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A systematic review of the harmful effects of surgical smoke inhalation on operating room personnel

K. Dixon[a,b,*], P. Dasgupta[c,d], N. Vasdev[e,f]

[a] Faculty of Life Sciences & Medicine, King's College London, London, UK
[b] University of Birmingham Medical School, Birmingham, UK
[c] Department of Urology, Guy's & St Thomas' NHS Foundation Trust, London, United Kingdom
[d] MRC Centre for Transplantation, King's College London, London, United Kingdom
[e] Hertfordshire and Bedfordshire Urological Cancer Centre, Department of Urology, Lister Hospital, Stevenage, United Kingdom
[f] School of Life and Medical Sciences, University of Hertfordshire, Hatfield, UK

A R T I C L E I N F O

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Surgery
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Surgeon

A B S T R A C T

Background: Surgical smoke refers to the plume produced by usage of energy-generating surgical equipment on tissues. This review aimed to assess the potential of this smoke to be a serious occupational hazard to theatre staff due to its composition, particularly during the COVID-19 pandemic.
Method: A search of Ovid MEDLINE, EMBASE, and PubMed databases was undertaken for publications reporting plume composition, presence of infectious material, carcinogenic potential and comparisons between production in laparoscopic versus open surgery. All human *in-vivo* and *ex-vivo* primary studies were included, provided English language translation was available. A narrative synthesis was conducted due to the methodologic heterogeneity of the studies.
Results: 25 studies resulted from the primary search, and an additional 3 from cross-referencing, leading to 28 included studies. Studies addressing particle size found that smoke particles were respirable in size. Viral DNA was present in 3 studies, while 2 studies demonstrated the ability for surgical smoke to produce infection of nasal epithelial cells. Chemical composition was explored in 8 studies, revealing the presence of carcinogenic compounds in concentrations above occupational safety limits. These chemicals are recognised as carcinogenic to humans by the International Agency for Research on Cancer criteria. Open surgery was found to generally produce less smoke than laparoscopic, however, both surgical methods resulted in particulate counts higher than Air Quality Index standards.
Conclusion: Surgical smoke contains a myriad of hazardous constituents, such as carcinogenic compounds and infectious materials, however, more research surrounding the implications of inhalation of surgical smoke is required to grasp the true extent to which these plumes may be harmful. Safety measures such as extraction of plumes using local exhaust ventilation, and usage of protective equipment such as N95 masks, should be instilled due to the components of this plume.

Introduction

Surgical smoke (SS) refers to the plume resulting from the thermal destruction of tissue by energy-generating surgical equipment, including electrocautery, lasers, ultrasonic scalpels, and other vessel-sealing devices; this technology has become commonplace in operating theatres, being utilised for haemostasis and tissue incision [1]. Despite the routine use of these devices, many operating theatre personnel remain unaware of their associated health risks.

The smoke generated through the use of this equipment contains gaseous and particulate composites, and may harbour hazardous chemicals, tumour fragments and infective material [2] that pose a risk to theatre staff upon inhalation. The exact composition of the plume is dependant on tissue type, whilst the size of the particulates depends on the energy device being utilised; electrocautery results in the generation of the smallest particles, whereas ultrasonic scalpels produce the largest [3]. This becomes pertinent when assessing the insidious nature of SS inhalation as the particle sizes of the components determine the extent of the respiratory risk. Current literature states particles of 10 μm in diameter may access the oropharynx upon inhalation [4], while particles smaller than 2.5 μm in diameter (PM2.5) have the ability to penetrate the defence mechanisms of the upper respiratory

* Corresponding author.
E-mail address: kxd892@student.bham.ac.uk (K. Dixon).

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Table 1
Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
• Primary studies • Documentation of 1 or more of the following: ○ Constituents of surgical smoke ○ Health implications of inhalation of surgical smoke ○ Presence of infectious or carcinogenic material in surgical smoke ○ Comparison of open and laparoscopic surgery with regards to surgical smoke • Studies of all languages, so long as reliable English translation available	• Secondary sources such as reviews, newsletters, government & legal information • Non-human studies • Opinion-based reports • Studies regarding health effects unrelated to inhalation – e.g., burns • *In-vitro* studies • Case reports

tract and reach the level of the alveoli, leading to respiratory tract irritation [5].

Additional fears surrounding SS pertain to the potential carcinogenic risk – being labelled as 'equally [as] mutagenic' as passive cigarette smoke [6] – and its infectivity potential through vaporisation of biological tissue. Since the acknowledgement of SARS-CoV-2, i.e., COVID-19, on the 31st of December 2019 by the World Health Organisation [7], concerns regarding the airborne transmission of viral matter, particularly of SARS-CoV-2, have peaked. Furthermore, this has led to concerns regarding laparoscopic surgery and whether the chimney effect of SS escaping from trocars during these procedures [8] may increase risk of COVID-19 transmission in particular.

According to the Control of Substances Hazardous to Health Regulations (COSHH), when diathermy smoke cannot be prevented, it should be controlled through the use of local exhaust ventilation (LEV) [9]. Notwithstanding this, many operating theatres continue to operate without use of such extraction devices [6] due to the noise they generate, the distractions they lead to, and the various ergonomic difficulties [10].

