Surgical Smoke – A Review of the Literature

a report by
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Electrocautery, laser tissue ablation and ultrasonic (harmonic) scalpel tissue dissection all create a gaseous by-product, commonly referred to as 'smoke', that can be seen and smelt easily. Concern about this smoke has led to numerous investigations in an effort to determine what, if any, risks this by-product poses to surgeons, operating room (OR) personnel and/or patients. Some of the findings from these investigations have led to significant concerns regarding the safety of surgical smoke.

What is Known?

General

Electrocautery, laser tissue ablation and ultrasonic (harmonic) scalpel tissue dissection all produce a smoke or aerosol with different properties. The mean aerodynamic size of particles generated varies greatly depending on the energy method used to create them. Electrocautery creates particles with the smallest mean aerodynamic size (0.07*u*m),[1] while laser tissue ablation creates somewhat larger particles (0.31*u*m),[2] with the largest particles being generated by the ultrasonic (harmonic) scalpel (0.35–6.5*u*m).[3] In general, smaller particles are more concerning from a chemical standpoint, and larger particles are more concerning from a biological standpoint.

Electrocautery

The chemicals present in the greatest quantity in electrocautery smoke are hydrocarbons, nitriles, fatty acids and phenols.[4] Of these chemicals, carbon monoxide (CO) and acrylonitrile are the most concerning. Other chemicals present in smaller quantities, but which are still of significant concern, include hydrogen cyanide, formaldehyde and benzene. Benzene has been proposed to be significantly responsible for the mutagenicity of electrocautery smoke.

CO production is of particular concern in laparoscopic procedures where smoke is trapped and concentrated in the peritoneal cavity. High levels of CO are produced during laparoscopic cholecystectomy.[5] Electrocautery during laparoscopic procedures has been shown to increase intra-abdominal CO to 'hazardous' levels, leading to small yet significant elevations of carboxyhaemoglobin (COHb).[6] Levels of CO in the intra-abdominal cavity at the end of a laparoscopic cholecystectomy have been found to be 100–1,900 parts per million (ppm)[5] above the 35ppm for a one-hour exposure set by the US Environmental Protection Agency (EPA).[7] In addition, CO is readily absorbed from the peritoneum into the bloodstream, creating a route for systemic intoxication.[8]

Acrylonitrile is a colourless, volatile liquid that is absorbed easily through the skin and lungs and exerts its toxicity by liberating cyanide.[9] The Occupational Safety and Health Administration (OSHA) has set the upper limit of ambient exposure to this substance at 2ppm. Exposure levels of OR personnel have been shown to be 1–1.6ppm, just under the established limit.[6]

Hydrogen cyanide is a toxic, colourless gas that is absorbed easily by the lungs, gastrointestinal tract and skin. It combines with ferric iron in cytochrome oxidase, thereby inhibiting cellular oxygen utilisation. In addition, it can act synergistically with CO in impairing tissue oxygenation. The US Department of Health and Human Services has set the short-term exposure limit at 10ppm. Levels in the ambient environment of the OR in one particular experiment were found to reach a mean of 5.7ppm and up to 10ppm, just at the allowed exposure limit.[6]

Laser

Numerous chemicals have been found in the plume generated by laser tissue ablation, including benzene, formaldehyde, acrolein, CO and hydrogen cyanide. These chemicals have been found in the smoke plume from both carbon dioxide and neodymium-doped yttrium aluminium garnet (Nd:YAG) laser interaction, even at very low power densities.[10] Cellular clumps and erythrocytes have also been found, suggesting the plume's infectious potential with lower irradiance levels producing more viable particles.[11]

To support the theory of potential infectivity, intact strands of human papillomavirus (HPV) DNA have been isolated from carbon dioxide laser plume during treatment of plantar warts[12,13] and in laser smoke from recurrent respiratory papillomatosis.[14] Viable bacteriophage have also been demonstrated to be present in laser plume.[15,16] The average size of particles carrying viable bacteriophage was determined to be quite large with a mean aerodynamic diameter of 7–55*u*m.[17] Whole intact virions have also been found and their infectivity demonstrated.[18]

In addition to viruses and virus particles, bacteria have been cultured from laser plume in two *in vitro* experiments.[19,20] A recent and more elaborate study demonstrated clearly the presence of infectious viral genes, infectious viruses and viable cells.[21]

Concern for the transmission of HIV infection led to a study that was able to identify HIV DNA in laser smoke and was able to demonstrate transmission of infection to cultured cells.[22] This infection lasted up to 14 days but did not last 28 days, suggesting that the DNA had been altered in a way that prevented its propagation after infection.

