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State of the Science: A Concept Analysis of Surgical Smoke

Rebecca Vortman, DNP, RN, CNOR; Sara McPherson, PhD, RN; M. Cecilia Wendler, PhD, RN, NE-BC

ABSTRACT

Surgical smoke has not been clearly defined in the literature and often is identified using surrogate terms (eg, plume). In January 2020, a literature search was performed and a principle-based concept analysis involving four general principles (epistemological, pragmatic, linguistic, and logical) was used to define surgical smoke and identify implications for perioperative personnel, patients, researchers, and policymakers. Surgical smoke is a visible plume of aerosolized combustion byproducts produced by heat-generating surgical instruments. It consists of water vapor and gaseous substances; can carry toxic chemicals, bacteria, viruses, and tumors; can obscure the surgical field; and can be inhaled. Surgical smoke has a distinctive noxious odor and can cause physical symptoms such as watery eyes and throat irritation. Perioperative leaders should promote protection from occupational harm by educating their staff members on the use of smoke evacuators to mitigate the effects of surgical smoke on perioperative patients and personnel.

Key words: *principle-based concept analysis, surgical smoke, surgical plume, heat-generating instruments, smoke evacuation.*

Since the 2000 National Academy of Medicine report *To Err Is Human: Building a Safer Health System*,[1] patient safety has been at the forefront of health care. The Joint Commission releases its National Patient Safety Goals annually to address emerging trends that put patients at risk for adverse events.[2] In 2012, the Joint Commission released a monograph connecting patient safety with occupational health and safety, suggesting that safety improvements can benefit both patients and health care workers.[3] Professional organizations have since launched initiatives such as the American Nurses Association's "Healthy Nurse, Healthy Nation" campaign in 2017[4] and the Institute for Healthcare Improvement's Quadruple Aim that focuses on "elevating health equity and joy in work,"[5] which have challenged health care organizational leaders to prioritize the health and safety of their employees.

The Occupational Safety and Health Administration recognizes that health care workers experience safety and health hazards while caring for patients in clinical environments and has established a list of workers' rights that includes the right to "working conditions that do not pose a risk of serious harm."[6] In the perioperative environment, the surgical team often is exposed to harmful chemicals, viruses, and bacteria that are emitted into the air when heat-generating instruments are used to cut and coagulate tissue during surgical procedures.[7] These devices include electrosurgical units, ultrasonic devices, and lasers. The byproduct emitted into the air has many identifiers, including *surgical smoke*, *smoke plume*, *bioaerosols*, *laser-generated airborne contaminants*, and *lung-damaging dust*.[7]

Hazardous toxins in surgical smoke may include gaseous compounds (eg, benzene, toluene, hydrogen cyanide), viruses (eg, human papilloma virus, HIV), viable cancer cells, blood fragments, and bacteria.[8] As early as 1981, researchers found that surgical smoke produced by using a carbon dioxide laser on a canine tongue contained similar mutagenic potency to tobacco cigarette smoke.[9] Perioperative nurses report twice as many respiratory-related health issues as the general public.[10] Not only is surgical smoke a workplace safety hazard,

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it also is a patient safety risk.[7] Smoke-related risks for patients include a reduction in the surgeon's visibility at the surgical field during minimally invasive procedures,[11] extended procedure time,[12] port-site metastasis,[13] carbon monoxide exposure,[14] and increased levels of carboxyhemoglobin.[14]

Promoting smoke-free ORs is an AORN policy agenda item[15] that is gaining momentum. Rhode Island was the first US state to pass surgical smoke evacuation acts,[16] with Colorado following one year later.[17] These acts require all state-licensed hospitals and ambulatory surgery centers to use smoke evacuation systems during procedures that generate surgical smoke.[16,17] A number of states (eg, Georgia, Tennessee, Illinois, Iowa, Kentucky, Connecticut, New Jersey) are introducing similar legislation.[18] In 2016, AORN published surgical smoke safety guidelines for practice to establish and optimize a safe environment for both patients and the perioperative team.[7]

In January 2020, we conducted a scientific literature search to gain a more thorough understanding of surgical smoke; however, we did not find a published concept analysis on the topic of surgical smoke, indicating a gap in the research. The purpose of this article is to present the findings from a principle-based concept analysis of surgical smoke to provide a more comprehensive definition for future research.

