SURGICAL SMOKE PLUME

Principles and Function of Smoke, Aerosol, Gases, and Smoke Evacuators

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There is substantial literature on various aspects of the hazards of smoke plume generated by electrosurgical instruments and lasers. Most studies address single issues. According to a recent survey of 4,500 Canadian physicians and surgeons (with 800 respondents), the more physicians are involved with electrosurgery, the more concerned they are about the hazards of surgical smoke. Plastic surgeons and anesthesiologists have the highest levels of awareness at 80% and 76.6% respectively.[1]

In Canada, the hazards of surgical smoke have an overall national awareness level of 39.6% among physicians. This shows that education about the hazards of surgical smoke, both laser plume and electrosurgical smoke, has not been greatly effective.[2]

IN BRIEF

△ This report compares the hazards of smoke generated by lasers and electrosurgical units.

△ It also explains how evacuators capture and filter surgical smoke.

△ The author provides eight important purchasing considerations.

Lasers and electrosurgical instruments produce large volumes of smoke that is a potential health hazard and impairs visibility of the surgical field. Volatiles and particulate matter irritate a person's eyes, nose, and bronchi. Smoke plume is also a demonstrated vector for infectious materials, such as the human papilloma virus (HPV).[3] Surgical smoke is generated whenever tissue is heated sufficiently to vaporize. It is estimated that 80% of surgical smoke is generated by electrosurgical units, while 20% is from laser units.

According to one laser specialist and research engineer,

> *. . . electrosurgical smoke is more dangerous than laser smoke and has the same potential for spreading viruses. . . . Electrosurgery heats up the tissue more than lasers so it creates more char. Although it's the same tissue component, overheating* (the tissue) *makes it more mutagenic—more dangerous—as far as breathing it in.*[4]

The volume of surgical smoke and aerosols generated during laser surgery or electrosurgery depends on the

- ▲ type of tissue,
- ▲ type of procedure and technique,
- ▲ power setting and duration,
- ▲ amount of tissue ablated or lased,
- ▲ ventilation system, and
- ▲ type of smoke evacuator and collection apparatus.

Table 1 shows temperatures of tissue exposed to a neodymium: yttrium aluminum garnet (Nd:YAG) laser over time. According to this researcher,

> *. . . pyrolytic products are generated in two different forms. They can either appear as gases or as larger particles. In addition to substances which are produced during the heating by the laser, the particles and the vapors contain substances which are not changed during laser application.*[5]

GASES

The gases (ie, vapors) produced during the use of lasers or electrosurgical units (ESU) consist of

- ▲ combustion degradation gases, such as carbon dioxide (CO_2), carbon monoxide, hydrogen sulfide, and ammonia;
- ▲ volatile organic compounds, such as toluene, styrene, methylpyrazine, benzaldehyde, indol, skatol, phenol, and benzyl cyanide;
- ▲ very volatile organic compounds, such as formaldehyde, benzene, ethanol, carbon disulfide, and tetrachloroethylene; and
- ▲ polyaromatic hydrocarbons, such as benz(a)pyrene, a well-known carcinogen.

Carbon monoxide and hydrocyanic acid are the most dangerous volatile substances in laser plume. The formation of carbon monoxide and carbonization indicates incomplete oxidation.

In the study using the Nd:YAG laser, gas chromatography identified 146 compounds, including the following:

- ▲ toluene and styrene, which were the predominant components among 20 aromatic hydrocarbons;
- ▲ methylpyrazine, followed by three isomers of dimethylpyrazine, which represent the main compounds in the group of 17 pyrazines identified;
- ▲ indol and skatol, which are present in the greatest concentration among the 19 non-pyrazine N-heterocycles;
- ▲ benzaldehyde, which is the dominating carbonyl compound;

- ▲ phenol and 4-methylphenol, the two other aromatic compounds that occur in higher concentrations; and
- ▲ the 25 identified forms of nitrile, which form the largest group, with benzyl cyanide as the main representative.

The study also found that the large proportion of aromatic compounds in the laser plume is striking—both with respect to qualitative distribution and to absolute amounts. Pyrazines are among those compounds with the most intense odor known. Together with indols and sulfur-containing compounds, these may account for the odor of the plume.