Ultrasonic (Harmonic) Scalpel

Large quantities of cellular debris (>1x107 particles/ml) were found in the plume generated by an ultrasonic scalpel and were approximated to be one-quarter the amount of particle concentration when compared with the plume generated by dissection of a similar amount of tissue with electrocautery.[3]

Concentrations of liquid (blood or serum) aerosol were produced in a directional spray pattern when either the hook or ball-tip was used and were detected up to 40cm from point of production.[3] In addition, fatty tissue was found to generate 17–23 times more particulate matter than lean tissue.

The ultrasonic scalpel is said by the manufacturer to produce a 'vapour,' not smoke, and the process has been described as low-temperature vapourisation.[23] This is concerning because cool aerosols in general have a higher chance of carrying infectious and viable material than higher-temperature aerosols.[24] One study stated that the particles created by the ultrasonic (harmonic) scalpel are composed of tissue, blood and blood by-products.[3]

Potential Hazards

Surgical smoke and aerosols are potentially dangerous to both OR personnel and patients. The potential risks to OR personnel include pulmonary irritation and inflammation, transmission of infection and genotoxicity. The potential dangers to patients occur primarily during laparoscopic procedures where surgical smoke is concentrated in the peritoneal cavity. These potential dangers include CO toxicity, port-site metastases from cancer spread through aerosolised cells and toxicity to the peritoneal compartment and its contents. Intra-peritoneal smoke also impairs visualisation of the surgical field. It is therefore necessary to recognise the evidence for these potential dangers and determine to what degree these potential dangers are a reality.

Respiratory Irritation

Many of the by-products resulting from pyrolysis of tissue are respiratory irritants.[25] It has been shown clearly that laboratory rats develop pulmonary congestion and lung abnormalities when exposed to a relatively large quantity of surgical smoke.[26] More specifically, it has been shown that surgical smoke can induce acute and chronic inflammatory changes including alveolar congestion, interstitial pneumonia, bronchiolitis and emphysematous changes in the respiratory tract.[27,28]

A study by the National Institute for Occupational Safety and Health (NIOSH) evaluated the air that OR personnel were exposed to during laser procedures and found that detectable levels of ethanol, isopropanol, anthracene, formaldehyde, cyanide and airborne mutagenic particles were found.

In a study performed during reduction mammoplasty, concentrations of airborne particles in the OR around OR personnel ranged from 0.4 to 9.4 milligrams per cubic metre (mg/m^3) of air. These levels were just below the allowable levels for nuisance dust evaluation criteria from OSHA ($15mg/m^3$) and The American Conference of Governmental Industrial Hygienists (ACGIH) ($10mg/m^3$).[29] These evaluation criteria, however, may not apply to surgical smoke because nuisance dust is assumed to be inert. In addition, it was found that laser vapourisation of more than three grammes of tissue would produce enough acrolein and polycyclic aromatic hydrocarbons to exceed OSHA limits for these chemicals in $1m^3$ of air.

Genotoxicity

Smoke has been shown to be mutagenic and therefore genotoxic.[30–32] The specific method of genotoxicity is most likely multifactorial and may include chemical and biologic modalities. Certain HPV types that infect the genital region preferentially have been found in a majority of cervical carcinomas and in a few oral and laryngeal malignancies, suggesting HPV DNA exposure as a risk factor.[33–35] One study pointed out that partial

