Respiratory Protection for LASER Users

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The plume produced by vaporizing tissue with a laser contains a variety of contaminants called laser-generated air pollutants (LGACs). LGACs consist of a mixture of toxic gas components, biomicroparticles, dead and living cells, and viruses. Toxic odors and thick smoke from surgical incisions and the coagulation of tissues can irritate eyes and airways, as well as cause bronchial and pulmonary congestion. Because of the potential risk of the smoke, it is advisable to appropriately remove it from the surgical site. We recommend using a smoke evacuator to remove the smoke. Suction nozzles should be placed as close as possible to the surgical site in a range of 2 cm or less. In-line filters should be used between the inlet and outlet of the surgical site. All air filtration devices should be capable of removing particles below 0.1 microns in size. The filter pack should be handled according to infection control procedures in the operating room. The laser mask can be an auxiliary protective device if it is properly worn. Some smoke inhaled under the nose wrap or over the side of the mask will not be filtered. As in electrosurgical operations, a suitable mask should be worn while smoke is present.

Key words
LASER; Plume; Protect; Mask; Air filtration
INTRODUCTION

Laser-Generated Air Contaminants (LGAC)

Exposure to laser heat causes laser smoke to break down tissue. The tissue mass consists of approximately 70% water and 30% dry mass and is affected by protein denaturation and thermal degradation in laser surgery. The removal of tissue masses by laser ablation or laser energy proceeds by carbon ignition of the cells to denature proteins and dehydrate cells, causing vaporization. The vaporization process forms surgical fumes as the internal contents of the cells are released with the vapor (Fig. 1). The target cells do not burn but are heated to the boiling point, which expands the cell membrane until the cell membrane ruptures, releasing cellular material, vaporization products, and particles.

The temperature of the tissue continues to increase throughout the ablation process until it reaches its peak at about 600°C–700°C. The cell contents are generally heated at laser temperatures between 100°C and 1,000°C, which boil the cell contents, expanding and destroying the cell wall.

CHEMICAL COMPOSITION STUDIES

Many studies have characterized some aspects of the chemical composition of LGACs. One of the earliest studies in this area of research was designed to identify the vapor phase products produced using excimer lasers to excite the human myocardium and atherosclerotic parts of coronary arteries. The laser was operated between 193 and 351 nm at a beam diameter of 1.0 mm, pulse duration 20 ns, pulse repetition frequency 20 to 40 Hz, and 75 joules per square luminous flux. The tissue samples were irradiated for 15 to 88 seconds in a tube, allowing the complete capture of released plumes. The main chemical components identified by gas chromatography-mass spectrometry (GC/MS) were methane, acetylene, ethylene, and ethane.

Two follow-up studies were performed to evaluate the laser smoke generated during the investigation of beef liver. This study was designed to detect and quantify the chemicals in laser smoke. The tissues were examined using continuous-wave CO₂ and Nd:YAG lasers. The CO₂ laser was set to 300 W with a beam diameter of 2 mm and an irradiation time of 0.1 seconds, with two power densities of 380 W/cm² and 10,000 W/cm² per square centimeter. The Nd:YAG laser was operated at 30 W with a beam diameter of 1.5 mm and a power density of 1.9 kW/cm². The generated smoke was collected in a gas syringe and condensed in a charcoal filter tube. The samples were analyzed using GC/MS.

The results showed that using CO₂ at typical power density (380 W/cm²), benzene, toluene, xylene, styrene, acetaldehyde, formaldehyde, and acrolein were produced. Specifically, benzene was found at 12.8 μg/50 mg tissue, polyaromatic hydrocarbons (PAH) at 3.6 μg/50 mg tissue, acrolein at 4.3 μg/50 mg tissue, and formaldehyde at 3.4 μg/50 mg tissue. The chemical composition of the plumes produced by the Nd:YAG and CO₂ lasers operating at higher power densities (10,000 W/cm²) was similar. Benzene was produced at a rate of 5 μg/10 mg tissue and...
trace amounts of PAH were produced.

