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Analysis of Surgical Smoke Produced by Various Energy-Based Instruments and Effect on Laparoscopic Visibility

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ABSTRACT

***Purpose*: We analyzed the smoke plume produced by various energy-based laparoscopic instruments and determined its effect on laparoscopic visibility.**

***Materials and Methods*: The Bipolar Macroforceps, Harmonic Scalpel, Floating Ball, and Monopolar Shears were applied *in vitro* to porcine psoas muscle. An Aerodynamic Particle Sizer and Electrostatic Classifier provided a size distribution of the plume for particles $>$500 nm and $<$500 nm, and a geometric mean particle size was calculated. A Condensation Particle Counter provided the total particle-number concentration. Electron microscopy was used to characterize particle size and shape further. Visibility was calculated using the measured-size distribution data and the Rayleigh and Mie light-scattering theories.**

***Results*: The real-time instruments were successful in measuring aerosolized particle size distributions in two size ranges. Electron microscopy revealed smaller, homogeneous, spherical particles and larger, irregular particles consistent with cellular components. The aerosol produced by the Bipolar Macroforceps obscured visibility the least (relative visibility 0.887) among the instruments tested. Particles from the Harmonic Scalpel resulted in a relative visibility of 0.801. Monopolar-based instruments produced plumes responsible for the poorest relative visibility (Floating Ball 0.252; Monopolar Shears 0.026).**

***Conclusions*: Surgical smoke is composed of two distinct particle populations caused by the nucleation of vapors as they cool (the small particles) and the entrainment of tissue secondary to mechanical aspects (the large particles). High concentrations of small particles are most responsible for the deterioration in laparoscopic vision. Bipolar and ultrasonic instruments generate a surgical plume that causes the least deterioration of visibility among the instruments tested.**

INTRODUCTION

DURING THE SURGICAL APPLICATION of energy-based technologies, there is a well-recognized production of “smoke” that can impede surgical progress. The confined spaces associated with laparoscopic procedures have made smoke production a more significant problem. The aerosolized particles can impair visibility by settling on the lens of the laparoscope or by remaining in suspension between the laparoscopic and the surgical objective. Coating the lens with particles necessitates removal of the laparoscope from the body cavity for cleaning. The aerosolized particles must be vented or aspirated or allowed to settle over a period of time to reestablish adequate visibility of the surgical field.

Energy-based surgical instruments produce various quantities and consistencies of smoke plume. At present, there is a paucity of data regarding the morphology, size, and composition of surgical smoke.[1–3] Also, the effects of smoke on laparoscopic visibility have not been quantified. The objective of this study was to characterize the smoke produced by four commonly used energy-based laparoscopic instruments. The effect of various smoke characteristics on laparoscopic visibility was compared.

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FIG. 1. Experimental set-up.

MATERIALS AND METHODS

Fresh porcine psoas muscle was harvested as a homogeneous tissue for application of energy-based instruments. The experiments were conducted in an air-tight custom-designed 50 × 50 × 25-cm Plexiglass chamber with a laparoscopic hand-assist device (Gelport; Applied Medical, Rancho Santa Margarita, CA) embedded in the top. The tissue was placed in the box, and the hand-assist device allowed introduction of different surgical instruments into the test chamber for application to the tissue (Fig. 1).

Four instruments were studied: Bipolar Macroforceps (Aesculap, Center Valley, PA) at 40 w; Harmonic Scalpel® LaparoSonic Coagulating Shears (Ethicon Endo-Surgery, Inc, Cincinnati, OH) at a generator power setting of 5; Floating Ball (TissueLink Medical Inc, Dover, NH) at 80 w; and Endopath monopolar shears (Ethicon Endo-Surgery) at 30 w. Each instrument was applied to the tissue for 3-second bursts every 10 seconds for a 3-minute interval for a total activation time of 54 seconds to simulate intermittent intraoperative use.