Box 1

Chemicals Identified within Electrosurgical Smoke

Acetonitrile
Acetylene
Acroloin
Acrylonitrile
Alkyl benzene
Benzaldehyde
Benzene
Benzonitrile
Butadiene
Butene
3-Butenenitrile
Carbon monoxide
Creosol
1-Decene (hydrocarbon)
2,3-Dihydro indene (hydrocarbon)
Ethane
Ethene
Ethylene
Ethyl benzene
Ethynyl benzene
Formaldehyde
Furfural (aldehyde)
Hexadecanoic acid
Hydrogen cyanide
Indole (amine)
Isobutene
Methane
3-Methyl butenal (aldehyde)
6-Methyl indole (amine)
4-Methyl phenol
2-Methyl propanol (aldehyde)
Methyl pyrazine
Phenol
Propene
2-Propylene nitrile
Pyridine
Pyrrole (amine)
Styrene
Toluene (hydrocarbon)
1-Undecene (hydrocarbon)
Xylene

viral or oncogene sequences can pose a significant health hazard for exposed personnel since they may have transforming potential and demonstrated less risk the further from the point of smoke production.[36] As stated before, it has been proposed that benzene is significantly responsible for the mutagenicity of electrocautery smoke.

CO in the Peritoneal Cavity

CO is one of the greatest constituents of surgical smoke. Exposure to CO can cause a plethora of signs and symptoms including headache, fatigue, nausea, vomiting, cardiac dysrhythmias, myocardial ischemia, lactic acidosis, syncope, convulsion and coma, depending on the degree of exposure and susceptibility of the individual.[37,38]

Elevated levels of intra-peritoneal and systemic COHb due to peritoneal absorption of CO during routine laparoscopic cholecystectomy have been found.[39] Absolute levels of intra-peritoneal CO in this study were found to increase from an average of 4.7ppm to an average of 326ppm and to peak levels of 686ppm at gall bladder take-down. COHb levels were found to increase from 0.7% +/− 0.6% to 1.2% +/− 0.7%.

The EPA has set the goal of maintaining non-smokers' COHb below 2%.[40] Levels of 2% to 4% have been found to significantly decrease the time of onset of angina in persons with coronary artery disease[41,42] and decreased behavioural performance.[43] When surgical smoke is not evacuated during laparoscopic procedures, an increase in MetHb and COHb occurs while oxygenation of tissue decreases. MetHb increases can remain above normal levels for up to six hours after a procedure and these changes make pulse oximetry inaccurate.[44] Levels in one study were found to be above the generally accepted human threshold tolerance level of 2%.[37]

Other studies have revealed that aggressive smoke evacuation and aggressive ventilation with high oxygen concentrations can offset the rise in COHb levels.[45] In this study, smoke was evacuated rapidly and two insufflators were used to maintain pneumoperitoneum.

Effectiveness of Surgical Masks

Surgical masks have not been shown to provide adequate protection in filtering smoke, though they are good at capturing larger-sized particles, generally 5*u*m and larger.[46–48] Different surgical masks perform very differently (1*u*m: 7% to 98% penetration) and poor fit can seriously compromise their filter performance.[49] Some surgical masks have been shown to have a filter efficiency of 97% against particles averaging 1*u*m in diameter, while penetration of particles up to 9*u*m (0.1% to 13% penetration) has been demonstrated in other masks.[50]

Recommendations by Authoritative and National Organisations

OSHA

OSHA estimates that 500,000 workers are exposed to laser and electrocautery smoke each year. It advises that employers should be aware of this emerging problem and inform employees of the hazards of surgical smoke. OSHA has no standards specific to laser and/or electrosurgery plume. It does cite general respiratory protection standards and acknowledges that surgical masks do not qualify as respiratory protection of medical employees.[51]

NIOSH

NIOSH acknowledges the dangers of surgical smoke and recommends that smoke evacuation systems be used where high concentrations of smoke and aerosols are generated. It specifically cites one of its own investigations and bases recommendations on the finding of the mutagenicity of the airborne compounds collected during its evaluation and the acute health effects reported by OR personnel.[52,29]

ANSI

The official statement from ANSI is somewhat confusing. It acknowledges the dangers of laser-generated airborne contaminants (LGACs) and states that electrosurgery devices create the same type of airborne contaminants and that they should all be evacuated from the surgical site.[53] ANSI goes on to state that, in certain laser operations, "localised exhaust ventilation" or smoke evacuators be used. It is not clear what methods are recommended when it states that "contaminants should all be evacuated" or what "localised exhaust ventilation" refers to.