Less volatile compounds do not occur as free molecules. They are adsorbed by the particles or condensed to droplets, which are formed during the laser/tissue interaction. Typical products of pyrolysis (ie, chemical change caused by heating) are polycyclic aromatic hydrocarbons (PAH)—a well-known class of carcinogens. Benz(a)pyrene is a well-known, strong carcinogen. The PAH are formed in the laser/tissue interaction zone, where temperatures are high and tissue is carbonized.[6]

Aerosols

One researcher compared the aerosol particle size distribution of smoke from laser treatment, electrocautery treatment, and other combustion processes (eg, tobacco smoke, diesel exhaust) and found only minor differences.[7] These results indicate that aerosols are generated because of incomplete combustion. The concentration of aerosols has a decisive influence on the particle size distribution (except in the case of the excimer laser, in which the short pulses produce particles by mechanical processes such as disintegration, explosion, or spray formation). Studies show that laser parameters (eg, wave length, power density) do not influence particle size distribution to a significant degree. In one study, 90% of aerosols were found to be less than 3 to 5 microns in size. This means that 90% of particles generated by laser treatment are likely to be inhaled and deposited on the alveolar surface of the lung.[8] In the case of excimer laser ablation, 90% of the aerosol mass consisted of particles between 0.9 and 12 microns. The detected particles between 0.08 and 0.15 microns in size are caused by thermal effects, as compared to particles between 2 and 12 microns, which are produced by more mechanical effects as described above.

Results obtained with a CO_2 laser on soft tissue and a erbium: yttrium aluminum garnet (Er:YAG) laser on different materials show that the different ablation processes lead to quite different velocities within the first 10 cm from the ablation site. The stopping range was different for different models. In the case of the CO_2 laser, the plume dynamics are comparable to that of a free gas jet; with the Er:YAG laser, the fast particles are stopped like moving particles in a viscous medium.[9]

In another study, in which aerosol samples were taken during 10 orthopedic surgical procedures, aerosol mass concentration and size distribution varied widely from procedure to procedure and from time to time during the same procedure.[10] Two modes in size distribution were found during the first six minutes of surgery during which electrocautery was the primary tool and irrigation/suction was the secondary tool. The smaller mode (ie, less than 0.3 micron) appeared to be generated by electrocautery due to vaporization and condensation of burned tissue; the larger mode (ie, peak around 3 microns) was probably produced by irrigation/suction when a water jet was injected into the surgical site.

The aerosol concentration was higher near the surgical site, as indicated by data from the impactors (ie, devices used to measure aerosols) worn by surgeons as compared to other OR personnel. Aerosol concentration was highest when the surgical site was open and electrocautery was the primary tool used with occasional applications of irrigation/suction.[11]

Viral particles became airborne during laser irradiation, suggesting that aerosol particles are scattered throughout an area of at least 56 cm^2 (almost 9 sq. inches) according to one study.[12] Positive transmission of airborne viruses in the laser plume between one cell culture and another also was demonstrated. The general recommendation from this researcher is to use evacuation systems whenever tissue is vaporized by laser or electrocautery.

Smoke Evacuators: Principles and Functions

Surgical smoke evacuators are multistage systems consisting of a capture nozzle, a prefilter for larger particles and aerosols (down to 5 to 10 microns), an ultra-low penetration

TABLE 1: TEMPERATURE DEVELOPMENT DURING CONSTANT IRRADIATION OF SAME SITE ON TISSUE SAMPLE

(Nd:YAG laser, noncontact)[1]

Time elapsed	Temperature	Effects	Tissue appearance
First 10 seconds	100° C		Color becomes lighter
11 to 17 seconds	No increase	Vaporization of cell water - steam	
17 seconds	Increases to 350° C	Carbonization and burning of tissue; further decomposition of organic molecules. Smoke, aerosols, and volatile compounds generated.	Surface turns black
50 seconds	400° C to 650° C	Tissue temperature rises as cooling effects of suction decrease when system is turned off.	

1. H Albrecht et al, "Evaluation of potential health hazards caused by laser and Rf-surgery: Analysis of gaseous, vaporized and particulate debris produced during medical treatment," presented at International Laser Safety Federation, 4 Oct 1995.

TABLE 2: VELOCITY AND PARTICLE SIZE EFFECTS

Filtration mechanism	Particle size effectiveness range	Velocity Increases	Velocity Decreases	Particle size Increases	Particle size Decreases
Diffusion effect	< 0.1 micron	-	+	-	+
Interception effect	0.1 to 3.0 microns	0	0	+	-
Inertia effect	> 3.0 microns	+	-	+	-

+ The filtration effect increases. - The filtration effect decreases. 0 The filtration effect is independent.

(Data provided by Filtra Corp., Hawthorne, NJ)

air (ULPA) filter for viral and small particulate matter, and a carbon filter for odor-containing gases. There are two essential features in evaluating smoke evacuation performance and efficiency:

▲ capture/collection and
▲ filtration.