Subsequent studies condensed LGACs with crude oil extract and analyzed the chemical components using GC/MS. A CO2 laser at 10 W was used to irradiate pig liver. The resulting plume was collected in 1 L/min irradiation chamber per minute and condensed with 150 g of water and solid material. One hundred forty chemicals were identified in the condensate.

The researchers suggested that most of the chemicals produced in the study came from the barrier layer of the cells because cholesterol and long-chain fatty acids were produced in the liver at 5–10 mg/g and the rest of the chemicals were produced directly from contact with between the laser and tissue. Among the chemicals identified, 17 were pyrazines, including 20 aromatic hydrocarbons, mainly toluene, and methyl pyrazine, measured between 10 and 20 μg/g.

Benzaldehyde was the predominant carbonyl compound, measured between 1 and 5 μg/g. Benzyl cyanide was identified as the dominant nitrile of 25 nitriles, collected at between 1 and 5 μg/g liver. To understand LGAC generation in a closed environment, such as the peritoneum or chest cavity, a laser atmosphere was created in an enclosed environmental emission chamber under different atmospheric conditions. A high-frequency electrocoagulation device was applied to pig liver for 15 for 40 minutes. To simulate surgical conditions, three atmospheric conditions were set up by introducing air, helium, and CO2 into the release chamber. Smoke was collected through inhalation and analyzed using GC/MS. Twenty-one chemicals were qualitatively identified by GC/MS, including hydrocarbons, nitriles, fatty acids, and phenols. The composition of the atmospheric conditions did not change the chemical composition results.

A similar study quantified the chemical concentration produced in the intraperitoneal area during laparoscopic laser surgery. The study performed surgery on pigs and sampled the discharged air from the pigs and the air from the intraperitoneal area through sampling ports placed in the laparoscopic trocars and endotracheal tubes of animals. The sampled gases were analyzed for CO, acrylonitrile, and benzene. CO was not measured in the vented gases. However, intraperitoneal CO levels peaked at 814 ppm ± 223 ppm and were in the 200–1,600 ppm range. Hydrogen cyanide reached a peak level of 5.7 ppm ± 0.7 ppm, acrylonitrile peaked at 1.6 ppm ± 1.0 ppm, and no benzene was produced at detectable levels.

During six surgeries, an electrical cauterization device was used to generate smoke. The smoke was collected in plastic tubes near the surgical site. The samples were analyzed by GC/MS and the maximum levels of benzene, styrene, ethylbenzene, carbon disulfide, and toluene detected were 71 μg/m³, 36 μg/m³, 32 μg/m³, 1.5 μg/m³, and 460 μg/m³, respectively. No nitrate, nitrite or nitrosamine was detected.

**OCCUPATIONAL EXPOSURES**

The National Institute for Occupational Safety and Health (NIOSH) conducted a health risk assessment at the University of Utah Health Sciences Center to assess the risks associated with surgical smoke exposure from laser use. The sampling areas and personal measurements included the operating room, the laser clinic, and the laser laboratory. The sampling techniques included Fourier transform infrared spectroscopy (FTIR), absorber tubes, glass bombers, and colorimetric detector tubes.

The results showed no cyanide or polynuclear aromatics, but fatty acid esters and hydrocarbons, such as acetone, ethanol, isopropanol, cyclohexane, toluene, and alkanes were identified. Ethanol was reported at 4.7 ppm and isopropanol was reported at 0.5–16.4 ppm. No aldehydes were detected, except formaldehyde at 0.2 to 0.8 ppm.