CONCEPT ANALYSIS METHOD

We used the principle-based concept analysis approach[19] to explore what is already known about surgical smoke. We selected this method so that we could identify the current state of the science, uncover the current truth for the concept, and analyze the scientific literature after a thoughtful and thorough inquiry to determine how best to advance the concept. We used a principle-based concept analysis to establish a clear definition of the concept to advance the science by using four broad principles:

- epistemological,
- pragmatic,
- linguistic, and
- logical.[19]

Using the epistemological principle, we performed a critical analysis of the various definitions and surrogate terms to determine if surgical smoke was strongly defined and well-differentiated from other concepts in the literature. Using the pragmatic principle, we examined the applicability and usefulness of the concept of surgical smoke and its commonality among disciplines other than nursing to determine if the concept is recognizable among multiple disciplines. We applied the linguistic principle to determine if authors used the term appropriately in the literature. Lastly, the logical principle helped us determine if the concept of surgical smoke could be integrated among other concepts and remain clear when building a theory from multiple concepts.[19] Using these four principles, we constructed a theoretical definition that precisely represents the current state of conceptual development[19] for surgical smoke.

The purpose of this article is to present the findings from a principle-based concept analysis of surgical smoke to provide a more comprehensive definition for future research.

In January 2020, we conducted a literature search using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses and the following key words: *surgical smoke*, *smoke plume*, *bioaerosols*, *laser-generated airborne contaminates*, *lung-damaging dust*, *surgical vapor*, *surgical aerosol*, and *surgical fume* (Figure 1). We searched the following electronic databases: CINAHL (Cumulative Index to Nursing and Allied Health Literature), PubMed, Web of Science, and the Cochrane Library. We chose these databases because they best represent the state of the science in both nursing and medicine because surgical smoke research is not limited to nursing. To determine the state of the science, we used a multidisciplinary approach to conduct our literature search.[19]

We included peer-reviewed research studies that were written in English and were specific to generating evidence about surgical smoke. We excluded news and media articles, editorials, opinion articles, literature and systematic reviews, and articles in which surgical smoke was not the main focus. Initially, we limited studies to those that met our inclusion criteria and were published in the last five years. However, as we conducted our principle-based concept analysis, we found that many of the articles were secondary sources for the information on surgical smoke.