CAPTURE/COLLECTION. Though much is known about filtration, there is a remarkable lack of knowledge and concern regarding capture and collection. In 1990, a researcher noted that the effects of a given nozzle on the surgeon's field of view and OR noise levels should be considered.[11] While several smoke evacuator manufacturers have addressed the issue of noise, only one company has addressed the issue of capture and collection.

A filtration system can remove airborne contaminants to varying degrees of efficiency only if they have been captured. A brief discussion of the sequence of events and aerodynamics that influence capture and collection will clarify this vital process.

When cellular water is vaporized, there is a thousand-fold increase in volume, and the material is propelled from the site at high velocity. The distribution of plume, which contains aerosols, gases, and cellular material, is influenced by air flow from room ventilation units. If the plume is not completely captured at the site, the smaller, higher velocity particles will disperse throughout the room. The OR staff members in closest proximity are at highest risk due to the higher concentration of the smoke. As the plume circulates, others in the room become exposed, albeit at lower concentrations.

PRINCIPLES AND FUNCTION OF CAPTURE/COLLECTION NOZZLES: TUBULAR (STANDARD). Standard nozzles or "wands" are cylindrical and commonly available with a diameter of 7/8 inch. Some smoke evacuator companies encourage the use of hoses with larger diameters (eg, up to 1 1/4 inch) without the wand to enhance capture. Suction nozzles exhibit extremely low linear velocity only a short distance from the nozzle end (ie, inrushing velocity is only 7.5% of linear velocity at one diameter from the end of the nozzle and less than 2% entry velocity at two diameters).[14] Therefore, larger motors or increased suction is of little consequence when nozzle geometry is the key factor. This is due to the area of the collapsing sphere of velocity profiles around the entry point extending in all directions. Such inefficiencies led one group of researchers to recommend that a minimum of 50 cubic feet per minute (CFM) be used with cylindrical nozzles to capture smoke plume generated by lasers. Further, it was noted that the wand must be held no further than two inches from the site of production. These researchers noted that collection efficiency improved when room air flow was in the direction of suction.[15]

PRINCIPLES AND FUNCTIONS OF CAPTURE/COLLECTION NOZZLES: FLARED HORN. A horn-shaped nozzle utilizes a different type of capture technology. As the evacuator motor pulls air through the nozzle, airflow is laminar instead of turbulent. An airfoil effect is generated by the hyperbolic shape of the horn. Air rushing inward radially creates a negative pressure on the front of the horn creating lift, thereby increasing its field of influence. [illegible] is increased by [illegible] and permanent flow loss is only 4%, compared with 93% for the standard tubular wand.[16] Because of greater utilization of energy, virtually no turbulence, and higher linear velocity at the capture point, the area of collection is increased by 60%.

The use of a horn-shaped nozzle reduces the need for large motors and high velocity from that necessary with the standard wand. Because of the increased capture efficiency and field of collection with the flared horn, smaller high velocity particles and aerosols are completely captured. These otherwise may escape collection due to

▲ distance from site of smoke generation,
▲ direction of room air flow, or
▲ movement of personnel or equipment.

Lower air velocities, in fact, allow filtration efficiencies of the ULPA filter to increase, making it essential to peak performance (Table 2).

FILTRATION. Since the introduction of a class of filters referred to as "absolute filters" (ie, high efficiency particulate air [HEPA], ULPA), smoke evacuators have used the latest and most efficient within this class—the ULPA filters. Generally, HEPA filters have an efficiency rating of 99.97% for particle size of 0.3 microns (ie, three particles out of 10,000 measuring 0.3 microns will get through the filter). The ULPA filters have an efficiency rating of 99.999+% for particle size of 0.12 micron (ie, one particle out of 100,000 measuring 0.12 micron will get through the filter). Because of health care professionals' concerns about viruses such as hepatitis B (0.042 micron), HPV (0.045 micron), and HIV (0.12 micron), smoke evacuator manufacturers have expressed ULPA efficiency ratings at 0.01 micron of 99.9999+% (ie, one particle out of a million measuring 0.01 micron will get through the filter).

Air velocity plays a major role in the efficiency ratings of these filters. In general, absolute filter efficiency decreases as air velocity increases. Therefore, higher CFMs will result in lower filtration efficiency. For example, if ULPA filtration efficiency measures 99.9999% at 0.01 microns at media velocity (ie, air passing through filter media) of 15 feet per minute (FPM), filtration efficiency would drop to 99.99% at 0.01 micron when air velocity increases to 45 FPM using the same test criteria. The four main collection modes of absolute filters are illustrated in Figure 1.