Within this systematic review, we aim to address the following:

(1) Is surgical smoke harmful to theatre staff?
(2) Is there an infection risk associated with surgical smoke inhalation?
(3) Is there a risk of carcinogenesis associated with surgical smoke inhalation?
(4) Does surgical smoke production vary between laparoscopic and open surgery? Our overall aim is to collate current literature to raise awareness of the harmful effects, and therefore open the door to future research surrounding long-term effects of diathermy smoke inhalation and the sufficient methods of extraction.

Methods

Search strategy

This manuscript was prepared in conjunction with The Preferred Reporting Items for

Systematic Reviews and Meta-Analyses (PRISMA) statement's 27 item checklist [11]. A comprehensive search of Ovid MEDLINE, Embase and PubMed was undertaken for studies published up to the 4th week of December 2021. The search terms included keywords such as 'surgical smoke' and its alternative terminologies, terms for the harmful effects that may be imposed by exposure, as well as 'theatre staff' and alternative phrases for those exposed to SS. Both free text terms and medical subject heading (MeSH) terms were used for PubMed and MEDLINE searches, with free text terms and Embase subject heading (Emtree) terms for Embase. The Boolean operators 'AND' and 'OR' were used when appropriate. A full list of the keywords is presented in Appendix 1. No language restrictions were installed. Once articles pertinent to our study aims were selected, additional records were identified through a reference search of these.

Study selection and inclusion/ exclusion criteria

Due to the nature of this research topic, no relevant randomised control trials have been executed, so all primary study types were included in the initial search. Initial search results were amalgamated and screened for duplicates. The retrieved studies were systematically screened by two independent reviewers – initially by title, then abstract, and finally by full text using the inclusion and exclusion criteria presented in Table 1. Any disparities between the two reviewers were settled by discussion.

Data extraction and synthesis

The following information was extracted from the full texts of included studies: first author, year of publication, country, study type, outcome measure addressed, procedure performed, electrosurgical unit (ESU) modality utilised, sample size, conclusion. Trials were categorised based on outcome measure, to allow for collation of all data surrounding a particular plume-related effect. Additional relevant material within these studies was noted for discussion, such as assessments related to the efficiency of SS evacuation methods. Of the studies containing both human and animal arms, only human results were considered. Due to the high heterogeneity of the studies, due to variations in methodology, a narrative synthesis was deemed the most appropriate approach for the synthesis of findings.

Risk of bias

To assess the quality of the included observational studies, The Newcastle-Ottawa

Scale (NOS) was utilised [12]. With this tool, studies are rated based on the categories 'selection', 'comparability', and 'outcome', and awarded a maximum of four, two, and three stars per category. Each study receives a total score ranging from zero (lowest quality) to nine (highest quality). To be considered a 'high quality' study, a score of seven or more stars was required. To assess the quality of experimental studies, the ROBINS-I tool was utilised [13]. This tool assesses risk of bias through evaluating various aspects of the methodology of the studies, such as whether there are confounding factors or any missing data. Quality appraisal was conducted by two researchers, with differences resolved through discussion.

Results

The primary systematic literature search generated 2759 studies after deduplication. Following title and abstract screening, 32 studies remained and were assessed for eligibility by full text review using the inclusion and exclusion criteria. A total of 7 studies were excluded during full text screening, and an additional 3 studies were produced through cross-referencing, leading to a total of 28 studies to be included in the final synthesis (Fig. 1). Studies were grouped by outcome measure and their key findings summarised accordingly.