Association of Operating Room Nurses

Association of Operating Room Nurses (AORN) is more specific in its recommendations. It recommends the use of smoke evacuation systems whenever smoke is generated. It also specifically cites the risk of viral contamination during laser vapourisation procedures.[54–56]

What can be Done to Minimise Exposure?

Open Surgery

Smoke evacuation systems can also be utilised. In general, however, these systems have been criticised for being noisy, expensive, annoying and cumbersome. Newer systems have shown improvement, but they have not been widely accepted, most likely because of their previously established poor reputation.

Laparoscopic Surgery

Two issues exist regarding surgical smoke in laparoscopic surgery. The first concerns the smoke that is generated and present in the pneumoperitoneum that both obscures the surgeon's vision and poses a potential risk to the patient. The second pertains to the smoke released from the cannulas into the OR, which potentially poses a threat to surgeons and OR personnel.

When smoke is released from a cannula, it is generally more concentrated than smoke generated from open surgery because it is accumulated and then released all at once in a relatively high velocity jet in a particular direction. If this jet is pointed in the direction of the surgeon or OR personnel, they can be exposed to a high concentration of smoke. To prevent this, people in the vicinity can make sure that the jet is not pointed towards them and move away if it is. Another technique is to partially open the Luer-Lok® valve on a cannula throughout the case or when electrocautery is used to prevent smoke build-up and rapid release. None of these techniques have been studied to evaluate their effectiveness.

Filters are available that can be attached to the Luer-Lok® valve on the cannula and can be set to allow continuous ventilation and filtration of the pneumoperitoneum. These add-on filters have been shown to reduce operative time by nearly eliminating the need to interrupt the procedure and release the accumulated smoke that obstructs the surgeon's view.[5] These filters remove most of the harmful chemicals and nearly all biologic material that might be present, as well as eliminating most of the smoke's odour to protect the surgeon and OR personnel from any harmful or unpleasant effects.

If CO exposure to the patient is a concern, the pneumoperitoneum can be vented continuously during and after electrocautery usage to ensure the lowest possible level of CO and other toxic substances in the peritoneal cavity.

Conclusions

Surgeons and OR personnel should be aware of the potential risks surgical smoke poses and utilise reasonable measures to minimise exposure and prevent adverse effects.

To summarise, there are a number of established and theoretical concerns regarding surgically generated smoke that are supported by scientific data:

- Human-to-human viral transmission can occur via laser smoke where the tissue being ablated contains a high concentration of virus, such as in cases of papilloma ablation. One case of viral transmission has essentially been proven and a number of others suggested.
- Electrocautery generates CO in the peritoneal cavity, which exceeds recommended ambient exposure levels and can lead to methemo-

globinemia that will not be indicated by pulse oximetry. This may be a contributing factor in the development of post-operative nausea and headaches after laparoscopic surgery.

- Surgical smoke and aerosols are irritating to the lungs and have approximately the mutagenicity of cigarette smoke. Risks from exposure are cumulative and are greater for those closer to the point of smoke production.
- The risks posed by the aerosol generated from the ultrasonic (harmonic) scalpel compared with that of laser and electrocautery are not known currently and may be greater due to the larger size of particles generated and because it is a cooler aerosol and therefore may contain more biologically viable particles.
- The toxic effects of aerosols on the intra-abdominal cellular immune system are not known currently and may decrease this system's ability to fight intra-abdominal infection and cancer.

Recommendations

- Surgeons and OR personnel should do all that is possible to protect themselves when smoke is being generated from tissue with a high viral concentration, such as during ablation of papillomas, to prevent transmission of viral diseases. This includes using smoke evacuators and high-filtration masks.
- During laparoscopic cases, surgeons should ventilate the pneumoperitoneum either continuously or intermittently and aggressively when smoke is produced from electrocautery and laser to reduce intra-abdominal levels of CO and other toxins.
- During laparoscopic cases, add-on cannula filters should be employed and perhaps incorporated into a future generation of cannulas. ■

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