Note that the key to filtration of sub-micron particles hinges on interception and diffusion (Figure 2). As the particle size increases with interception, efficiency increases. However, with diffusion, the opposite is at work—efficiency increases as particle size decreases. Where the two intersect, is the most penetrating particle size (MPPS), which is the weakest point of the filter efficiency. For ULPA filters, the MPPS is 0.12 micron. Ironically, as particle size decreases to 0.01 micron or increases to 1.0 micron, efficiency increases due to diffusion and interception, respectively.

Purchasing Considerations

Filtration efficiency ratings for absolute filters are determined when the filters are still in sheet form during the manufacturing process. The sheet is then subjected to handling, pleating, and fabricating. The finished filter product, therefore, may be perforated or compromised during the fabrication process, resulting in a lower filtration efficiency. While there are currently no universal industry or regulatory standards, a number of considerations are presented for standardizing filters.

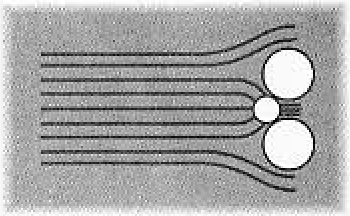
- ▲ Filtration efficiency of the finished product should be assured after fabrication. This is the more accurate measure of the product in actual use. Due to the long test time involved (ie, two to three hours or more), testing each filter is impractical. Leak testing, however, should be performed and certified for each ULPA filter. The highest filtration efficiency is of no use if the filter, canister, or housing leaks.
- ▲ ULPA filters filter particles down to 0.01 microns in size, including viral particles and other harmful by-products. The National Institute

FIGURE 1: PARTICLE CAPTURE MECHANISMS—ABSOLUTE FILTERS

There are four main collection modes used in absolute filters.

1. Straining **3. Interception**
2. Inertial impaction **4. Diffusion**

1. Straining

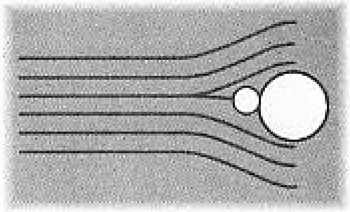


Filtration size: >1.0 micron

Method: Straining occurs in a filter when particles enter flow passages between two or more fibers that have flow passage dimensions of less than the particle diameter.

Efficiency: Straining is the least effective of the four collection modes.

2. Inertial impaction

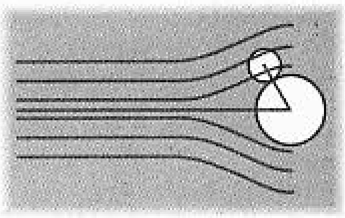


Filtration size: >1.0 micron

Method: An airstream is broken up into many smaller streams as it travels through the randomly oriented fiber filter bed. These streams are capable of bending around the fibers and rejoining on the downstream side of the filter. Any particles that have sufficient inertia will not bend around the fibers with the airstream and therefore, collide with the fibers and are captured. These particles have either sufficient mass or velocity (or both) to prevent them from altering their path along with airstream.

Efficiency: Inertial impaction is most effective against particles that are larger than 1.0 micron in diameter. Therefore, for absolute (HEPA/ULPA) filters that are used primarily for sub-micron aerosols, inertial impaction is of secondary importance.

3. Interception

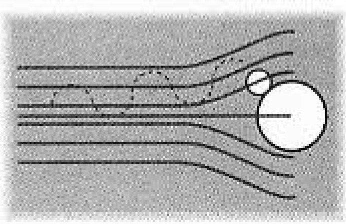


Filtration size: 0.1 to < 3.0 micron

Method: Smaller diameter particles will alter their path along with the flow lines around the fiber. If the particle follows a path that would cause it to make contact with the fiber (ie, a flow-line whose distances from the fiber is less than the radius of the particle), it is captured and retained.

Efficiency: Interception is more important for relatively large particles (greater than 0.1 micron). The interception effect is dependent only upon air velocity insofar as the flow pattern around the filter is altered by changes in flow rate.

