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Surgical Team Exposure to Cautery Smoke and Its Mitigation during Tonsillectomy

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Abstract

Objectives.—To assess the exposure of surgical personnel to known carcinogens during pediatric tonsillectomy and adenoidectomy (T&A) and compare the efficacy of surgical smoke evacuation systems during T&A.

Study Design.—Prospective, case series.

Setting.—Tertiary children's hospital.

Subjects and Methods.—The present study assessed operating room workers' exposure to chemical compounds and aerosolized particulates generated during T&A. We also investigated the

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Daniel C. O'Brien, substantial contributions to the acquisition, analysis, and interpretation of data for the work; drafting the work and revising it critically for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work; **Eun Gyung Lee**, substantial contributions to the design of the work and the acquisition, analysis, and interpretation of data for the work; revising it critically for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work; **Jhy-Charm Soo**, substantial contributions to the design of the work and the acquisition, analysis, and interpretation of data for the work; revising it critically for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work; **Sherri Friend**, substantial contributions to the analysis of data for the work; revising it critically for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work; **Sarah Callaham**, substantial contributions to the interpretation of data for the work; revising it critically for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work; **Michele M. Carr**, substantial contributions to the conception and design of the work and the interpretation of data for the work; revising it critically for important intellectual content; final approval of the version to be published; agreement to be accountable for all aspects of the work.

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effect of 3 different smoke-controlling methods: smoke-evacuator pencil cautery (SE), cautery with suction held by an assistant (SA), and cautery without suction (NS).

Results.—Thirty cases were included: 12 in the SE group, 9 in SA, and 9 in NS. The chemical exposure levels were lower than or similar to baseline background concentrations, with the exception of methylene chloride and acetaldehyde. Within the surgical plume, none of the chemical compounds exceeded the corresponding occupational exposure limit (OEL). The mean particulate number concentration in the breathing zone during tonsillectomy was 508 particles/cm^3 for SE compared to 1661 particles/cm^3 for SA and 8208 particles/cm^3 for NS cases. NS was significantly different compared to the other two methods ($P = .0009$).

Conclusions.—Although the exposure levels to chemicals were considerably lower than the OELs, continuous exposures to these chemicals could cause adverse health effects to surgical personnel. These findings suggest that the use of a smoke-evacuator pencil cautery or an attentive assistant with handheld suction would reduce exposure levels to the aerosolized particles during routine T&A, compared to the use of cautery without suction.

Keywords

surgical smoke; surgical plume; tonsillectomy; smoke evacuation; occupational safety; operating room; electrocautery

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Over the past 2 decades, we have become increasingly aware of the risks of surgical smoke exposure. Surgical smoke, or surgical plume (SP), comes from heating and boiling of intracellular water, resulting in localized desiccation and obliterative high-temperature coagulation.[1] SP consists of 95% water vapor and 5% combustion by-products.[2] SP can contain viable human papillomavirus DNA, viable cancer cells, and harmful chemicals such as polycyclic aromatic hydrocarbons.[3–7] Some believe that exposure to the plume from destroying 1 g of tissue is equivalent to smoking 6 cigarettes.[1,7] Most surgical masks are made to filter particles larger than 5 μm, but particles produced during surgery have an average diameter of 0.5 to 2.5 μm.[8–12] Smoke evacuation (SEvac) has been shown to mitigate the risk of SP exposure, and its routine use is recommended.[13,14]

While there has been some study of the laser plume in laryngeal surgery, there are limited data regarding otolaryngologist exposure to SP.[6,16] Electrocautery is used by 57% of pediatric otolaryngologists for tonsillectomy.[18] With about 500,000 tonsillectomies done annually in the United States,[17,18] otolaryngologist SP exposure is measurable.[16]

The purpose of this study was to determine the contents of the SP produced during electrocautery tonsillectomies and to compare the efficacy of different SEvac systems. We hypothesized that any type of SEvac system would help reduce surgical team exposure to hazardous compounds, with SEvac close to the site of cautery being more effective.