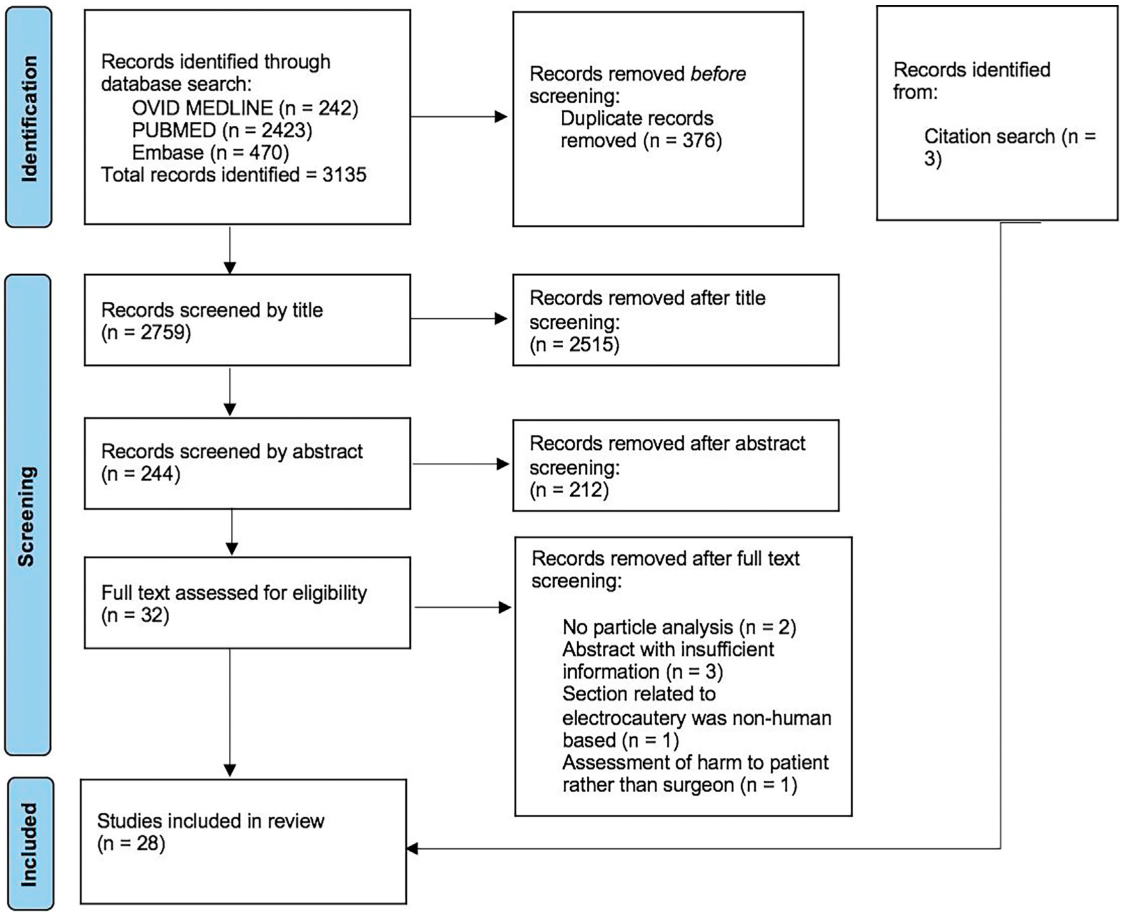

Fig. 1. Prisma 2020 flow diagram for new systematic reviews.

Dates of publication ranged from the year 1987 to 2021. Detailed characteristics of the 28 included have been summarised in Table 2. The majority of the studies ($n = 26$, 92.86%) were experimental studies, with 22 analysing SS generated from operations on living human patients, and 4 relating to surgical procedures performed on cadaveric material. The 2 remaining studies were observational in nature – 1 cohort ($n = 1$, 3.57%), 1 case control ($n = 1$, 3.57%).

Particle size

Nine studies evaluated the size of particles present in surgical plume [14–22]. Across all nine studies, the aerodynamic equivalent diameter (AED) of aerosol particles generated by surgical procedures ranged from 0.1 µm to greater than 25 µm. The tenth study solely focused on the assessment of ultrafine particles (UFPs) [23] – particles with the potential to deposit in the alveoli – and found a dominating mode diameter of 9 nm in SS generated by nephrectomy, hip replacement surgery, and transurethral resection of the prostate (TURP). Procedures such as breast reduction surgery and abdominoplasty produced UFPs with a dominating mode of 70 and 81 nm, respectively.

Chemical composition and carcinogenicity

Eight studies [24–31] explored the chemical composition of SS, along with the associated harms of said chemicals. The vast majority of chemical concentrations were below the European Union Maximum Acceptable Concentration [25], however, particular compounds, such as formaldehyde [27] and furfural [28], exceeded exposure limits set by the National Institute of Occupational Safety and Health (NIOSH).

Formaldehyde levels continued to exceed NIOSH limits following filtration [27]. Additionally, Zhao et al. [31] reported that more gases were generated in electrosurgery of malignant tumour tissues compared to benign.

One study determined the carcinogenicity of SS produced during mastectomy by estimating a cancer risk for 70-year lifetime exposure of 117×10^{-6} for surgeons and 270×10^{-6} for anaesthetic technologists (ATs) due to the concentration of polycyclic aromatic hydrocarbons [32]. These estimations were calculated by using a toxicity equivalency factor. Cancer risk was higher in ATs due to longer working hours in the operating theatres. Total lifetime cancer risks to the surgeons and ATs were 46.8×10^{-6} and 29.3×10^{-6} per hour exposure respectively, with risk per hour being higher for surgeons due to closer contact to the plume.

A comprehensive list of all chemical compounds detected in SS throughout these studies is displayed in Table 3, with chemicals that are carcinogenic to humans according to the International Agency for Research on Cancer (IARC) criteria [33] being marked with an Asterix.

Infection risk

Of the seven publications [34–40] addressing infection risk associated with SS, four examined whether human papillomavirus (HPV) DNA was present in SS. Three out of the four studies found evidence of HPV DNA in 56.67% [34], 16.67% [35] and 29.9% [36] of samples. Zhou et al. extended their experiment to calculating the positive rate of HPV DNA in the nasal epithelial cells of surgeons after performing a loop electrosurgical excision procedure (LEEP), finding a positive rate of 1.5% [36]. The detected HPV subtypes were HPV-6, HPV-11, HPV-16,

Table 2
Study characteristics of included studies.