Another study quantified the LGAC exposure profile in the operating suite during a simulated work procedure. To vaporize pig skin in the operating room, the study used a continuous wave CO2 laser with a beam diameter of 0.6 to 1.2 mm and collected dust from seven points in the operating room, including the approximate location of the worker’s breathing area, the working field, and near the ventilation inlet and outlet. The chemical composition was characterized only in the respiratory area of the operator. The release rate of VOC (volatile organic compound) was measured with focused beams (diameter < 0.8 mm) and unfocused beams (diameter = 3 mm). Most of the VOC concentrations were higher in the unfocused beams and ranged from 1 ng/m³ to 198 ng/m³ of isovaleraldehyde. The concentration of toluene ranged from 26 to 52 ng/m³, ethylbenzene from 6 to 7 ng/m³, and benzaldehyde from 7 to 13 ng/m³.

**PARAMETER INFLUENCE**

Many aspects of the surgical procedures affect the amount and composition of LGACs. These aspects include the surgical techniques, the target tissues, the energy and force of the device, and the depth of the operation.

In one study, CO2 and excimer lasers were used to cut
pig tissue. Cutting was performed in a closed release chamber and smoke was collected at 40 L/min through the sampling probe. The laser cut was delivered for 10 minutes at 1.7 mm/s. The samples were analyzed using GC/MS. The results showed a difference in the chemical composition of the generated laser plume, depending on whether a 10 W continuous wave CO2 laser or a 10 W pulsed excimer laser was used. Subsequent studies have shown that laser cutting speed affected the amount of the chemicals produced.

In addition, higher laser power [30 W and 10 W] has been associated with higher LGAC chemical concentrations. The VOC emission rates for 10 W and 30 W lasers have been reported at 5 and 44–64 μg/g benzene, 67–85 μg/g and 279–319 μg/g toluene, 4–8 μg/g and 42–56 μg/g ethylbenzene, and 6–9 μg/g and 39–49 μg/g styrene. The carbon monoxide concentrations ranged from 11–15 ppm and nitrogen oxides ranged from 0–2 ppm.

The chemical composition of laser smoke produced by the use of excimer lasers contained ethylbenzene and styrene and these chemicals were not contained in smoke produced by CO2 lasers. In addition, excimer lasers produced more aromatic compounds. The substances found in all plumes were 0.04 mg of benzene and toluene, 0.03 mg of ethylbenzene, and 0.02 mg of styrene. The laser that generated the highest release rates, 300 ± 20 μg/g tissue of toluene, 48 ± 6 μg/g tissue of ethylbenzene, and 44 ± 5 μg/g tissue of styrene, was a high laser power (30 W) with a low laser cutting speed (0.5 mm/s).

Another study examined the relationship between VOC production and temperature by comparing the VOC concentrations produced at two power densities. The experiment used a CO2 laser in two different modes, including a 20 W focused area with a power density of 3.18 kW/cm² and a 20 W scatter area with a power density of 0.057 kW/cm². The results showed that the lower power density produced more of all the measured VOCs. The following VOCs were generated: 290–490 μg/g tissue of pyrrole, 250–640 μg/g tissue of toluene, 51–84 μg/g tissue of ethylbenzene, and 40–81 μg/g tissue of styrene. Overall, less concentrated power density (0.057 kW/cm²) produced higher chemical mass.

**HEALTH EFFECTS**

The general health effects of exposure to LGACs have been identified in several studies and include mutagenicity, genotoxicity, and cytotoxicity.7,8 There was no quantitative epidemiological study of the risks associated with occupational exposure to LGACs. A qualitative investigation method was used to estimate the risk. In one study, questionnaires were sent to registered surgical staff and nurses. The researchers received 1,261,405 follow-ups for a rate of 95.6% over the 16 years of the study. The study reported no significant increase in the proportion of lung cancer associated with exposure to lasers in the OR environment.11

Another survey study sent a questionnaire to surgeons working at the Mayo Clinic from 1988 to 1992. The questionnaire asked about the health history of the surgeon, including warts (esophagus, nasopharynx, genitals, and perianal). The results generally indicated that the incidence of warts was not significantly increased in surgeons using lasers.12

Retrospective studies used questionnaires to determine the association between the incidence of acquired lesions and laser use. The questionnaire was sent to members of a group of experts involved in the use of lasers. More than 4,000 questionnaires were initially received and showed that exposure to LGACs did not cause acquired lesions.