Method

Smoke Generation during Tonsillectomy and Adenoidectomy

This study was approved by the West Virginia University Institutional Review Board. Electrocautery SP was evaluated during tonsillectomy and adenoidectomy (T&A) in consecutive children. During the removal of tonsils, 3 different SEvac methods were considered: (1) SEvac via a smoke-evacuation cautery pencil (Neptune ESEP Smoke Evacuation Pencil; Stryker, Kalamazoo, Michigan) connected to a smoke evacuator (ViroVac; Buffalo Filter, Lancaster, New York) (SE group); (2) pencil cautery (Valleylab button-switch pencil cautery; Covidien, Mansfield, Massachusetts) with SEvac by assistant-held Yankauer suction (Cardinal Health, Waukegan, Illinois), connected to wall suction via a canister (SA group); and (3) no smoke removal (NS group). During adenoidectomy, a wall suction attached to a suction coagulator was used (Valleylab suction coagulator; Covidien). Coagulation power was set to 12 W for tonsillectomy and 30 or 35 W for adenoidectomy.

There were 2 to 4 cases per day in an operating room (OR), and each case lasted <1 hour with up to 1.5 hours between cases. Each case was performed in 1 of 2 rooms of similar size. Cases were randomly assigned to rooms independent of the SEvac used. To minimize the effect of airborne particle exposures from a previous case, we assigned patients to the same SEvac method per day. Cautery time and patients' age were not controlled. Patients did not undergo any additional procedures with T&A.

Exposure Sampling

Airborne particulate concentrations were measured with direct reading instruments (DRIs) on a movable cart. The diagonal distance between the inlets of DRIs and the operating table ranged from 1.5 to 2.1 m. Instruments included a condensation particle counter (CPC, model 3007; TSI, Shoreview, Minnesota) to measure particle number concentration every second (measurable size range 0.01–1.0 μm), a scanning mobility particle sizer (SMPS, model 3034; TSI) to measure particle number concentration based on the size distribution every 2 minutes (size range 10–420 nm), an aerodynamic particle sizer (APS, model 3321; TSI) to measure particle number concentration based on the size distribution every minute (size range 0.5–20 μm), a light-scattering laser photometer (DustTrak DRX Aerosol Monitor, model 8534; TSI) to measure particle mass concentrations every 5 seconds (size range 0.1–15 μm), and a viable particle counter (BioTrak, model 9510-BD; TSI) to detect airborne total and viable particle counts every minute (size range of 0.5–5 μm). A personal measuring device, DISCmini (diffusion size classifier miniature v1.0; Matter Aerosol AG, Wohlen, Switzerland), was worn by the operating surgeon to measure particle number concentration every second in the breathing zone (size range 20–300 nm). Prior to sample collection, empty OR background concentrations were measured each day. Collection of background concentrations between each case was not possible because the room was never vacant between cases. Cleaning and preparation between cases required personnel to enter and egress regularly, making it impossible to obtain stable background measurements. Thus, we used concentrations measured prior to the first case as background concentrations daily.

Two inhalable samplers (IOM; SKC, Eighty-Four, Pennsylvania) loaded with polycarbonate filters (0.4 μm pore size) were placed in baskets 1.5 m from the operating table. These instruments characterized the morphology of the airborne particles and were later used to determine the chemical elements in the sample using a field emission scanning electron microscope equipped with energy-dispersive X-ray spectrometry (FESEM model S4800;

Hitachi High Technologies America, Clarksburg, MD). At least 25 particles were examined per filter.

Volatile organic compound (VOC) and other chemical compounds were collected using various sampling media to collect personal and/or area exposure. For area exposure measurements, we placed 4 sampling media in a basket at 1.5 m from the operating table. The sampling media used were (1) soda lime sorbent tube (SKC) to measure hydrogen cyanide using National Institute for Occupational Safety and Health (NIOSH) method 6010, (2) XAD-2 (2-hydroxymethyl piperidine) sorbent tube (SKC) to measure acrolein using Occupational Safety and Health Administration (OSHA) method 52, (3) 2,4-dinitrophenylhydrazine (DNPH)-coated silica gel tube (SKC) to measure formaldehyde and acetaldehyde using NIOSH method 2016, (4) polytetrafluoroethylene filter (2.0 μm pore size) preloaded in a cassette followed by XAD-2 sorbent tube (SKC) to measure poly-nuclear aromatic hydrocarbons (PAHs) using NIOSH method 5506, and (5) thermal desorption tube (Carbotrap 300, Sigma-Aldrich, St. Louis, MO) to measure various volatile organic chemicals using the Environmental Protection Agency (EPA) TO-17 method. To minimize work disturbance, personal exposure measurements (including the operating surgeon, resident, scrub nurse, and circulator) were limited to VOCs. Both area and personal samples were collected for all cases to maximize retrieval. At the end of sampling, field blank samples were collected. All sampling media were analyzed by the NIOSH contract laboratory.