Refs.	Country	Study design	Outcome measure	Surgery performed	Type of intervention	N	Conclusion
Capizzi, P.J 1998	USA	Experimental	Bacterial and viral infection risk	Facial resurfacing	CO_2 laser	13	5/13 bacterial cultures resulted in growth of coagulase-negative Staphylococcus- 1/5 had growth of Corynebacterium and 1/5 had growth of Neisseria. No viral growth
Chung, Y. J 2010	Japan	Experimental	Carcinogenicity / chemical composition	TURP	Electrosurgery	12	3 of the chemicals found were toxic gases: carcinogens 1,3-butadiene, vinyl acetylene and acrylonitrile
DesCoteaux, J. G 1996	Canada	Experimental	Particle size	Laparoscopic: Cholecystectomy Sigmoid resection Nissen	Electrocautery	5	Particle diameters ranging from 0.1 to >25 μm, with most being 0.1–1μm
Dobrogowski, M 2015	Poland	Experimental	Carcinogenicity / chemical composition	Laparoscopic cholecystectomy	Electrosurgery	Unstated	Many mutagenic, carcinogenic and teratogenic compound found within smoke samples. Concentrations were below the hygienic standards allowed by the European Union Maximum Acceptable Concentration
Gianella, M, 2014	Switzerland	Experimental	Carcinogenicity / chemical composition	Laparoscopic colorectal resections	LigaSure	6	Harmless concentrations of methane, ethane) and ethene detected. Traces of carbon monoxide and of the anaesthetic sevoflurane
Gloster, H. M 1995	USA	Case control	Viral infection risk	Laser wart removal	CO_2 laser	31 surgeons 6124 patients	CO_2 laser surgeons no more likely to acquire warts than a person in the general population.
Ha, H. I, 2019	Korea	Experimental	Carcinogenicity / chemical composition	Laparoscopic gynaecological	Electrocautery	7	5 volatile organic compounds and 5 aldehydes. Most chemicals were below the exposure limits set by NIOSH. Formaldehyde concentration before and after filtration was above the NIOSH limit
Hollmann, R. 2004	Switzerland	Experimental	Carcinogenicity / chemical composition	Mammoplasty	Electrocautery	1	11 gas components were identified. 2-fur-ancarboxaldehyde (furfural) concentration was 12 times higher than the occupational exposure limit
Hu, X. 2021	China	Cohort	Viral infection risk	LEEP	Electrosurgery	700	HPV infection rate of participants performing electrosurgery or LEEP significantly higher than controls. Most prevalent genotype was HPV16
Kameyama, H 2021	Japan	Experimental	Laparoscopic versus open	Colectomy	Electrosurgery	31	PM2.5 counts during operation were significantly higher in open surgery compared to laparoscopic. Concentrations considered 'unhealthy for sensitive groups' by AQI standards
Kashima, H. K 1991	USA	Experimental	Viral infection risk	Excision of laryngeal lesions	CO_2 laser	22	HPV-6 or HPV-11 identified in 17/30 samples from recurrent respirator papillomatosis (RRP) lesions and in 0/3 non-RRP lesions.
Li, C. I 2020	Taiwan	Experimental	Particle size Laparoscopic versus open	Obstetric and gynaecological procedures	Electrosonic knife	30	Particle size of 0.3 μm was highest in concentration. Cumulative particle numbers of 0.3 μm and 0.5 μm in laparoscopic surgery were higher than those in laparotomy
Liu, Y 2021	China	Experimental	Carcinogenicity / chemical composition	LEEP	Electrosurgery	5	Smoke contained potentially toxic chemicals such as Formaldehyde concentration was significantly higher during surgery than before
Neumann, K 2018	Germany	Experimental	Viral infection risk	LEEP	Electrosurgery	24	Surgical plume contaminated with high-risk HPV in 4/24 patients. Subtypes: HPV-16, 39, 53
Nezhat, C 1987	USA	Experimental	Particle size	Laparoscopic treatment of endometriosis and/or adhesions	CO_2 laser	17 patients 32 plume samples	Median aerodynamic particle diameter: 0.31 μm with a range of 0.10–0.80μm
Okada, Y 2017	Japan	Experimental	Carcinogenicity / chemical composition	TURP	Electrosurgery	54	2 known carcinogens found: benzene, ethylbenzene
Radge, S. F 2016	Norway	Experimental	Particle size	Nephrectomy TURP Hip replacement Breast reduction Abdominoplasty	Electrosurgery	Unstated	Nephrectomy, TURP and hip replacement surgery produced smallest sized particles Breast reduction surgery and abdominoplasty produced larger sized particles
Sharma, D 2021	USA	Experimental	Particle size	Rigid nasal endoscopy Postoperative debridement	Unstated	24	Aerosol particles during postoperative debridement: 0.30–10.0 μm. Particle size during rigid nasal endoscopy: 2.69–10.0 μm

(*continued on next page*)

Table 2 (*continued*)