An Aerodynamic Particle Sizer and Electrostatic Classifier (TSI, Inc, St. Paul, MN) provided a size distribution of the plume for particles >500 nm and <500 nm, and a geometric mean particle size was calculated. A Condensation Particle Counter (TSI) provided the total particle concentration.

Smoke particles produced by the various surgical instruments were collected on electron microscope grids by depositing them using an electrical field.[4] These were then viewed in a scanning electron microscope (SEM) to observe the shape and size of the particles.

The degradation of visibility was calculated using the measured size-distribution data and the Rayleigh and Mie light-scattering theories.[5] The measured number concentration was scaled to a smaller volume corresponding to the peritoneal cavity. These adjusted number concentrations were used in the light-scattering equation to determine the reduction in the intensity of visible light. Using these models, digitally recreated laparoscopic images were produced to compare subjectively differences in visibility among the various instruments. A software program was developed to reduce the intensity of the different pixels in the picture from a reference image based on the calculated reduction in the intensity of the visible light.

RESULTS

Table 1 summarizes the geometric standard deviation, geometric mean size, and number concentration of the smoke particles produced by each surgical instrument. Background measurements are also tabulated for comparison. Each instrument produced two aerosolized particle-size distributions. Bipolar energy produced the smallest number of large particles, while bipolar energy and the Harmonic Scalpel both created a relatively small number of small particles. In contrast, the standard monopolar scissors and the Floating Ball device both created a large number of both small and large particles. Scanning electron microscopy of the smoke particles confirmed the presence of two distinct populations: smaller spherical particles and larger irregularly shaped particles (Fig. 2).

Relative to the background, visibility was adversely affected by the smoke particles generated by each surgical instrument. Figure 3 shows the relative visibility in the smoky environment associated with the application of each instrument. Figure 4 shows digitally recreated laparoscopic images that were produced to compare differences in visibility among the various instruments tested relative to background visibility using the particle data.

TABLE 1. SMOKE PARTICLE SIZE AND CONCENTRATION

	Geometric standard deviation		*Geometric mean size*		*Number concentration*	
Instrument	*Small mode*	*Large mode*	*Small mode (nm)*	*Large mode (nm)*	*Small mode (No./cm^3)*	*Large mode (No./cm^3)*
Bipolar	1.60	1.58	66.7	889	5.35×10^5	869
Harmonic	1.92	1.55	68.3	994	6.10×10^5	1.48×10^3
Floating ball	1.58	1.73	69.9	1080	1.65×10^7	6.61×10^3
Monopolar	1.54	1.62	99.1	924	4.4×10^7	8.13×10^3
Background	–	–	97.0	675	3.86×10^3	17