During surgery, 1 person recorded cautery starting and ending times to compare the particle concentrations separately during tonsillectomy and adenoidectomy.

Data Analyses

After adjusting the DRIs exposure data, one-way analysis of variance (ANOVA) tests were conducted to determine the effect of different SEvac methods by comparing particle number concentrations (measured with CPC and DISCmini) and ratios between the viable particle concentrations and the total particle concentrations (measured with BioTrak). In addition, pairwise multiple comparisons were performed using the post hoc Tukey test. SAS/STAT software (version 9.4; SAS Institute, Cary, North Carolina) was used with a significance level of .05.

For the VOCs and other chemical compounds, sampling time ranged from 16 to 220 minutes for personal exposure measurements and from 21 to 216 minutes for area exposure measurements. A full-shift time-weighted average (TWA) concentration would be lower than the corresponding measured concentration if the sample collection time was less than the full-shift exposure (ie, assuming zero concentration for nonsampling time). Because we did not collect samples for all cases (eg, 2 of 4 T&A cases) for some days, the measured concentrations were considered the full-shift TWA concentrations by assuming that the surgical team was doing T&A cases all day.

Results

We included 12 cases in the SE group, 9 in the SA group, and 9 in the NS group. Table 1 summarizes case number, cautery setting, and electrocautery duration.

Airborne Particulate Concentrations: Breathing Zone Exposure

Figure 1 and Table 2 show results of particle number concentrations measured in the surgeon's breathing zone, separated by procedure. For tonsillectomy, the NS group showed about 16 times higher particle concentration than the SE group and about 5 times higher concentration than the SA group ($P = .0009$). The pairwise comparisons revealed statistically significant differences between the NS group compared to the other 2 groups, while there was no statistical difference between SE and SA groups (Figure 1). Suction cautery was used for all adenoidectomies, so ratios of average particle concentrations between groups were not different ($P = .4919$).

For tonsillectomy, the maximum particle concentrations for individual cases ranged from 499 to 8437 particles/cm^3 for the SE group, 823 to 21,6195 particles/cm^3 for the SA group, and 86,940 to 799,796 particles/cm^3 for the NS group (Figure 2, $P < .0001$). The pairwise comparisons revealed statistically significant differences between the NS group and the other 2 groups, while there was no difference between SE and SA. For adenoidectomy, no statistically significant differences were detected ($P = .4107$).

Airborne Particulate Concentrations: Area Exposures

Table 3 shows the results of particle number concentration measured with CPC. Because the measurable particle size ranges between the DISCmini and the CPC are different, particle concentrations from the CPC were not comparable to those with the DISCmini. The same pattern of particle concentration between the 2 instruments was observed for tonsillectomy (ie, lowest concentration for the SE group and highest for the NS group) ($P = .002$). For adenoidectomy, no differences were observed among different groups ($P = .4035$).

The CPC was also used to compare the variations among different cases per day. For the NS group, the variations (coefficient of variations) were 0.30, 0.45, and 0.36 for 2 cases, 3 cases, and 4 cases per day, respectively.

Particle size distribution by number measured with the SMPS is shown in Figure 3. The particle diameter was smaller for the NS group (82 nm) compared to the other 2 groups (about 100 nm) for tonsillectomy. A similar pattern was observed for adenoidectomy. For the particle size range of 0.5 to 20 μm (measured with APS), numerical particle distribution was considerably lower (<6 particles/cm^3 regardless of the type of SEvac used; results were not included here).

The average viable particle number concentrations measured with BioTrak were 0.001 particles/cm^3 across all types of SEvac. The ratios between the viable particle concentrations and the total particle concentrations were <0.4% (Figure 4). No statistical differences of ratios were observed among the different groups ($P = .2241$). For adenoidectomy, statistically significant differences were observed among the 3 groups ($P = .0222$). Pairwise multiple comparisons revealed no significant differences between the NS group and the other 2 groups, while there was a difference between the SE and SA (Figure 4).

The average mass concentrations measured with the DustTrak during T&A were lower than 8 μg/m^3 regardless of SEvac method (results not shown). These mass concentrations were lower than the average mass concentrations (<40 μg/m^3) reported by Lee et al.[14] For both procedures, no statistical differences were observed among different groups (P = .4473 for tonsillectomy and P = .2079 for adenoidectomy).