Refs.	Country	Study design	Outcome measure	Surgery performed	Type of intervention	N	Conclusion
Subbarayan, R. S 2020	USA	Experimental	Viral infection risk	Transoral resection of oropharyngeal cancer	Electrocautery	6	No detectable HPV16 DNA in the electrocautery fumes.
Tan, W, 2019	China	Experimental	Particle size	Hemihepatectomy	Electrosurgical knife Ultrasonic scalpel	50	PM2.5 produced throughout operations. Highest concentration produced by the electrosurgical knife was from liver tissue, followed by muscle, adipose and vascular.
Taravella, M. J 2001	USA	Experimental	Particle size	Corneal stroma ablation	Laser	2	Mean particle diameter of 0.22 μm (range 0.13–0.42 μm).
Taweerutchana V, 2021	Thailand	Experimental	Laparoscopic versus open	Cholecystectomy	Electrosurgery	12	Particle size counts were all higher in open versus laparoscopic. Smoke evacuator use led non-significant decrease in particles.
Tseng Hsin-Shun, 2014	Taiwan	Experimental	Carcinogenicity	Mastectomy	Electrocautery	10	Cancer risk for surgeons calculated to be 117×10^{-6}. Cancer risk for anaesthetic technologist was calculated to be 270×10^{-6}.
Wang, H. K 2015	China	Experimental	Particle size Laparoscopic versus open	Inguinal lymph node dissection Partial nephrectomy Radical prostatectomy Laparoscopic partial nephrectomy TURBT	Electrosurgery	25	In superficial, abdominal and pelvic: peak PM2.5 concentrations of 245.7, 149.4, 165.1 μg/m^3 3– In laparoscopic: peak concentration was 517.5 μg/m^3 after opening trocar valve ('hazardous' according to AQI)
Ye, M. J 2021	USA	Experimental	Particle size	Mandible and midface fixation	Electrocautery	2	Particles sized from 0.300 to 6.451 μm. Average change from baseline particle concentration was 317% higher in the standard group
Ye, M. J 2021	USA	Experimental	Particle size	Orbital repair	Electrocautery	6	Aerosol concentrations during standard electrocautery were significantly higher than control in all size groups
Zhao, C 2013	China	Experimental	Carcinogenicity / chemical composition	TURB TURP	Electrosurgery	36	39 gases generated from TURB. 16 gases generated from the TURP. There were differences in the types of gases between benign hypertrophic prostate and malignant bladder tumour tissues
Zhou, Q 2019	China	Experimental	Viral infection risk	LEEP	Electrosurgery	134 outpatients 31 surgeons	Positive rate of HPV in smoke was 29.9%. Positive rate in the nasal epithelial cells of surgeons after LEEP was 1.5%

Legend:.
TURP Transurethral resection of the prostate.
TURB Transurethral resection of the bladder.
TURBT Transurethral resection of bladder tumour.
LEEP Loop electrosurgical excision procedure.
AQI Air Quality Index.
NIOSH National Institute for Occupational Safety & Health.

HPV-39, HPV-53, HPV-33, HPV-52, HPV-58 [34–36]. The fourth study yielded no detectable HPV16 DNA in the SS [37].

Additionally, two out of the seven publications addressed whether viral matter in SS could produce infection in theatre staff. One concluded that CO2 laser surgeons were no more likely to acquire HPV warts than a person in the general population [38], while the second study revealed the rate of HPV infection in nasal epithelial cells was significantly higher in surgeons performing LEEP than in those who did not perform this procedure [39].

The final study confirmed the presence of bacterial activity in SS by demonstrating that 38.46% of SS samples from patients undergoing laser resurfacing resulted in bacterial cell culture growth of coagulase-negative Staphylococcus [40]. One of the five samples that tested positive for Staphylococcus also grew Corynebacterium, with another growing Neisseria.

Laparoscopic versus open surgery

Four of the included studies [15,20,41,42] compared the concentration of SS particles generated by laparoscopic and open surgery. Two of the four studies recorded real-time PM(2.5) concentrations, with one study reporting significantly greater concentrations in open surgery compared to laparoscopic [41], and the other contrastingly demonstrating that peak PM(2.5) concentration was greater in laparoscopic urological surgeries following the opening of the trocar valve than in superficial, abdominal and pelvic open surgeries [20]. Both studies were in agreement that the particle counts they had recorded exceeded Air Quality Index standards, labelling them as 'unhealthy for sensitive groups' [42] and both 'unhealthy' or 'very unhealthy', and 'hazardous' in open and laparoscopic surgery respectively [20]. The remaining two studies concluded that particle counts were higher in open versus laparoscopic surgery [42,15] for overall particle count, particle sizes under 5 μm and particles greater than 5 μm in diameter [42]. Two of the four studies concluded that smoke extraction reduced particle concentration, but non-significantly [20,42].

Risk of bias

A low risk of bias was found in 25 experimental studies, with no studies having a critical risk. The risk of bias assessment of experimental studies is presented in Table 4. One observational study was 'high

Table 3
List of chemical compounds detected in surgical smoke.