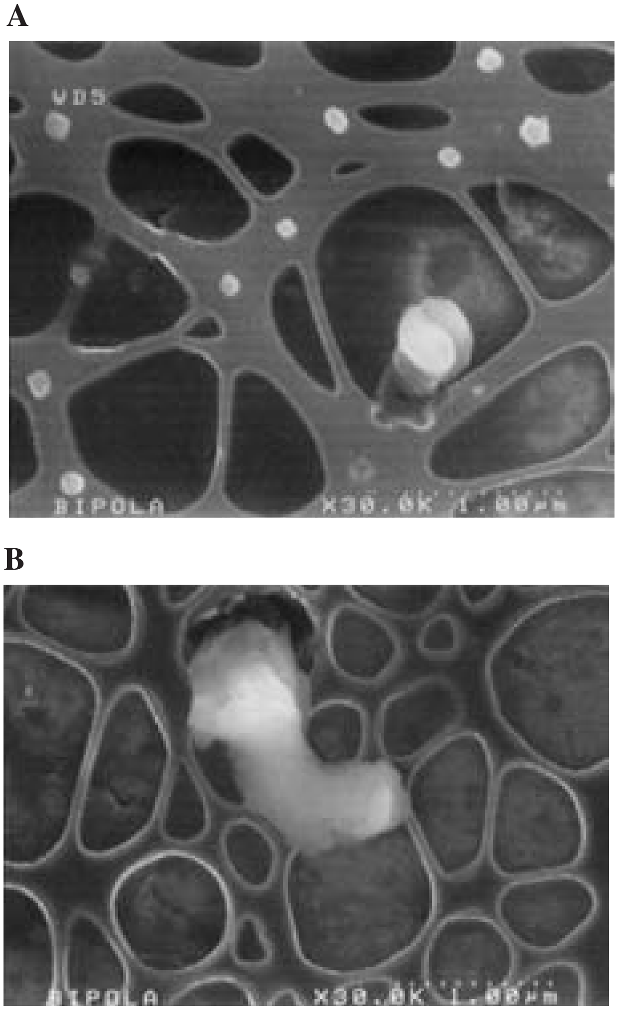

FIG. 2. Electron microscopy. (**A**) Smaller homogeneous spheres. (**B**) Larger irregular fragments.

DISCUSSION

Traditionally, surgeons refer to the gaseous and particulate byproduct of any energy-based instrument as "smoke." The term *smoke* describes a collection of suspended particles produced by combustion. Generalized terms such as "aerosol" or "plume" describe a suspension of particles in a gas and are more accurate for describing particles produced by electrosurgery.[1] In this paper, however, we refer to the gaseous/suspended particulate byproducts of all energy-based instruments as "smoke," as this term is more familiar to medical professionals.

The *in-vitro* design of the current study offered several advantages. As shown in Figure 1, the collection tubing was positioned approximately 5 cm directly over the interface between the surgical instrument and the tissue. This position allowed excellent sample collection, as even relatively large particles, which have a tendency to travel only short distances from their point of production, could be collected.[6] Additionally, the expeimental set-up was designed with smoke collection at a distance from the site of smoke production similar to the position the tip of the laparoscope would occupy in a clinical setting. Therefore, the smoke analysis at this position correlates closely with actual laparoscopic visibility. Also, to optimize the consistency of smoke production with each energy modality, we chose a homogeneous consistent tissue on which to deploy the instruments. In doing so, we eliminated the variability of smoke amounts that can occur with different or inconsistent target tissues.[7]

There were several limitations to our *in-vitro* evaluation. Although the smoke was produced in a confined space similar to that of laparoscopic surgery, this preliminary study was not conducted under insufflation or with venting or suction of the smoke. Additionally, each instrument was fired for the same length of time, whereas during operative procedures, the various instrument would be fired for longer or shorter times. For example, in the authors' experience, the Floating Ball typically is activated for as long as 60 seconds without interruption to attain hemostasis during partial nephrectomy. In contrast, the bipolar forceps and the Harmonic Scalpel usually are deployed for a few seconds at a time. Future studies may incorporate these parameters to identify the most problematic instruments better. Additionally, in this preliminary study, we have only quantitated the smoke plume and described the particle configuration. Certainly, the nature of the particles has great clinical relevance, as there are both oncologic concerns and worries about the spread of infection.

Electrosurgery creates particles with a mean size of around 70 mm.[2] We report mean geometric sizes for electrocautery particles in the smaller mode between 66.7 and 99.1 mm, with much higher small-particle concentrations. Previous authors have identified chemicals found in electrosurgical smoke.[8] One of the most worrisome is carbon monoxide. During laparoscopic procedures, high levels of CO are produced that can lead to slight elevations of carboxyhemoglobin.[9,10] In addition, infectious virions have been isolated from electrocautery smoke.[11]

Previous reports have shown that Harmonic Scalpels generate particles 350 to 650 nm in diameter at approximately a quarter of the particle concentration seen with electrocautery.[12] Our