Electron Microscopy Analysis

The particle's shapes were amorphous, ranging from a few hundred nanometers to sub-micrometer size (Figure 5). Most were composed of carbon and oxygen with a few particles containing other chemical elements (including chromium, copper, sulfur, manganese, calcium, iron, chloride, nickel, aluminum).

Volatile Organic and Other Chemical Compounds

Table 4 shows concentrations of VOCs and other chemical compounds identified. For each chemical, we selected the lowest occupational exposure limit (OEL) from either the NIOSH recommended exposure limit (REL)[19] or the OSHA permissible exposure limit (PEL).[20] Measured concentrations for all chemicals were considerably lower than the corresponding OELs regardless of SEvac method. Most samples were between the limit of detection (LOD) and the limit of quantification (LOQ). Depending on the substance, the frequency of detection ranged from 1 to 12 times per group for personal exposure measurements and 1 to 8 times per group for area exposure measurements. There are 135 sets of substance measurements when considered by group (SE, SA, and NS) and exposure type (personal and area). This includes VOCs (18 substances × 3 groups × 2 exposure type = 108) and non-VOCs (9 substances × 3 groups × 1 area exposure = 27). Among these, 78% of the substances (105 of 135 substances) were present <6 times for each condition (group and exposure type). Measurement of workplace exposure to inhalational agent standards set by the European Committee for Standardization (EN 689)[21] recommends a minimum sample size of 6 to obtain a reliable statistical result. Because the majority of substances were detected <6 times per cell in Table 4, no further statistical tests were conducted.

The chemical compounds detected from the background measurements were lower than or similar to those measured during the surgeries. It may be that most of the exposures were from the background or chemicals used in the OR. The exceptions include methylene chloride and acetaldehyde. While not detected in the background sample, methylene chloride was identified from the personal exposure and area exposure, respectively. Also, acetaldehyde was identified from the area exposure measurements, although these exposure levels were considerably lower than the OEL.

For VOCs, the personal exposure concentrations were similar to the area exposure concentrations except for toluene, which was higher among area samples than personal exposure samples but still lower than the background concentration, indicating that the exposure to toluene might not be from the use of cautery. The exposure concentrations for all chemicals detected were similar across all SEvac groups except for methylene chloride.

For personal exposure concentrations, the SE group generated the lowest exposure (0.6 μg/m^3) to methylene chloride followed by the SA group (3.4 μg/m^3) and NS group (9.9 μg/m^3). Among several thermal desorption tubes collected during T&As, only 1 tube per SEvac method detected methylene chloride (methylene chloride was below the limit of detection in most tubes). For the non-VOC compounds (which were limited to area exposures), there was no pattern of exposure levels among the groups.

Discussion

We set out to determine the composition of SP created during a routine T&A and to compare the efficacy of SEvac systems used during surgery. We found known carcinogens in the SP, with higher concentrations of methylene chloride and acetaldehyde than background concentrations. Other known-carcinogenic chemicals (eg, benzene, formaldehyde, hydrogen cyanide) were also detected, but these were likely from the background rather than from the SP.

SP exposure has been associated with headache, epiphora, cough, sore throat, foul hair odor, nausea, drowsiness, dizziness, sneezing, and rhinitis.[22,23] Multiple animal studies of prolonged SP exposure showed postmortem evidence of chronic inflammation of larynx and lungs.[24,25] Benzene is the best studied of the chemicals found; it has a known dose-related relationship with lifetime risk of leukemia.[26,27] Benzene was also detected in the measurements of personal and area exposures but not greater than the background concentrations as described above (Table 4). To date, there has been no increased risk of pulmonary or other aerodigestive cancers identified for OR workers in large observational cohort studies.[28] Our team found many harmful compounds, but none approached hazardous levels according to established OELs.

When the aerosolized particle number concentrations were compared among the groups, the smoke-evacuator cautery pencil was most effective. Particle concentration was higher for assistant-held smoke evacuator when compared to smoke-evacuator cautery pencil, even though it was not statistically significant. This lack of statistical significance is likely because of limited power to detect differences with our small sample size. Note that in this study, the assistant-held suction is likely optimal, as a degree of the Hawthorne effect upon the surgical assistant would be expected. During study days, the assistant was alert to the reason for the study and positioned the suction handpiece well and quickly. However, if the assistant is not attentive during tonsillectomies, the surgical team exposure to SP may approximate the group without suction. Thus, to reduce the effect of an inattentive assistant, adoption of a smoke-evacuator pencil cautery in practice may be reasonable.