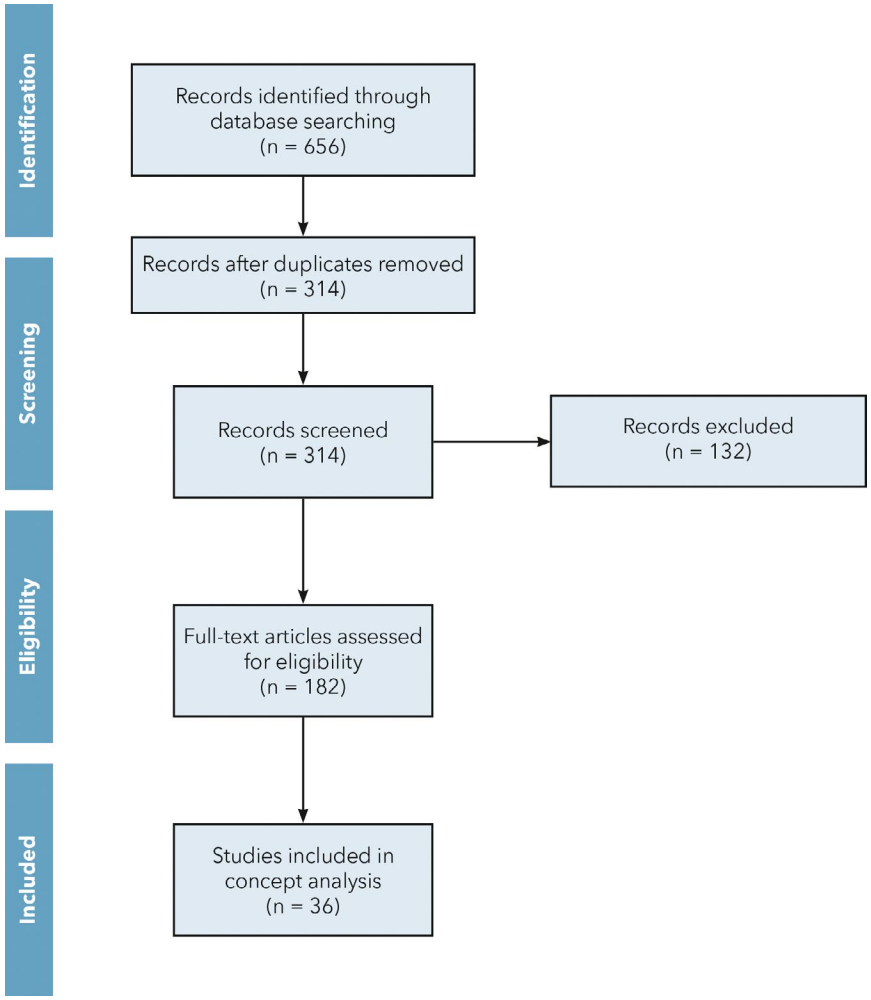

Figure 1. Flow diagram of review of articles investigating surgical smoke, modified for a concept analysis. *Adapted from Moher D, Liberati A, Tetzlaff J, Altman DG; The PRISMA Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement*. PLoS Med. *2009;6(7):e1000097*. https://doi.org/10.1371/journal.pmed.1000097.

We therefore expanded our search beyond the initial five-year limitation to locate the primary source (ie, original research) for the information in identified articles that included surgical smoke definitions.

We assigned a list of studies to each investigator to read and determine if the articles were applicable to the concept analysis. We documented the included studies in a table that identified the article name, authors, type of journal (ie, medical, nursing, occupational, public health), and Penrod and Hupcey's[19] method of broad-based principles. We convened bimonthly to discuss the studies and ensure each investigator followed the same inclusion and exclusion criteria. Ultimately, we identified 36 studies that were appropriate for inclusion.

Epistemological Principle

The epistemological principle asks if the concept has been well-defined and well-differentiated.[20] For this step, we examined the current definitions of surgical smoke. All 36 studies included a surgical smoke definition. In the more detailed definitions, the authors included causes and consequences of surgical smoke. We uncovered several definitions that included the chemical components, particles, and viable suspensions found in surgical smoke[21-27] and instruments that produce surgical smoke.[28-36]

Inhalation of particulate matter can negatively affect the health of OR staff members.[21] Particles released in surgical smoke can range in size based on the type of energy-generating device used and have been measured at <0.1

Sidebar 1. Potential Contents of Surgical Smoke

- Acetone[1,2]
- Acrylamide[3]
- Acrylonitrile[4]
- Aldehydes[3,5] (eg, acetaldehyde,[1] formaldehyde[4])
- Bacteria[6]
- Benzene[1-6]
- Blood fragments[7]
- Butadiene[8,9]
- Carbon monoxide[4]
- Carcinogens[2,10]
- Chloroform[2]
- Ethylbenzene[2]
- Furfural[6]
- Hydrogen cyanide[6,9]
- Isobutylene[8]
- Methane[6]
- Naphthalene[3]
- Nitriles (eg, acrylonitrile)[4]
- Phenol[2]
- Propylene[8]
- Polycyclic aromatic hydrocarbons[10,11]
- Styrene[1,2,5]
- Toluene[1,3-6,8]
- Viruses[7] (eg, human papillomavirus,[12] HIV[13])
- Volatile organic compounds[2,10]
- Xylene[1,5]

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micrometers (µm) in diameter when using electrocautery, 0.3 µm when ablating tissue with a laser, and 0.35 to 6.5 µm when using an ultrasonic scalpel.[28] The components of surgical smoke are listed in Sidebar 1.