Chemical	CAS no.	Reference	Chemical	CAS no.	Refs.
Propylene	115–07–1	24, 31	*Acrylonitrile**	107–13–1	[24,29,31]
Allene	463–49–0	24, 31	*Butyrolactone*	96–48–0	[24,31]
Isobutylene	115–11–7	24, 28, 31	*Other Aldehydes*		[25,27,28,31]
1,3-butadiene*	106–99–0	24, 28, 31	*Benzene**	71–43–2	[25,27,29–31]
Vinyl acetylene*	689–97–4	24, 31	*Toluene*	108–88–3	[25,27–31]
Mecaptomethane	60–24–2	24, 31	*Ethylbenzene**	100–41–4	[25,27,29–31]
Ethyl acetylene*	107–00–6	24, 31	*Xylene**	1330–20–7	[25,27,29,31]
Diacetylene	460–12–8	24, 31	*Furfural*	98–01–1	[28]
Ethanol	64–17–5	24, 31	*Dioxins*		[25]
Piperylene	504–60–9	24, 31	*Methane*	74–82–8	[26]
Propenylacetylene	2206–23–7	24, 31	*Ethane*	74–84–0	[26]
1,4-pentadiene	591–93–5	24, 31	*Ethylene*	74–85–1	[26,28]
Cyclopentadiene	542–92–7	24, 31	*Carbon monoxide*	630–08–0	[26,29]
Styrene	100–42–5	27, 29	*Sevoflurane*	28,523–86–6	[26]
Formaldehyde	50–00–0	27	*Ammonia*	7664–41–7	[28]
Ozone	10,028–15–6	25	*1-Decene*	872–05–9	[28]
Methacrolein	78–85–3	25	*1-ethenyl 3-methylbenzene*	100–80–1	[28]
Acetone	67–64–1	25, 31	*Heptene*	592–76–7	[28,30,31]
Furans		25	*Thiocyanic acid*	463–56–9	[28]
Butyl acetate	123–86–4	29	*Propanenitrile*	107–12–0	[28]
1,2-dichloroethane	107–06–2	29	*1-chloro-1,1-difluoroethane*	75–68–3	[31]
Phenol	108–95–2	29	*Chlorine*	7782–50–5	[29]
Cyanide	57–12–5	29	*Hydrogen cyanide*	74–90–8	[29]
Vinylcyclopentane	3742–34–5	30	*1-Octene* 111–66–0		[30]
Cyclohexane	110–82–7	30	*1-Undecanol*	112–42–5	[30]
Doducane	112–40–3	30	*1-Pentene*	109–67–1	[24,31]
Pentafluoroethane*	354–33–6	31	*m-Ethyltoluene*	620–14–4	[31]
Isopropyl alcohol	67–63–0	31	*2-methoxyethanol*	109–86–4	[31]
Hexane	110–54–3	31	*Isopentanal*	110–62–3	[31]
Cyclohexane	110–82–7	31	*n-Heptane*	142–82–5	[31]
2,6-Dimethyloctane	2051–30–1	31	*1,1-Ethylenedioxy-2-Phenylpropane*		[31]
Methylcyclohexane	108–87–2	31	*3-Methyloctane*	2216–33–3	[31]
2-Methylnonane	871–83–0	31	*n-Octane*	111–65–9	[31]
3-Methylnonane	5911–04–6	31	*1,3,5-Trimethylbenzene*	108–67–8	[31]
2 Ethylhexanol	104–76–7	31	*3,3-Dimethyloctane*	4110–44–5	[31]
Dodecane	112–40–3	31	*Isopropylbenzene*	98–82–8	[31]
2,4-Dimethyl-1-Decene	55,170–80–4	31	*Ethylcyclohexane*	1678–91–7	[31]
Hexadecane	544–76–3	31	*5,6-Dimethyl-Undecane*	1636–43–7	[31]
Heptadecane	629–78–7	31	*2,3-Dimethylnonane*	2884–06–2	[31]
Acetaldehyde*	75–07–0	31			

Legend:.
CAS no. Chemical Abstracts Service number.
* = carcinogenic to humans according to IARC.

quality', while the other was considered high risk of bias. The risk of bias assessment for observational studies is presented in Table 5.

Discussion

This systematic review acts as an update of the 2013 review by Mowbray et al. [43] which concluded that the full risk of infective cells in SS to the theatre staff is unproven and future work regarding long-term consequences of smoke exposure is required. Since then, many studies have been published, particularly regarding viral transmission due to the onset of the COVID-19 pandemic. With the addition of recent data, evidence regarding the infective potential of SS, along with carcinogenicity has increased.

