on Operating Room Personnel

The inhalation of surgical smoke is associated with a broad spectrum of physical health complications, ranging from immediate acute irritation to severe chronic pathologies and potential oncogenesis [2, 3, 43, 44]. Operating room (OR) personnel, particularly nurses and surgical technicians who spend extended hours in the sterile field, are at the highest risk of developing these conditions [22, 43, 45]. Clinical and survey-based data indicate that the

incidence of respiratory symptoms among OR staff is significantly higher than in the general population, with some studies reporting twice the rate of respiratory issues in perioperative nurses [43].

Acute symptoms are the most frequently reported manifestations of smoke exposure and typically occur during or immediately following a surgical procedure. These include upper respiratory tract irritation, characterized by coughing, sore throat, sneezing, and nasal congestion, as well as ocular symptoms such as burning, itching, or watering eyes [39, 43, 44]. Systemic acute effects are also common, with staff frequently reporting headaches, dizziness, nausea, and general physical exhaustion, which may impair cognitive performance during complex tasks [39, 44, 46]. Experimental animal models have supported these clinical findings, demonstrating that even short-term exposure to electrocautery smoke can induce significant histopathological changes and inflammation in the laryngeal mucosa [46].

Beyond transient irritation, chronic exposure to the chemical and particulate elements of surgical smoke is linked to the development of serious respiratory diseases. A large-scale epidemiological study involving a massive cohort of nurses found that OR nurses have a significantly elevated risk of developing severe persistent asthma compared to those in administrative or outpatient roles [22]. This correlation remains strong even after adjusting for smoking status and other environmental factors, suggesting that the cocktail of VOCs and submicron particles acts as a potent respiratory sensitizer [9, 22]. Furthermore, in vitro toxicological evaluations have demonstrated that surgical smoke is directly cytotoxic to human small airway epithelial cells and macrophages, inducing oxidative stress and inhibiting cell proliferation, which may permanently compromise the local immune defence mechanisms of the lungs [18, 23].

The potential for long-term oncogenesis remains one of the most significant concerns of occupational smoke exposure. The presence of known carcinogens such as benzene, formaldehyde, and polycyclic aromatic hydrocarbons (PAHs) allows for the calculation of an increased lifetime cancer risk for surgical staff based on cumulative exposure hours [18, 45, 47]. Studies have calculated that the ablation of 1g of tissue is equivalent to the mutagenicity of six unfiltered cigarettes. Based on average OR activation times, this suggests that the daily exposure to the plume in certain surgical specialties is equivalent to 27 to 30 cigarettes [47].

While this comparison remains a powerful advocacy tool for mandatory evacuation, it has faced academic critique. Critics note that the cigarette analogy may oversimplify the differences between tobacco combustion and tissue pyrolysis, particularly regarding inhalation efficiency and the absence of certain tobacco-specific additives. However, the fundamental mutagenic potential of surgical smoke remains undisputed in in vitro and animal models.

While the latency period for cancer development makes prospective data collection challenging, the documented clinical cases of oropharyngeal and laryngeal cancers in surgeons (linked to the transmission of oncogenic viruses through the plume) provide clear evidence of site-specific carcinogenic potential [18-21]. Physiological and histopathological changes have also been observed in the nasal mucosa of healthcare professionals. Chronic inhalation of the plume can lead to epithelial distribution changes and even pre-neoplastic transformations in the nasal lining, similar to those seen in workers exposed to industrial formaldehyde [32, 44]. Additionally, systemic absorption of these toxins has been confirmed through the detection of elevated benzene metabolites in the urine of both patients and personnel after surgery, indicating that the hazards of surgical smoke extend beyond the respiratory system and enter systemic circulation [28, 32, 44]. These findings collectively demonstrate that surgical smoke is not merely an environmental nuisance but a multisystemic health hazard that requires aggressive management and standardized protective protocols.

5. Protective Measures and Barriers to Compliance

The mitigation of surgical smoke hazards relies on a combination of engineering controls, personal protective equipment (PPE), and administrative strategies, yet the implementation of these measures remains highly variable across clinical settings [5, 24, 39]. Engineering controls, specifically dedicated smoke evacuation systems (SES), are recognized as the most effective method for capturing pollutants at the source before they enter the breathing zone of the surgical team [8, 48]. High-quality mobile and integrated SES units have demonstrated the ability to remove over 90% of VOCs and particulate matter, whereas standard wall suction or Yankauer devices are significantly less effective, often capturing only a fraction of the generated plume [8, 48]. In laparoscopic surgery, the use of built-in-filter ports and activated carbon fiber filters has proven essential for neutralizing the concentrated gases and halocarbons released from the CO₂ pneumoperitoneum [30, 49, 50]. Even localized solutions, such as

suction pads, have shown a measurable reduction in average particulate exposure during specific interventions like spine surgery [51].

Despite the availability of high-efficiency evacuation technology, the choice of respiratory protection remains a critical factor in personal safety. Extensive research comparing standard surgical masks (SMs) with N95 and N100 respirators consistently shows that SMs provide inadequate protection against the submicron and ultrafine particles that characterize surgical smoke [11, 26, 52]. While standard masks are designed to protect the patient from the wearer's large droplets, they lack the peripheral seal and filtration efficiency required to block the fine chemical and viral aerosols found in the plume [11, 26]. In contrast, N95 respirators significantly reduce the inhalation of hazardous particles and have been shown to specifically prevent the detection of HPV DNA in the nasal mucosa of surgeons during high-risk procedures [16, 26, 40]. Additionally, adjusting surgical tool settings, such as using the lowest effective wattage, can reduce the baseline volume of particulate matter generated during tissue ablation [53].