Surgical smoke is "instantaneously dispersed in the ORs after its formation."[37(p383)] The consequences and occupational health risks of inhaling surgical smoke were discussed in the literature as early as the 1980s[9] and have since been validated.[21,37,38] Surgical smoke may be as mutagenic as cigarette smoke.[9,22] In several articles, the authors mentioned the instruments or devices that produced surgical smoke, which included heat-generating devices, such as lasers,[28] electrosurgical units,[28-35] and ultrasonic power tools;[35,36] some included the type of tissue, power setting, and amount of cutting or coagulation that can produce health consequences for patients and perioperative personnel.[23,29]

Surgical smoke may be as mutagenic as cigarette smoke.

Surgical smoke acts as an aerosol and particles are able to enter the upper respiratory tract through masks.[39] It also can affect the eyes and subsequently vision, which can interfere with performing surgery.[40] Of the 36 articles, 2 discussed visual obscurities as a consequence of surgical smoke.[41,42] Problems that may persist outside the OR for exposed personnel include headache, nausea, weakness, throat irritation, watery eyes, and vertigo.[43]

Pragmatic Principle

To identify markers for the pragmatic principle, we examined the applicability, usefulness, and commonality of the phenomenon of surgical smoke to determine if the concept fits and is useful among the disciplines of nursing, medicine, and both occupational and public health.[19] The broad definition of surgical smoke was a mixture of gaseous byproducts of vaporized tissue produced from heat-generating devices during surgical procedures.[24,38,44-47] However, researchers have suggested additional terms to describe surgical smoke by examining its components, which include water, vapor, and one or more of the following: viruses,[24] bacteria,[22] blood cell fragments,[33] and harmful chemicals.[22,25,26]

In the nursing literature, discussions of surgical smoke mainly focused on health consequences (eg, headache, weakness)[33,43] from exposure and the subsequent means of protection. In one nursing study, the authors suggested that nurses exposed to surgical smoke prefer to use smoke evacuation devices rather than an aspiration catheter during surgical procedures for improved air quality in the OR.[43] In another study, personnel used surgical masks as their primary protection method; 69% of nurses and surgeons reported they did not use smoke evacuation devices because there were none available.[33] In the medical, occupational, and public health literature, researchers focused on the components of surgical smoke, effectiveness of protective devices, and unintended consequences for patients and the perioperative team. The patient is at risk because surgical smoke can cause visual disturbances among the surgical team, reducing their ability to see the surgical field clearly during laparoscopic procedures.[36]

Several of the studies included in our concept analysis investigated the components of surgical smoke,[22-24,27] which included human papillomavirus DNA during cervical loop electrosurgical procedures[24] and viable cancer cells during ultrasonic scalpel use.[23] In the study involving the ultrasonic scalpel, the researchers injected laboratory mice with surgical smoke produced by the device and reported tumor growth after 14 days.[23] Other researchers have identified additional components of surgical smoke, including carcinogenic compounds (ie, butadiene, benzene, furfural)[22] and hepatitis B.[27]

Studies in the medical, occupational, and public health literature also evaluated the size of surgical smoke particles. Because surgical smoke particle sizes may vary widely,[33] the diameter may drive the process for selecting appropriate smoke evacuation devices. Cell components and chemicals <2 µm in size may become lodged in the bronchioles and alveoli, which may be harmful to the respiratory system because particles <2 µm cannot be exhaled effectively.[48] To protect the respiratory health of the perioperative team, AORN recommends that personnel evacuate surgical smoke with a 0.1-µm-filter evacuation system.[7]

Linguistic Principle

We applied the linguistic principle to determine how to describe surgical smoke appropriately and consistently

based on context.[19,20] An analysis of the linguistic principle revealed that surgical smoke was consistently used in the literature in three main working contexts:

- hazardous chemicals and toxins found in surgical smoke,[22,35,41]
- health consequences from exposure to surgical smoke,[24,32-34,37,43] and
- protection from surgical smoke.[22,33,40,45,46]

By examining the state of the science, we identified a clear, precise, and mature definition (epistemological principle) to describe and characterize surgical smoke in the OR environment.