The otolaryngology SP literature is limited to SP produced during laryngeal laser surgery.[6,10,15,23] Research regarding SP is significant in general surgery, including laparoscopic, and colorectal surgery. In the general surgery literature, multiple authors have found that the intensity of the energy used to divide and cauterize tissue correlates to particle size.[1,3,29] For example, the harmonic scalpel produces fewer volatile particles compared to monopolar electrocautery. Higher electrocautery settings were associated with smaller, more volatile particulates.[1] Viable cells were found in harmonic scalpel plume but not in electrocautery plume.[3] The present study found less than 0.4% viable cells. Higher wattage cautery during peritonectomy was associated with smaller, ultra-fine particles compared to lower electrocautery settings.[29] We limited our study to 1 wattage and determined that most particles were ≤ 100 nm (Figure 3); our findings suggest that most surgical masks currently available would not be protective.[8–12] Using an N95 surgical mask, which has a protection factor 200 times higher than a standard surgical mask, would reduce exposure to SP.[30]

In our center, an electrosurgical pencil costs US$10 and a smoke-evacuator pencil cautery costs US$30.[31] There are about 10 people exposed to SP per case (trainees, surgeons, nurses, anesthesia team members, and OR/facilities technicians), so the cost per person is relatively low. The smoke-evacuator pencil we used is similar in size to the electrosurgical pencil. We also found that having suction closer to the surgical field improved surgeon visualization and removed the possible obstacle of assistant-held suction obstructing the surgeon's view inside the mouth.

Limitations to this study include the small sample size, so only large differences would be significant. Second, the instruments used, such as DRIs, were usually at the lower limit of their ability to detect chemicals of interest. With the small concentrations detected, door opening/closing could lead to air currents through the OR, altering instrument sampling. The same SE method was used for all cases daily to prevent exposures from previous cases, but the efficacy of this in mitigating bias is unknown. Finally, the study was conducted with different surgeons, and so the height of the personal collection device varied slightly. It is unlikely that these limitations affected the core findings that low levels of toxic chemicals are created during electrocautery tonsillectomy and that these chemicals are best controlled with local suction.

Conclusion

We found several harmful organic and nonorganic aerosolized by-products from tonsillectomy. The harm from long-term low-level exposure to surgical smoke is unknown, but its mitigation with suction is recommended. Both assistant-held suction and smoke-evacuator electrocautery pencil ameliorated SP, although the latter required no assistant. Further work would be beneficial to assess the risk of surgical smoke to OR personnel in other common otolaryngology procedures.

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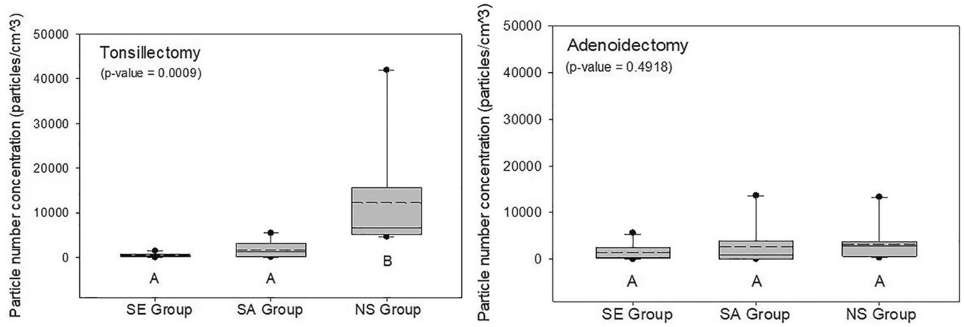

Figure 1.

Particle number concentration (particles/cm^3) measured with DISCmini in surgeon's breathing zone. Letters indicate statistically significant differences. Each boxplot represents 10th, 25th, 50th (median), 75th, and 90th percentiles. Solid circles = 5th and 95th percentiles. Dashed line = mean. NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

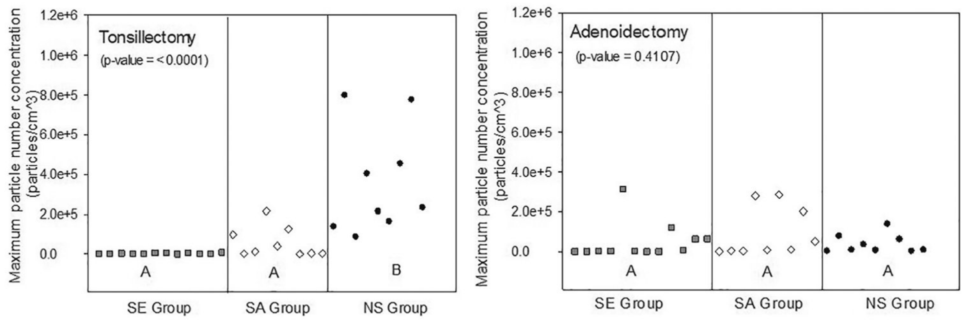

Figure 2.