However, a significant "prevention gap" exists between scientific recommendations and actual clinical practice. Surveys of operating room personnel reveal that while awareness of the general hazards of surgical smoke is high, consistent use of evacuators and respirators is low [24, 54]. Barriers to compliance are multifaceted and include perceived physical deterrents, such as the loud noise generated by SES units and the bulkiness of specialized evacuation tubing, which surgeons often feel interferes with their dexterity and surgical field visibility [24, 25, 55]. Furthermore, many healthcare professionals cite a lack of institutional mandates and formal training as reasons for non-compliance, with some reporting that safety guidelines are often available but rarely read or enforced [24, 25, 56].

Educational interventions and administrative support have shown promise in bridging this gap. Targeted programs that explain the specific chemical and biological risks of the plume – rather than just listing them as generic hazards – have been successful in increasing the self-reported use of SES and N95 masks among perioperative nurses [25, 55]. Hospitals that establish "smoke-free" policies and invest in the latest low-noise, integrated evacuation tools see higher rates of staff satisfaction and compliance [6, 43, 57]. Patient perception also supports these changes as randomized trials have shown that patients undergoing procedures under local

anaesthesia report higher comfort levels and less anxiety when smoke evacuation is utilized [58]. Ultimately, the transition to a smoke-free surgical environment requires a cultural shift that prioritizes long-term occupational health over immediate ergonomic convenience, supported by mandatory national standards for air quality in the operating theatre [25, 43, 54].

6. Discussion and future perspectives

The cumulative evidence demonstrates a significant disconnect between the toxicological reality of surgical smoke and the safety culture currently prevailing in modern operating rooms. While energy-based devices (EBDs) are essential for modern surgical precision, the resulting plume is a complex chemical and biological aerosol that contains dozens of carcinogens and infectious pathogens and cannot be dismissed as a mere environmental nuisance.

The "prevention gap" remains the primary obstacle to occupational safety, as ergonomic complaints regarding the noise of evacuation systems or the bulkiness of specialized tubing often take precedence over the long-term health concerns of the surgical team. Although some researchers have argued that smoke levels in the operating room may be comparable to urban environmental pollution, the specific concentration of high-risk carcinogens like benzene and the documented transmission of oncogenic viruses provide a compelling counterargument for a zero-tolerance approach to smoke exposure and air quality in the OR [6, 18, 20-22].

The impact of surgical smoke also extends beyond the medical staff to the patients themselves. Evidence of systemic absorption, characterized by elevated urinary biomarkers of benzene and toluene in patients following laparoscopic procedures, suggests that the smoke trapped within the pneumoperitoneum presents an internal exposure risk through peritoneal absorption [28, 36]. This finding shifts the perspective of surgical smoke from a purely occupational hazard to a patient safety concern, necessitating the integration of filtration technology into the standard laparoscopic circuit [14, 30].

Looking toward future perspectives, the evolution of surgical technology may offer new solutions. Innovations such as nebulization technology designed to clear laparoscopic smoke and the development of training tissues that produce non-toxic water-based plumes represent promising steps toward hazard reduction at the source [2, 38]. Furthermore, as robotic-assisted surgery continues to gain prominence, the integration of automated, synchronized smoke

evacuation that does not interfere with the surgeon's console-based workflow will be paramount to ensuring the safety of the bedside assistants and nursing staff [4, 30]. Ultimately, ensuring a safe physical environment for OR workers will require a broad range of advancements: improved ergonomic design of evacuation tools, rigorous and targeted clinical education focusing on the specific chemical and biological risks, and the implementation of mandatory national standards for surgical air quality [9, 24, 25, 43].

7. Conclusions

Surgical smoke represents a multi-dimensional health hazard in the perioperative environment. It is a complex aerosol containing carcinogenic volatile organic compounds, submicron particulate matter, and a wide array of infectious biological agents, including HPV and human coronaviruses, that frequently exceed international safety thresholds [2-5, 8, 30, 40]. There is a definitive clinical and epidemiological correlation between chronic exposure to this plume and adverse health outcomes, ranging from acute respiratory and neurological symptoms to severe persistent asthma and the transmission of oncogenic viruses to surgical staff [18-22, 43, 44].

Because standard surgical masks provide insufficient protection against the physical and biological constituents of the plume, the use of N95 respirators and dedicated, high-efficiency smoke evacuation systems must be considered for all energy-based procedures [11, 26, 48]. To effectively bridge the current "prevention gap," healthcare institutions must prioritize the implementation of smoke-free policies, invest in integrated, low-noise evacuation technologies, and foster a professional culture that prioritizes the long-term physical health of the surgical team over immediate ergonomic convenience [24, 25, 43]. Ultimately, the transition to a safer operating room requires a shift from voluntary compliance to mandatory safety standards that protect both healthcare providers and their patients from the invisible dangers of the surgical smoke.

Disclosures

Author's contribution:

Conceptualisation: Martyna Szepietowska, Dominika Janik

Methodology: Alicja Sikorska, Nina Nowicka, Julia Parda

Software: Oliwia Zuzanna Gańska, Nina Nowicka

Check: Martyna Szepietowska, Dominika Janik, Zuzanna Zapart

Formal analysis: Emil Mian, Alicja Sikorska, Agata Sochocka

Investigation: Agata Sochocka, Martyna Szepietowska, Alicja Sikorska, Jakub Bundyra

Resources: Dominika Janik, Oliwia Zuzanna Gańska, Emil Mian

Writing rough preparation: Jakub Bundyra, Martyna Szepietowska, Oliwia Zuzanna Gańska

Writing review and editing: Martyna Szepietowska, Zuzanna Zapart

Visualization: Nina Nowicka, Julia Parda, Agata Sochocka

Project administration: Martyna Szepietowska

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