When analyzing surgical smoke from a linguistic perspective, we noted that the literature frequently included a discussion of its chemical components[21-23,31-33,40] that expanded into a discussion of the symptoms and illnesses associated with surgical smoke exposure[31-33] and concluded with the devices used to protect the health of the perioperative team and patients.[22,33,38,40,45,49] Several studies mentioned the particulate matter found in surgical smoke during specific surgical procedures, such as liver procedures,[44] transurethral resection of the prostate,[21] robotic and laparoscopic colon resections,[27] and breast reduction procedures.[31]

Particulate matter reached unhealthy levels for OR staff members when heat-generating instruments produced surgical smoke.[30] Particulate matter counts were at the highest and most unhealthy levels for OR staff members when the surgeon used an ultrasonic device on liver tissue.[44] Additionally, researchers found hepatitis B in surgical smoke during robotic and laparoscopic colon resections[27] and identified chemicals with known cytotoxic effects during a transurethral resection of the prostate.[21]

The presence of particulate molecules in surgical smoke suggests that exposure to this byproduct can have adverse effects on human health.[21] Studies indicate that perioperative team members experience acute and chronic symptoms from exposure to surgical smoke, including

- headache,[32,33,43]
- sore throat,[32,33,43]
- coughing,[32,33]
- sneezing,[33]
- weakness,[32,43]
- eye irritation,[32,33,43]
- chronic bronchitis,[32]
- asthma,[32]
- rhinitis,[33]
- nausea,[32,33,43]
- drowsiness,[33] and
- dizziness.[32,33,43]

The presence of particulate molecules in surgical smoke suggests that exposure to this byproduct can have adverse effects on human health.

Lastly, the literature identified a variety of protective devices that reduce the risk of surgical smoke exposure. Examples included ultrasonic devices,[36] polytetrafluoroethylene (ie, Teflon)-coated electrosurgery blades,[40] smoke evacuation systems,[38,39,49] and inline filters.[41] Visibility during laparoscopic hysterectomies improved when using ultrasonic devices compared with monopolar energy-based surgical devices.[36] There was an 85% decrease in exposure to carcinogens during laparoscopic surgery when using a carbon filter for smoke evacuation.[41] Built-in-filter trocar systems employed during laparoscopic rectal cancer resections using electrosurgical and ultrasonic devices also were effective at reducing smoke.[35]

Using Teflon blades during electrosurgery decreased the amount of smoke produced,[40] and portable smoke evacuation systems reduced—but did not eliminate—surgical smoke particulates in the air.[22,46] Perioperative personnel reported using surgical masks as a protective measure instead of using portable smoke evacuation systems; however, surgical masks are ineffective at filtering surgical smoke.[33] Researchers have hypothesized that surgical smoke evacuation may prevent surgical site infections because evacuation may protect the patient by preventing live bacteria from aerosolizing and landing on the surgical equipment and instruments used during surgery.[50]

Logical Principle

The logical principle guided our determination of whether the concept of surgical smoke can stand alone or merges with other concepts.[19] We identified surgical smoke as a concept

that held its own boundaries and stood alone across disciplines. Researchers across disciplines consistently reported surgical smoke as a visible vapor with a distinct, noxious odor produced by heat-generating instruments.[23,31,32,40] Based on our concept analysis, it appears that surgical smoke is a mature concept and is recognizable if heat-generating surgical instruments are used. Because surgical smoke is only produced when personnel use heat-generating instruments to cut and cauterize tissue, it cannot be mistaken for any other phenomenon; therefore, surgical smoke holds its own boundary in vivo and in the literature. Researchers used explicit definitions of surgical smoke that left no room for confusion or doubt about the phenomenon being discussed.

