



Applying an air curtain to reduce surgical smoke concentration

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Received: 27 October 2022 / Accepted: 3 June 2023 / Published online: 26 June 2023
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Abstract

Operation room personnel are exposed to high concentrations of surgical smoke during electrosurgery and laser treatment. Surgical smoke contains viral aerosol, particulate matter, volatile organic compounds, and microorganisms. Current local exhaust ventilation control methods can be noisy, bulky, and expensive. In this study, we are the first to build a cost-effective air curtain device to remove surgical smoke. Experiments were conducted in an operating room by cutting porcine samples with electrosurgical units. An air curtain system was installed below the surgical light. We measured the particle number and mass concentrations in the breathing zone. The concentrations were recorded under four scenarios: no control, commercial smoke evacuation pencil, low-velocity air curtain, and high-velocity air curtain. Results indicate that the air curtain reduces the concentration of particulate matter and produces less noise than commercial smoke evacuation pencils. The particle number removal efficiencies for the smoke evacuation pencil, low-velocity air curtain, and high-velocity air curtain were 88.52%, 70.79%, and 91.29%, respectively. The respective PM_{2.5} removal efficiencies were 90.92%, 85.38%, and 97.99%. Thus, installing an air curtains under surgical lights is a promising method for reducing surgical smoke and protecting medical personnel.

Keywords Particulate matter · surgical smoke · operating room · air curtain · surgical light · PM_{2.5} · smoke evacuation pencil

Introduction

The use of electrosurgery devices by surgeons has grown in recent years due to technological advancement and greater procedure volumes (Lewin et al. 2011). Surgical

smoke generated from electrosurgery contains water vapor, microorganisms, particulate matter, volatile organic compounds, and viral aerosols (Alp et al. 2006; Naslund Andreasson et al. 2012; Yang et al. 2018; Chen et al. 2022). High PM_{2.5} concentrations have been detected in operation rooms (Mohammadyan et al. 2019; Tan et al. 2019; Tanaka et al. 2022). Human papillomavirus (HPV) (Cox et al. 2020; Fox-Lewis et al. 2020; Palma et al. 2021), hepatitis B virus

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(HBV), and human coronavirus RNA viruses have been found in surgical smoke (Kwak et al. 2016; Yokoe et al. 2021). In addition, one study indicates that SARS-CoV-2 may exist in surgical smoke (Bogani et al. 2021). Moreover, research indicates that approximately 500,000 medical personnel in the United States are chronically exposed to surgical smoke each year (OSHA 2016).

In a typical operating room, air curtains and diffusers are mounted on the ceiling to supply air from above. This can help guide the surgical smoke toward the return grill near the floor for removal (Wagner et al. 2014). However, the surgical light underneath the air curtain or diffuser can block the airflow from the ceiling. This results in a buildup of surgical smoke under the surgical light where the healthcare personnel is located (Mcneill et al. 2013). Currently, most medical personnel wear surgical masks or N95 respirators during surgical procedures. However, N95 respirators only show reliable protection when fit-tests are conducted. Furthermore, shortages of respirator masks may occur during a pandemic (Aljadeed et al. 2021; Hetzmann et al. 2021). Another method utilizes local exhaust ventilation (LEV), such as with the standalone smoke evacuator and smoke evacuation pencil (see Fig. 1). Studies show that the LEV removal efficiency ranges from 40% - 88% (Pillinger et al. 2003; Wang et al. 2015; Liu et al. 2020). However, LEV can be costly and noisy, and the smoke evacuation tube can be easily blocked by tar, soot, or blood clot (Mattes et al. 2010; Michaelis et al. 2020). In addition, LEV can be inconvenient due to its size and a common requirement that another person holds the suction (Ball 2010). The above problems will hinder

its popularity in operating rooms. A study pointed out that only about 14% of medical personnel in the United States use LEVs during surgical procedure (Steege et al. 2016). Although some surgeons are aware of the risks of surgical smoke, many do not employ hazard reduction strategies such as smoke evacuators and surgical masks (Georgeses and Lipner 2018). Another study attached negative ions to an electrosurgical pencil to help reduce surgical smoke concentration. However, this still requires an add-on device and may affect the hand movement of surgeons (Ninh et al. 2022).

Another option to reduce surgical smoke concentration is to use an air curtain (Tzeng 2021). Air curtains are traditionally used to prevent energy, heat, and pollutants from entering or escaping (Huang et al. 2007; Hu et al. 2008). One study shows that the efficiency of an air curtain in preventing CO₂ from entering a mine refuge was 55% (Zhang et al. 2016). In another study, Li et al. (2021) used an air curtain to prevent the dust generated in a tobacco factory from escaping the suction hood. The above studies show that an air curtain is an effective method to confine air pollutants. However, air curtains have not yet been used with surgical lights to help reduce surgical smoke concentration. Here, we are the first to install an air curtain beneath the surgical light (Fig. 1) to help reduce the exposure of operating room personnel to surgical smoke. By installing an air curtain beneath the surgical light, the generated airflow from the air curtain will not be blocked by the surgical light. We examined the efficiency of this new device for reducing surgical smoke concentration.