Several lines of evidence regarding viral transmission through occupational exposure to SS surround the risk of HPV spread, concluding that HPV DNA can exist within surgical plume [34–36], and that this viral matter could produce infection of the nasal epithelial cells of theatre staff [36,39]. Less evidence surrounding the possibility of SARS-CoV-2 infection through exposure to SS exists, however, a 2021 paper [44] explored the transmission of SARS-CoV-1 and SARS-CoV-2 during aerosol-generating procedures. This paper concluded that specific aerosol-generating procedures, such as endotracheal intubation, are high risk for the transmission of these viruses from patients to healthcare workers through the inhalation of the plume. Furthermore, safety equipment – N95 masks, gloves and gowns – were found to be significantly protective to the healthcare workers performing these procedures from contracting COVID-19. The evidence presented in this study, combined with the ability for SARS-COV-2 to remain viable and infective in aerosols for at least 90 min [45], along with the positive evidence for detection of other viral matter – such as HPV DNA – in SS, suggests that transmission of SARS-COV-2 through SS inhalation may be possible. These findings also support the conclusion for the utilisation of protective equipment. More evidence regarding the detection of SARS-COV-2 in SS is required in order to prove these hypotheses with certainty.

The long-term consequences of SS exposure have been explored through studies included in this latest review. In particular, a study by Zhou et al. reported that HPV infection rate in surgeons completing LEEP for cervical intraepithelial neoplasia [36] was 6.45%, with 2 surgeons testing positive for HPV DNA in their nasal epithelial cells; these genotypes were consistent with those in the corresponding SS, therefore demonstrating the risk of airborne transmission of HPV DNA to surgeons. These surgeons were consequently followed up for 6 months via nasal swabs, and tested negative for HPV DNA. This provides insight into long-term effects, demonstrating that the HPV DNA was not persistent. In addition to this, another study regarding HPV infection

Table 4
ROBINS-I assessment of experimental studies.

Refs.	Bias due to confounding	Bias in selection of participants into study	Bias in classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reported result	Overall risk of bias
Capizzi et al., 1998	Low	No information	Low	Low	Low	Moderate	Low	Low
Chung et al., 2010	Low	Low	Low	Low	Low	Low	Low	Low
DesCoteaux et al., 1996	Low	Low	Low	Low	Low	Moderate	Moderate	Low
Dobrogowski et al., 2015	Low	Low	Moderate	Low	Low	Low	Moderate	Low
Gianella et al., 2014	Low	Low	No information	No information	Low	Moderate	Low	Low
Ha et al., 2019	Low	Low	Low	Low	Low	Moderate	Low	Low
Hollmann et al., 2004	Low	Low	Low	Low	Low	Low	Low	Low
Kameyama et al., 2021	Low	Low	Low	Low	Low	Moderate	Low	Low
Kashima et al., 1991	Low	Low	Low	Low	Low	Moderate	Low	Low
Li et al., 2020	Low	No information	Low	Low	Low	Low	Moderate	Low
Liu et al., 2021	Low	Low	No information	Low	Low	Moderate	Low	Low
Neumann et al., 2018	Low	Low	Low	Low	Low	Low	Low	Low
Nezhat et al., 1987	Low	Low	Low	Low	Low	Low	Low	Low
Okada et al., 2017	Low	Low	Low	Low	Low	Low	Low	Low
Radge et al., 2016	Low	Low	Low	Low	Moderate	Low	Moderate	Low
Sharma et al., 2021	Low	Low	No information	Low	Low	low	Low	Low
Subbarayan et al., 2020	Low	Low	Low	Low	Low	Low	Low	Low
Tan et al., 2019	Moderate	No information	No information	Low	Low	Moderate	Low	Moderate
Taravella et al., 2001	Low	Low	Low	Low	Low	Low	Low	Low
Taweerutchana V, 2021	Low	Low	Low	Low	Low	Moderate	Low	Low
Tseng Hsin-Shun, 2014	Low	Low	Low	Low	Low	Low	Low	Low
Wang et al., 2015	Low	No information	Low	Low	Low	Low	Low	Low
Ye et al., 2021	Low	No information	No information	Low	Low	Low	Low	Low
Ye et al., 2021	Low	Low	Low	Low	Low	Low	Low	Low
Zhao et al., 2013	Low	Low	Low	Low	Low	Low	Low	Low
Zhou et al., 2019	Low	No information	Low	Low	Low	Low	Low	Low

Table 5
NOS assessment of observational studies.

Refs.	*Article title*	*Selection*	*Comparability*	*Outcome*	*Total*
Gloster et al., *1995*	Risk of acquiring HPV from the plume produced by the COS laser in the treatment of waters	*	*	*	3
Hu et al.*, 2021*	Prevalence of HPV infections in surgical smoke exposed gynaecologists	**	**	***	7

rate in the nasal epithelial cells of gynaecologists performing electrosurgery followed up the 46 surgeons who were infected with HPV and found that 43.48% became negative after 3 months, and 100% after 24 months [39]. These studies provide evidence that surgeons exposed to SS are at risk of acquiring HPV infection, although there seem to be no associated long-term consequences. These articles are recent, being performed in 2019 and 2021 respectively, and therefore provide up-to-date findings. Separate from this review, there have been a number of case reports regarding longstanding exposure to SS resulting in long-term HPV infection and carcinoma. In 2013, A 53-year-old male gynaecologist, with no risk factors except 20 years of exposure to laser plume generated by LEEP, presented with HPV-16 positive tonsillar squamous cell carcinoma [46]. In this same report, the case of a 62-year-old gynaecologist who developed HPV-16 positive base of tongue cancer following 30 years of LEEP was discussed. However, anecdotal reports can only infer, not deduce, as they cannot demonstrate a definite link between exposure and effect.