The literature also revealed that surgical smoke is measurable and its particle size is based on the heat-generating instruments used during surgery.[28] Additionally, researchers consistently discussed health consequences from exposure to surgical smoke and made reference to protective measures to prevent exposure to surgical smoke. Surgical smoke can be clearly defined, measured, and controlled, and is distinguishable from similar topics when examined carefully from a logical principle perspective. Through this concept analysis, we were able to extract a clear definition of surgical smoke and provide implications for clinical practice to protect patients and health care workers in the perioperative environment.

DEFINITION OF SURGICAL SMOKE

Surgical smoke is a visible plume[32,33] of aerosolized[32,44,50] combustion byproducts[46] produced during electrosurgery. It comprises water vapor and gaseous substances.[51] Surgical smoke is suspended and distributed in the OR environment and is capable of being inhaled.[22] It is produced by the use of heat-generating surgical instruments specific to procedural settings[29,34,39,46,50,52] and can be thick enough to obscure the surgical field.[36,52] Surgical smoke has a distinctive, noxious odor[33,52] and can cause physical symptoms such as eye[40] and throat irritation.[32,43] Surgical smoke may contain toxic chemicals,[22,23,31,41,53] bacteria or viruses,[22,24,27,38,44,50] or tumor cells.[23,53] Personnel can mitigate some of these effects by employing surgical smoke evacuation devices and practices.[32,38,39,46,49,50]

Defining Characteristics

This principle-based concept analysis provided a precise and clear understanding of the phenomenon known as surgical smoke within the perioperative environment; it is classified as a mature concept.[19] Surgical smoke appears in the environment when the surgical team uses specific surgical tools to cut, resect, destroy, or cauterize living tissue for the purpose of treating or curing an underlying issue or problem for which the patient has sought help.[29,34,37,39,46,50,52] The vapor, smoke, or plume that is created when heat-generating surgical instruments are used generally occurs in a highly controlled environment with regard to personnel, air flow, temperature, and sterility.

This principle-based concept analysis provided a precise and clear understanding of the phenomenon known as surgical smoke within the perioperative environment; it is classified as a mature concept.

The cautery and laser devices that are used to cut, resect, dissect, and control bleeding do so by destroying cells and tissue, which creates a toxic, visible plume of vapor that, if not properly evacuated from the environment, may cause immediate and long-term health effects for perioperative personnel.[32,33,43] For surgical smoke to be created, the planned procedure must require heat-generating instruments. These surgical tools destroy and aerosolize tissues and cells, along with any pathogens present (eg, bacteria, viruses, tumor cells). The resulting surgical smoke is readily visible and has a distinctive, noxious odor that is unlikely to be confused with other odors.[33,52]

IMPLICATIONS FOR CLINICAL PRACTICE

By conducting a formal principle-based concept analysis, we were able to identify and describe the phenomenon of interest—surgical smoke—clearly and thoroughly. The uniform language presented in this definition facilitates an understanding of surgical smoke and its surrogate terms. The process of ascertaining the state of the science through a principle-based concept analysis has uncovered implications for research, surgical team practices, and health care leaders.

Surgical smoke is a phenomenon unique to procedural areas and creates an occupational hazard.[39] Although the long-term health consequences remain unknown, the presentation of a strong, principle-based theoretic definition of surgical smoke

Key Takeaways

- In the perioperative environment, the surgical team often is exposed to harmful chemicals, viruses, and bacteria that are emitted into the air when surgical team members use heat-generating instruments to cut and coagulate patient tissue. The byproduct emitted into the air has many identifiers, including surgical smoke, smoke plume, and surgical vapor.
- A concept analysis was conducted using a principle-based approach to identify the current state of the science, uncover the current accuracy of the concept, and analyze the scientific literature after a thoughtful and thorough inquiry to determine how best to advance the concept. After performing a literature review, the authors considered the epistemological, pragmatic, linguistic, and logical principles of the concept to construct a theoretical definition that precisely represents the current state of conceptual development for surgical smoke.
- Surgical smoke is a visible plume of aerosolized combustion byproducts produced during electrosurgery by heat-generating surgical instruments and can be thick enough to obscure the surgical field. It has a distinctive, noxious odor and can cause physical symptoms as a result of exposure or inhalation, such as eye and throat irritation.
- Surgical smoke may contain toxic chemicals, bacteria or viruses, tumor cells, or other substances that may have health consequences for perioperative personnel and patients. Personnel can mitigate some of these effects by employing surgical smoke evacuation devices and practices.