Although the specific health effects of LGACs have not been fully identified, the general health impacts associated with exposure to chemicals identified in LGACs have been established by the occupational health community. The chemicals of interest in this study are CO, CO2, toluene, benzene, ethylbenzene, formaldehyde, and HCN. These chemicals were chosen because of reports between LGAC exposure and potential health effects.3

Carbon monoxide is produced during laser surgery through the incomplete combustion of tissue and the conversion of ambient CO2 into CO.13 Carbon monoxide competes with oxygen molecules for hemoglobin in the blood of exposed individuals. Chronic exposure can lead to heart disease and acute exposure affects the blood’s ability to carry oxygen to tissues, causing hypoxia, headache, nausea, dizziness, weakness, rapid breathing, unconsciousness, and death.3

VOCs are carbon-containing compounds that are considered volatile when evaporated under normal indoor atmospheric conditions (Environmental Protection Agency, 2011). According to the Environmental Protection Agency (EPA), health effects associated with VOC exposure include eye, nose, and throat irritation, headache, loss of coordination, nausea, and damage to the liver, kidneys, and central nervous system. VOCs are classified as suspected and known human carcinogens.3

The VOCs of interest in this study were benzene, toluene, and ethylbenzene. Benzene irritates the eyes, nose, and respiratory system. Exposure can cause headaches, dizziness and nausea and chronic exposure can cause...
blood disorders. Benzene is classified as a human carcinogen by the International Cancer Institute [IARC, 2008]. Toluene exposure can cause eye and nose irritation, confusion, euphoria, dizziness, headache, tearing, anxiety, muscle fatigue, insomnia, paresthesia, dermatitis, as well as liver and kidney damage [National Institute of Industrial Research Safety and Health, 2005]. The IARC judged that there was not enough evidence to classify toluene as a human carcinogen [International Agency for Research on Cancer, 2008]. Ethylbenzene can cause eye and neck irritation, as well as dizziness in high exposure areas. It has also been shown to cause kidney damage, inner ear, and hearing damage in animals. According to the literature available, ethylbenzene has been labeled as a human carcinogen by the Agency for Toxic Substances and Disease Registry in 2007 [IARC].

Health effects associated with HCN absorption include headache, weakness, throat irritation, vomiting, difficulty breathing, lacrimal gland irritation, abdominal pain, and nervousness. Other health effects include thyroid and blood changes and toxicity to the central nervous system (CNS) and cardiovascular system. Formaldehyde irritates the eyes, nose, neck, and skin and low levels of exposure can cause asthma. There is evidence that formaldehyde causes cancer of the nose and throat and it is classified as a known human carcinogen. However, the evidence for formaldehyde’s carcinogenicity is not conclusive. Other health effects from inhalation include respiratory irritants, headaches, tearing, bronchitis, pulmonary edema, pneumonia, and death. The regulations and recommended levels associated with the chemicals of interest are detailed in Table 1.

**RELATED LASER HAZARDS**

The focus of this study was the chemical composition of LGACs, but it is important to note that there are other inhalation hazards. One such risk is the inhalation of particulate matter, which can lead to acute and chronic cardiovascular diseases. Respiratory symptoms resulting from the inhalation of LGACs include poor lung function, lung disease, asthma and bronchitis, and acute and chronic inflammatory changes in the respiratory system.

Due to the way the particles move into the air and lungs, the size of the particulate matter determines the health effects associated with exposure. The particle size of the LGACs depends on the amount of energy used. Electrosurgery produces the smallest particles (average aerodynamic diameter < 0.1 μm), laser ablation procedures produce larger particles (~3 μm), and ultrasonic scalpels produce the largest particles (0.35–6.5 μm).