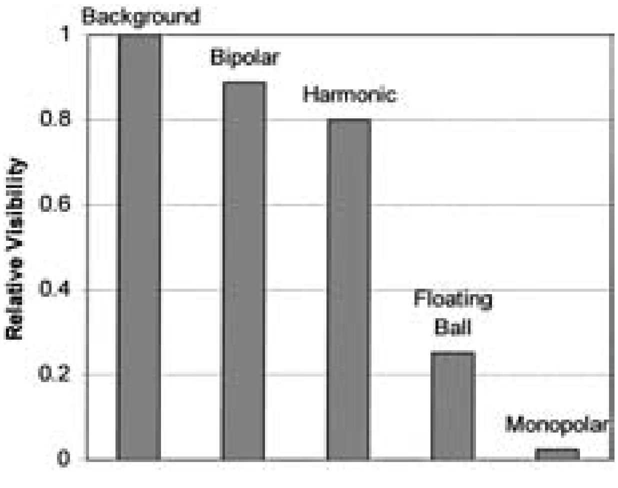

FIG. 3. Visibility associated with application of each instrument.

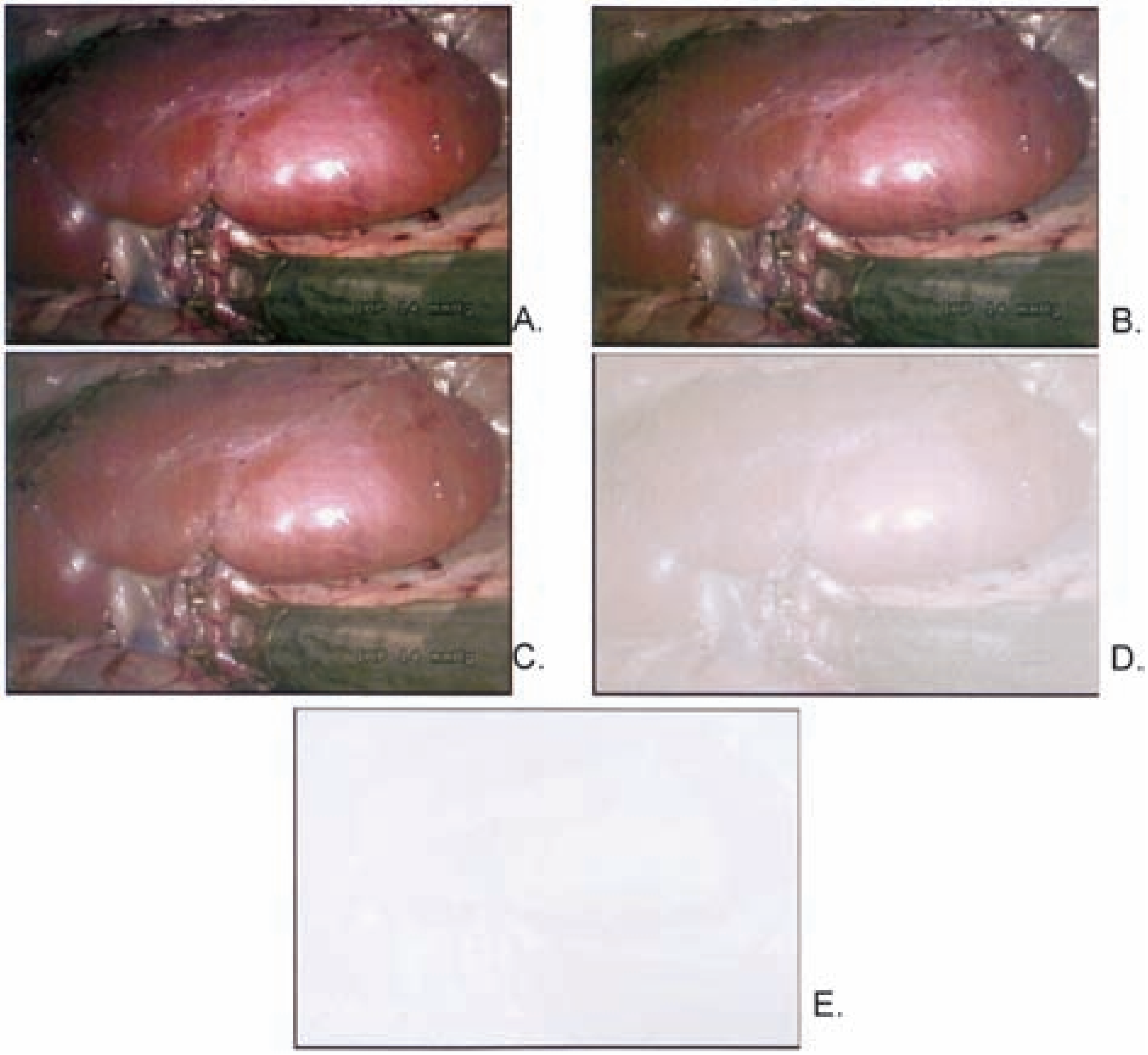

FIG. 4. Digitally recreated images of visibility of background (**A**) and visibility in presence of smoke produced by Bipolar Macroforceps (**B**), Harmonic Scalpel (**C**), Floating Ball (**D**), and Monopolar Shears (**E**).

data revealed particles with mean geometric sizes in the smaller mode of 68.3 nm and in the larger mode of 994 nm.

The bimodal distribution of particles produced by surgical instruments has been described previously.[3] The smaller spherical particles result from vaporization followed by nucleation, a process by which vapors are converted to tiny particles (droplets) of fluid. These particles contain sodium, chloride, potassium, magnesium, calcium, and iron and are produced by uniform drying of liquid dropplets in a gas flow.[13] The larger particles result from explosion and fragmentation of tissue. Energy-dispersive spectrometry shows these particles to contain carbon and oxygen.[3]

We calculated laparoscopic visibility in the presence of smoke produced by various surgical instruments using the measured size-distribution data and the Rayleigh and Mie light-scattering theories.[5] Rayleigh scattering of light by particles smaller than the wavelength of the light and occurs when light travels in transparent gases. The amount of Rayleigh scattering of a beam of light is dependent on the size of the particles, the particle concentration, and the wavelength of the light. Rayleigh's law states that the intensity of the scattered light varies inversely with the fourth power of the wavelength. Scattering from particles of about the same size as the wavelength is handled by the more complex theory of Mie, for which a closed form solution cannot be obtained, as in Rayleigh's theory.

Visibility is most impaired by the monopolar instruments. The best instruments in terms of visibility are the Bipolar Macroforceps and the Harmonic Scalpel. Our intraoperative observations during laparoscopic surgery correlate with these results. In addition to visibility advantages, we find the Bipolar