With regard to particle size and chemical composition of SS, all studies included are in agreement of the rough particle size ranges present in the smoke, along with the chemicals contained within. However, the study regarding UFP concentration [23] states that their experimental study, and experimental studies in general, have difficulty determining how great the amount of particle loss during collection is, and for which particle sizes, indicating that estimations of the particle sizes may not be completely representative as certain sizes may not be detected. This missing data could be a cause of information bias.

Findings relating to chemical composition are consistently a source of concern given the presence of carcinogenic compounds such as formaldehyde [27]. Inhalation of formaldehyde in itself can lead to bronchospasm, pulmonary oedema and organ damage; it is a dangerous chemical with no antidote [47]. When this is considered along with the presence of carcinogens such as benzene [25,27,29–31] – which can cause leukaemia with long-term exposure [27] – and other toxins, the constituents are confirmed to be a definite health risk. However, the key aspect is concentrations of these constituents, which have been reported as too low [27] to cause serious risk to exposed workers. Nevertheless, it must be acknowledged that particular compounds, such as formaldehyde, were found in concentrations above NIOSH recommendations and may still provide a degree of harm [27]. Moreover, included studies have reported that particular chemical concentrations remained above NIOSH recommendations following extraction [27,28], which opens the door to the need for more research surrounding the effectiveness of such extraction devices. Additionally, the plume generated from electrocautery of malignant tumours contained more carcinogenic gases than the plume generated from electrocautery of benign tissue [31]; this may imply an increase in toxicity of SS generated from malignant tissue.

Concern surrounding the funnelling of SS during laparoscopy [8] has led to fears of increased risk of COVID-19 transmission due to the increased generation, and therefore inhalation, of SS. Within this review, three studies demonstrate higher concentrations of particles in open surgery [15,41,42], with one study reporting higher concentrations in laparoscopic surgery following the removal of the trocars [20]. This suggests that SS is beneficially contained within the cavity during laparoscopic surgical procedures, and smoke levels during laparoscopy only rise above those of open upon removal of trocars. The literature thereby insinuates that conversion from laparoscopic to open surgery in the midst of the COVID-19 pandemic solely based on the risk of aerosol contamination may be counterintuitive. More evidence is required for a definitive conclusion to be made regarding the necessity of protocol changes. Methods to facilitate the reduction in aerosol contamination in laparoscopic surgery include the complete desufflation of the pneumoperitoneum at the end of the surgical procedure to remove the enclosed gas and surgical smoke from the abdomen, along with the addition of smoke evacuation systems [48], such as the AirSeal System. It has been suggested that these modifications to surgical practice may reduce the risk COVID-19 aerosol transmission to operating room personnel [48].

Conclusion

This review has collated evidence surrounding the potential for SS to act as an occupational hazard for operating theatre staff. Following critical analysis of the literature, it can be concluded that live viral and bacterial particles have the potential to persist within the smoke, however, high-level evidence confirming the infectivity potential of the smoke does not exist. Studies to date have demonstrated a possible link between SS exposure and HPV infection, with long-term follow-ups suggesting that SS did not cause permanent health problems. Carcinogenic chemicals were found to be present within the plume, however, the overall carcinogenic potential of the smoke appears to be low. The practical implications of this review are that a push for appropriate use of smoke evacuation devices – such as local exhaust ventilation systems – and protective equipment – such as N95 surgical masks – are required. Additionally, there is a need for evidence-based research evaluating the efficiency of these methods of prevention. With regard to laparoscopic versus open surgery, insufficient data has been acquired to support the contraindication of laparoscopic surgery solely based on risks associated with SS.

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Appendix 1. Details of literature search

Database	Search terms	Limits applied
PubMed	1. surgical smoke OR airborne byproducts OR diathermy OR plumes OR cautery 2. harmful effects or effects or respiratory or health problems or hazards or cancer or COVID-19 3. theatre staff or surgeons or operating staff or healthcare professionals or healthcare workers or personnel 4. 1 AND 2 AND 3	Human only studies
Embase	1. surgical smoke*.mp. or electrosurgery 2. airborne byproducts OR diathermy OR plumes OR cautery 3. 1 or 2 4. harmful effects or effects or respiratory or health problems or hazards or cancer or COVID-19 5. theatre staff or surgeons or operating staff or healthcare professionals or healthcare workers or personnel 6. 3 AND 4 AND 5	Human only studies
MEDLINE	1. surgical smoke$.mp. or Electrocoagulation/ or Electrosurgery 2. airborne byproducts OR diathermy OR plumes OR cautery 3. 1 or 2 4. harmful effects or effects or respiratory or health problems or hazards or cancer or COVID-19 5. theatre staff or surgeons or operating staff or healthcare professionals or healthcare workers or personnel 6. 3 AND 4 AND 5	Human only studies

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