4. Diffusion



Filtration size: 0.01 to 0.1 micron

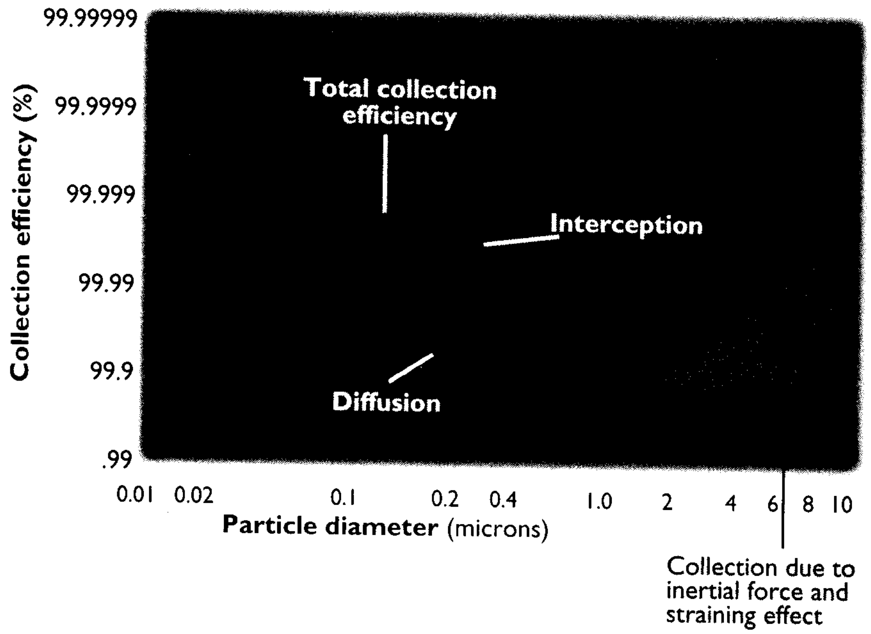
Method: The random motion of the airborne contaminants increases the probability of collision with a filter fiber (ie, Brownian movement). Additionally, once a particle collides with a fiber, it is retained by strong intermolecular forces (ie, Van der Waal's forces). A decrease in filtering velocity will further increase the probability of collision with a fiber and thereby increase capture efficiency.

Efficiency: Capture by diffusion favors small particles (less than 0.1 micron in diameter) and low filtering velocities.

(Data provided by Filtra Corp., Hawthorne, NJ) for Occupational Safety and Health (NIOSH) has recommended that such filters be handled according to the Occupational Safety and Health Administration's (OSHA) bloodborne pathogen rule. The ideal ULPA filter, therefore, should be contained in a closed housing so those who handle and dispose of these filters will not be exposed to contaminants.

- ▲ Larger aerosols and particles are collected on the nozzle or wand, prefilter, and tubing. The components should be disposed of and handled according to OSHA's bloodborne pathogen rule at the end of each procedure.
- ▲ Charcoal is used to adsorb odor-containing gases. Macroscopic charcoal has larger pores and is designed to more efficiently filter larger gas molecules, such as fatty molecules commonly found in surgical smoke. Microscopic charcoal has smaller pores and is ideal for filtration of gases such as toluene and styrene. The ideal smoke evacuator charcoal filter will contain both macroscopic and microscopic charcoal. Currently most smoke evacuator manufacturers use only microscopic charcoal.
- ▲ The order of filter assembly is important. The optimal performance of a smoke evacuator should start with an efficient collection nozzle for complete capture of smoke produced at the site. A prefilter will filter larger particles and aerosols between 3 and 20 microns. An ULPA filter as the next stage will filter particles down to .01 microns. The charcoal filter should be placed last to adsorb odor containing gases. A fiber filter can be used to prevent charcoal dust from entering the room atmosphere. A number of smoke evacuator filters place charcoal first, which causes it to act as a physical filter rather than the function for which it is designed (ie, adsorbing odor containing gases). Further, the charcoal dust coats the ULPA filter, reducing its efficiency and filter life.
- ▲ Smoke evacuator filters should be monitored so that operators can be assured that smoke evacuator filter life is not exceeded, according to NIOSH recommendations. Timers measuring cumulative time of operation provide an essential and convenient means of monitoring filter life.
- ▲ Currently, there are no regulatory or industry standards regarding evacuator noise levels. Manufacturers' claims are often made with measurements conducted in soundproof rooms (anechoic). This means that, because most ORs are not soundproofed, those units will sound louder than the decibels claimed. For purposes of comparison, all manufacturers should use one standard of conditions for measuring evacuator noise.
- ▲ Cost of disposables per procedure should be a major part of the purchase consideration because it is the most expensive factor in the use of smoke evacuation systems. △

FIGURE 2: OVERALL EFFICIENCY CURVE



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6. *Ibid.*

7. *Ibid.*

8. *Ibid.*

9. *Ibid.*

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Editor's note: The flared horn nozzle described is the TX Nozzle (a trademark of Acuderm, Inc., Ft. Lauderdale, Fla.) and subject of allowed United States patent application.