provides critical parameters that may allow rigorous research (eg, longitudinal studies) to proceed. Little research exists that identifies the actual health risk to personnel who are exposed to surgical smoke; however, we do know that some researchers have isolated toxic chemicals[22,23,31,41] and living organisms[22,27,38,39,44,50] from surgical smoke. Therefore, research is needed to determine the effect of short- and long-term exposure to surgical smoke on perioperative personnel and to identify the best approaches to control and mitigate surgical smoke and reduce occupational exposure and risk.

Patients also are exposed to surgical smoke in the perioperative environment; the effects of surgical smoke on patients are unknown. However, the effects may be mitigated by controlling or eliminating surgical smoke through consistent use of smoke evacuation devices and interventions. If heat-generating surgical devices are required for a specific procedure, the procedure setup should include preparing to use smoke evacuation devices.[7]

It is important for a culture of safety in surgical services that facility leaders help protect staff members from occupational harm by educating them on the use of smoke evacuation devices[32,45] and ensuring that perioperative personnel use these devices as first-line prevention of surgical smoke inhalation.[7] Perioperative nurse leaders should investigate the relationship between exposure to surgical smoke and perioperative personnel turnover; the effect that surgical smoke exposure has on career decision making and progression is unknown. Leaders can support a culture of surgical smoke mitigation by identifying and removing barriers to these mitigation strategies.

Defining surgical smoke also has health policy implications. At present, only two US states require surgical smoke control and mitigation by law: Rhode Island and Colorado.[16,17] Our definition provides a clear explanation of what surgical smoke is and the ways in which it is harmful. Perioperative nurses could use this information in discussions with lawmakers about the importance of mandating the evacuation of surgical smoke to prevent the consequences of this occupational hazard from affecting perioperative personnel.

LIMITATIONS

Our initial literature search was limited to the last five years, which diminished our understanding of the historical context of surgical smoke. Because many studies that defined surgical smoke were secondary sources, we needed to broaden our search date range to locate the original research to ensure accuracy in our developed definition of surgical smoke. Examining earlier literature may have helped us strengthen the concept development from a historical and evolutionary point of view.

Another key component that was lacking in the literature reviewed was identification of the amount of education needed for perioperative personnel to understand the hazards and management of surgical smoke. Overall, few studies on surgical smoke exist in the nursing literature published within the last five years. This paucity of research represents an opportunity for perioperative nurses to contribute to the body of evidence to advocate for respiratory protection for perioperative personnel and for the safety of surgical patients.

CONCLUSION

Through a principle-based concept analysis, we established a definition for surgical smoke. The concept is mature, and clinicians can use this definition to improve their practice settings, culture, and research. It also may facilitate discussion with lawmakers to craft laws that protect perioperative personnel and patients. Additional research is needed to identify the short- and long-term effects of exposure to surgical smoke on the health and well-being of perioperative personnel and patients.

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Rebecca Vortman, DNP, RN, CNOR, is a clinical assistant professor in the Department of Population Health Nursing Science, University of Illinois at Chicago College of Nursing. *Dr Vortman has no declared affiliation that could be perceived as posing a potential conflict of interest in the publication of this article.*

Sara McPherson, PhD, RN, is a clinical assistant professor in the Department of Biobehavioral Nursing Science, University of Illinois at Chicago College of Nursing. *Dr McPherson has no declared affiliation that could be perceived as posing a potential conflict of interest in the publication of this article.*

M. Cecilia Wendler, PhD, RN, NE-BC, is a clinical associate professor in the Department of Biobehavioral Nursing Science, University of Illinois at Chicago College of Nursing. *Dr Wendler has no declared affiliation that could be perceived as posing a potential conflict of interest in the publication of this article.*

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