There is no agreement on the diameter of particulate matter associated with health effects. Average diameter estimates of 0.22 ± 0.56 μm, 10–1 μm, 0.1–1 μm, 110–149 nm, and 0.31 μm have been reported. The concentration of particulate matter reported in the literature also varies from 10,000 organized tissues/cm³ to 14 mg/g and from 1.2 to 306.3 μg/m³. The lack of agreement between particle size and concentrations can be attributed to different experimental conditions, surgical techniques, and laser parameters such as power, laser type, and energy.

Particulate matter is dangerous when associated with

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**Table 1. Occupational exposure recommendations for chemical of interest**

| Chemical      | OSHA PEL   | NIOSH REL (NIOSH, 2005) | ACGIH TLV (ACGIH, 2012) | Rational for Limits               |
|---------------|------------|--------------------------|--------------------------|-----------------------------------|
| Benzene       | 1 ppm TWA* | 0.1 ppm TWA              | 0.5 ppm TWA              | Carcinogenicity                   |
| Ethylbenzene  | 5 ppm STEL**| 1 ppm STEL               | 2.5 ppm STEL             | Cardiovascular effects,           |
| Carbon Monoxide| 50 ppm TWA | 35 ppm TWA               | 25 ppm TWA               | elevated carboxyhemoglobin       |
| Carbon Dioxide | 5000 ppm TWA| 5,000 ppm TWA           | 5,000 ppm TWA           | Asphyxiant, CNS damage            |
| Ethylbenzene  | 100 ppm TWA| 125 ppm STEL             | 125 ppm STEL             | Carcinogenicity                   |
| Formaldehyde  | 0.75 ppm   | 0.016 ppm                | 1 ppm                    | Carcinogenicity                   |
| Hydrogen Cyanide | 10 ppm TWA | 4.7 ppm STEL             | 4.7 ppm Ceiling          | Risk of thyroid blood and         |
| Toluene       | 200 ppm TWA| 10 ppm TWA               | 50 ppm TWA               | respiratory effect, acute         |

*Time weighted average, TWA: **Short-term exposure limit, STEL.
bioaerosols, such as bacteria, mycobacteria, fungi, and viruses. Viral DNA of genital condylomata, human papillomavirus, ape immunodeficiency virus, human immunodeficiency virus, and herpes virus has been found in laser-generated plumes. However, the survival of DNA was demonstrated in only one of two studies. Some studies have not been able to demonstrate virus dissemination or viability.  

There were two case studies in which occupational exposure to LGACs caused viral transmission. Surgeons and nurses developed laryngeal papilloma in the vocal cord area after exposure to LGACs containing papillomavirus. Tumor cells have been found in plumes, suggesting mechanisms for tumor delivery and transplantation. In another study, tumor cells collected from laser plumes were transplanted and grown in mouse tissues to show the propagation of viable tumor tissues. However, two studies reported that viable tumor cells could not be detected in laser pillars.  

Bacteria have also been identified in LGACs. Bacteria (Staphylococcus aureus, Corynebacterium, Neisseria, Escherichia coli, and Bacillus subtilis) were collected and grown from smoke generated by laser ablation. However, the risk of spreading these bacteria in laser plumes is low or negligible. Inconsistencies within the results may be related to laser parameters, since viable bacteria were found within plumes generated at low power densities, but not at high power densities (750 W/cm²).  

CONCLUSION

Estimated exposure is below the level of health concern, but considers only a subset of LGAC and laser types in clinical use. Particulate matter and other chemical components can pose health risks to healthcare professionals and patients. The frequency of use of the smoke evacuator is low, depending on the procedure, but the use of smoke evacuators is recommended and is the most effective tool for surgical smoke control.

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CONFLICT OF INTEREST

The authors report no conflicts of interest.

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