Macroforceps and Harmonic Scalpel to be a highly effective combination for hemostasis and dissection during laparoscopic procedures.

The most striking variation among the particle parameters across the various instruments is noted in the small mode concentration. The Floating Ball smoke was 31 and 270 times more concentrated than the bipolar and Harmonic Scalpel smoke, respectively. The smoke created by the Monopolar Shears was 82 and 721 times more concentrated than the smoke from the Bipolar Macroforceps and the Harmonic Scalpel, respectively. The high concentrations of the small particles produced by the Floating Ball and Monopolar Shears correlate with the marked impairment of visibility associated with these instruments.

Particle size also has a weak effect on visibility. Whereas all other parameters are relatively the same, the mean size of the small particles produced by the Monopolar Shears is 30 nm larger than the mean size of the Floating Ball small particles. This corresponds to a mean particle volume almost three times larger for the Monopolar Shears. The slightly worse visibility calculated for the Monopolar Shears compared with the Floating Ball is likely attributable to the larger particle size in the small-mode population.

The most significant influence on laparoscopic visibility is small-particle concentration, with small-particle size of secondary importance. The large particles probably have little or no influence on visibility because of their tendency to settle quickly. Thus, models such as this can be used in future studies to assist in the design of new energy-based surgical tools that produce less small-particle smoke to minimize degradation in visibility.

CONCLUSION

Surgical smoke is composed of two distinct small- and large-mode particle populations. Bipolar and ultrasonic-based instruments generate a surgical plume that causes the least deterioration of visibility among the instruments tested, while monopolar instruments degrade visibility the most. The small-particle concentration is the factor with the most influence on laparoscopic visibility.

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