Maximum particle number concentration (particles/cm^3) of individual cases measured with a DISCmini. Letters indicate statistically significant differences. NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

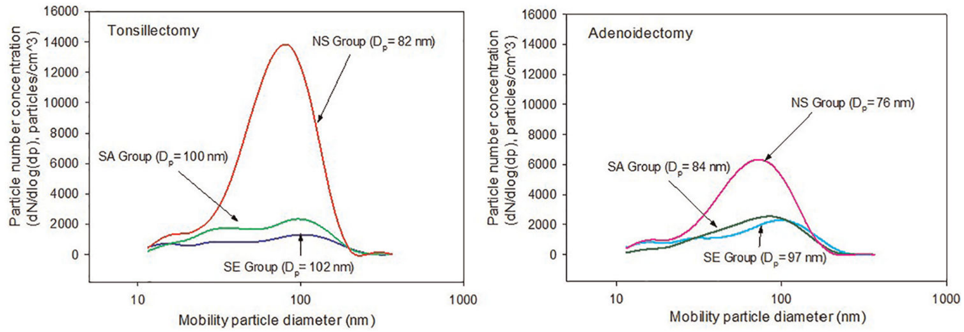

Figure 3.

Particle size distributions by number measured with a scanning mobility particle sizer (area exposure). D_p indicates the diameter showing the peak particle number concentration. NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

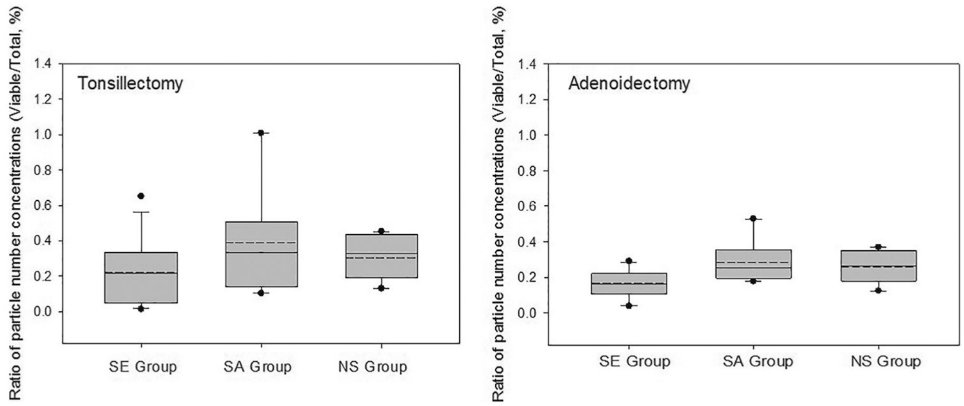

Figure 4.

Ratios of viable particle number concentrations and total number concentrations (BioTrak). Each box plot represents 10th, 25th, 50th, 75th, and 90th percentiles. Solid circles = 5th and 95th percentiles. Dashed line = mean. NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

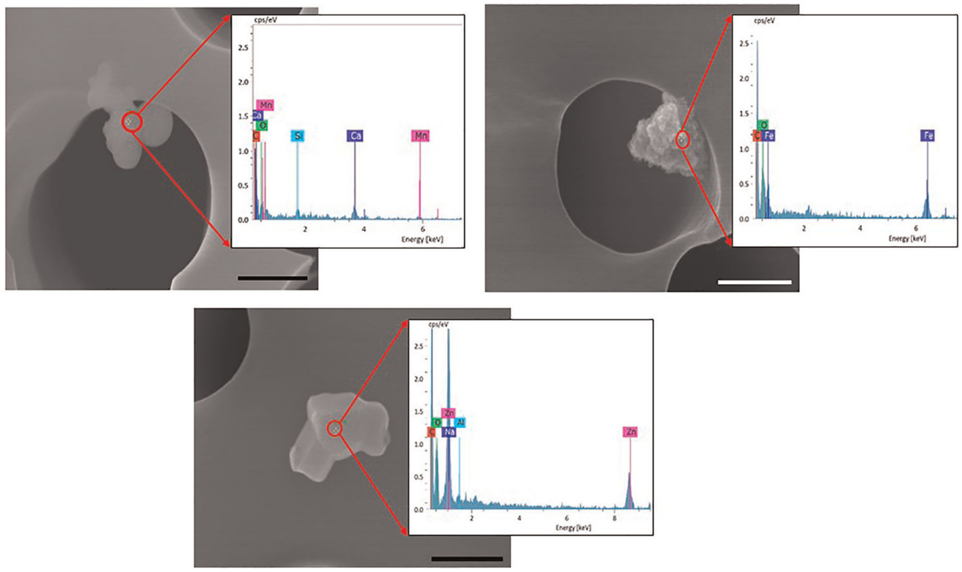

Figure 5.

Morphology of particles and observed chemical elements by scanning electron microscopy (scale bars represent 400 nm).

Table 1.

Summary of the Number of Cases, Coagulation Setting, and the Duration of Cautery Time.

		Tonsillectomy		Adenoidectomy	
Type of Smoke Evacuation	**No. of Cases**	**Coagulation Setting**	**Cautery Time (Mean), min**	**Coagulation Setting**	**Cautery Time (Mean), min**
SE group	12	12	2.0–6.3 (4.1)	20, 30, or 35	4.6–25 (12.5)
SA group	9	12	2.0–5.4 (3.4)	20 or 30	2.2–22 (9.6)
NS group	9	12	0.7–4.4 (3.3)	20, 30, or 35	4.0–16.6 (9.4)

Abbreviations: NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

Table 2.

Summary of Particle Number Concentration (Particles/cm^3) Measured with DISCmini (Breathing Zone Exposure).

		Tonsillectomy				Adenoidectomy			
Type of Smoke Evacuation	**No. of Cases**	**Range**[a]	**Mean (Median)**	***P* Value**[b]	**Pairwise Comparison**[c]	**Range**[a]	**Mean (Median)**	***P* Value**[b]	**Pairwise Comparison**[c]
SE group	12	16–1445	508 (405)	.0009	A	3–5668	1444 (465)	.4918	A
SA group	9	40–5458	1661 (1250)		A	41–13,615	2711 (1000)		A
NS group	9	4612–15,717	8208 (6080)		B	331–13,311	3091 (1603)		A

Abbreviations: NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

[a]Range of particle number concentration represents mean concentrations of individual cases.

[b]Testing differences of particle number concentrations among 3 groups.

[c]"A" groups are significantly different from "B" groups but not from each other.

Table 3.

Summary of Particle Number Concentration (Particles/cm^3) Measured with Condensation Particle Counter (Area Exposure).

		Tonsillectomy				Adenoidectomy			
Type of Smoke Evacuation	**No. of Cases**	**Range[a]**	**Mean (Median)**	***P* Value[b]**	**Pairwise Comparison[c]**	**Range[a]**	**Mean (Median)**	***P* Value[b]**	**Pairwise Comparison[c]**
SE group	12	23–2634	808 (663)	.0002	A	22–3399	1332 (1234)	.4035	A
SA group	5	125–3498	1489 (1461)		A	46–10,793	3031 (352)		A
NRS group	9	1294–13,218	6052 (5575)		B	262–10,849	2749 (2121)		A

Abbreviations: NS, cautery without suction; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery.

[a]Range of particle number concentration represents average concentrations of individual cases.

[b]Testing differences of particle number concentrations among 3 groups.

[c]"A" groups are significantly different from "B" groups but not from each other.

Table 4.

Average Exposure Concentrations (μg/m^3) of Volatile Organic and Other Chemical Compounds during Surgeries.[a]

			Personal Exposure Concentration, Mean (CV)			Area Exposure Concentration, Mean (SD)		
Substance	OEL, μg/m^3	Background Concentration	SE	SA	NS	SE	SA	NS
VOCs								
1,2,4-Trimethylbenzene	125,000	0.9	1.2 (1.1)	0.4 (0.4)	0.3 (0.3)	0.7 (1.5)	0.3 (0.2)	0.4 (0.2)
1,3,5-Trimethylbenzene	125,000	<LOD	0.6 (0.5)	0.3	<LOD	0.4 (1.1)	0.2 (0.7)	<LOD
1,4-Dichlorobenzene	450,000	<LOD	<LOD	1.6	<LOD	<LOD	<LOD	<LOD
Benzene	319	2.3 (0.9)	2.7 (1.5)	0.8 (0.6)	0.9 (0.3)	0.7 (0.5)	0.6 (0.4)	0.8 (0.2)
Carbon tetrachloride	62,900	<LOD	0.3	<LOD	0.3 (0.4)	0.5	<LOD	0.3 (0.2)
Chloroform	*b*	0.9 (0.4)	0.4 (0.6)	1.0 (0.4)	0.8 (0.2)	0.3 (0.3)	1.0 (0.4)	0.9 (0.7)
Ethylbenzene	435,000	1.1 (0.5)	0.9 (0.7)	0.5 (0.2)	0.4 (0.4)	0.7 (0.9)	0.5 (0.2)	0.4 (0.4)
Isopropylbenzene	245,000	<LOD	0.3 (0.4)	0.2 (0.4)	0.3 (0.1)	0.3	<LOD	<LOD
Methylene chloride	86,750	<LOD	0.6	3.4	9.9	1.0	<LOD	<LOD
m-Xylene and p-xylene	43,5000	1.9 (0.4)	3.4 (0.9)	1.4 (0.2)	1.1 (0.5)	2.4 (1.2)	1.3 (0.2)	1.1 (0.4)
Naphthalene	50,000	<LOD	0.3 (0.6)	0.7 (1.2)	0.6	0.2 (0.1)	0.3 (0.2)	<LOD
n-Propylbenzene	NL	<LOD	0.4 (0.04)	<LOD	<LOD	0.4	<LOD	<LOD
o-Xylene	435,000	1.5 (0.6)	1.2 (0.9)	0.6 (0.2)	0.5 (0.4)	0.9 (1.1)	0.5 (0.2)	0.4 (0.4)
p-Isopropyltoluene	NL	2.1	0.5 (0.5)	0.8 (0.7)	0.8 (0.7)	0.4 (0.2)	0.4 (0.2)	0.4 (0.5)
Styrene	215,000	2.3	0.4 (0.4)	0.4 (0.5)	0.4 (0.4)	0.4 (0.4)	0.4 (0.3)	0.5 (0.3)
Tetrachloroethene	678,000	<LOD	0.1 (0.1)	0.2 (0.02)	1.0 (0.04)	0.1 (0.1)	0.1	0.9 (0.02)
Toluene	375,000	781 (1.3)	19(1.7)	15.5 (1.0)	16.0 (0.5)	87.9 (1.7)	318 (1.0)	678 (0.9)
Xylenes, total	435,000	1.5 (0.2)	1.5 (0.3)	2.1 (0.2)	1.6 (0.4)	1.2 (0.03)	1.8 (0.2)	1.5 (0.4)
Other chemical compounds								
Acetaldehyde	360,000	14 (0.6)		*c*		27(1.3)	26 (0.4)	13 (0.9)
Acrolein	250	<LOD				<LOD	<LOD	<LOD
Formaldehyde	19.7	8.6 (0.5)				6.5 (0.5)	5.8 (0.6)	5.6 (0.4)
Hydrogen cyanide	12,100	15				2.9 (0.1)	4.9 (0.6)	<LOD
Acenaphthene[d]	NL	5.7				<LOD	1.2 (0.5)	<LOD
Acenaphthylene[d]	NL	1.7 (0.03)				0.4 (0.01)	1.9 (1.0)	1.1 (0.8)

Substance	OEL, µg/m^3	Background Concentration	Personal Exposure Concentration, Mean (CV)			Area Exposure Concentration, Mean (SD)		
			SE	SA	NS	SE	SA	NS
Benzo(b)fluoranthene[d]	NL	<LOD				<LOD	0.9 (0.4)	0.4
Benzo(e)pyrene[d]	NL	2.3 (0.8)				0.4 (0.6)	2.9 (0.6)	1.1 (0.9)
Chrysene[d]	100	<LOD				<LOD	0.8 (0.5)	0.5

Abbreviations: CV, coefficient of variation (standard deviation divided by mean); LOD, limit of detection; NL, not listed; NS, cautery without suction; OEL, occupational exposure limit; SA, cautery with suction held by an assistant; SE, smoke-evacuator pencil cautery; VOC, volatile organic compound.

[a] CV not listed if substance was detected in only 1 sample.

[b] No OEL for full-shift time-weighted average concentration present.

[c] Area samples only.

[d] Polycyclic aromatic hydrocarbons chemicals.