Fig. 1 Three surgical smoke removal devices, from left to right: smoke evacuator (from <https://acuderm.com/>), smoke evacuation surgical pencil, and air curtain (this study)

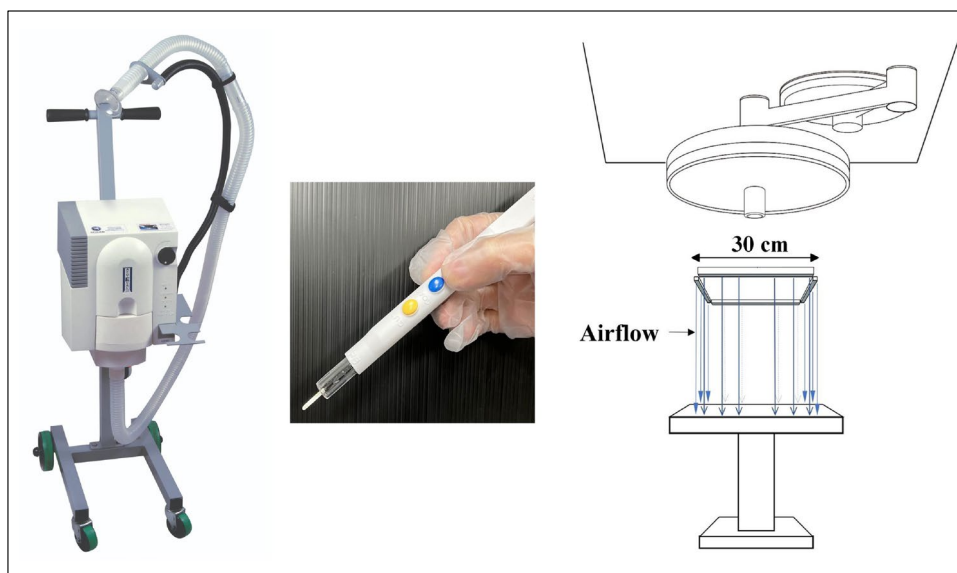
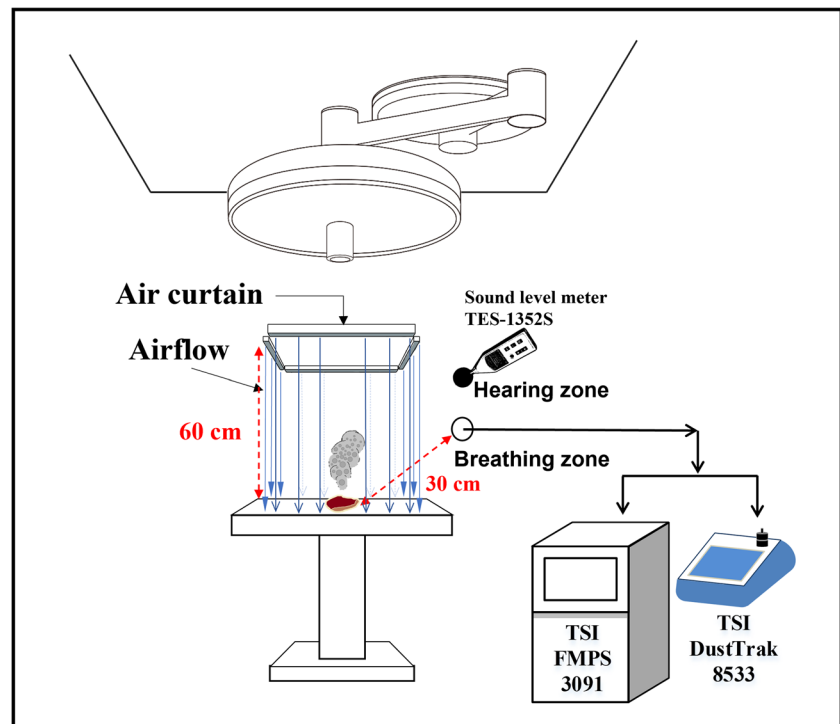


Fig. 2 Illustration of the experimental setup with air curtain under surgical light



Methods

Experimental setup

Figure 2 illustrates the experimental setup in this study. The experiments were conducted in an operating room (5.0 m wide x 2.4 m high x 4.0 m long) located in the National Cheng Kung University (NCKU) Laboratory Animal Center. The operating room temperature and relative humidity were controlled at 20–23°C and 55–60 %, respectively. The operating room was equipped with high-efficiency particulate air (HEPA) filtered air that was supplied from the ceiling, and the air change per hour (ACH) was 12.5. An electrosurgical unit (generator model: Sabre 180, Conmed, NY, USA; electrosurgical pencil model: SW12200, Shinmed, New Taipei, Taiwan) was used to incise pork shoulder butt. The generator was set to 30 watts, each incision took 20 seconds to perform, with an incision length and depth of 8.0 and 1.5 cm, respectively. The particle concentration was measured during the incision time (20 seconds) in the breathing zone (30 cm from the source). We started each incision after the total particle number concentration dropped below 1000 #/cm³. Three different kinds of control methods were used: commercial smoke evacuation pencil (model: SW12200, SHINMED, Taipei, Taiwan), low-velocity air curtain (3 m/s), and high-velocity air curtain (6 m/s). The smoke evacuation pencil was set to 40 (Liters/min, LPM) since it is a common setting in hospitals. For each control method, ten sets of the experiment were performed; each set included

one without control and one with control methods. The particle mass concentrations (PM_{2.5}) were measured by DustTrak DRX 8533 (TSI Inc., MN, USA). A Fast Mobility Particle Sizer (FMPS, Model 3091 series, TSI Inc., MN, USA) was used to measure particle number concentration and size distribution (5.6 – 560 nm). The resolution time for both DustTrak and FMPS scan times was 1 second. At the beginning and end of each day's experiment, a HEPA filter (Pall Corporation, New York, NY, USA) was attached to the sampling inlet to ensure the sampling line has no leaks. Finally, we used a sound level meter (TES-1352S, TES Inc., Taipei, Taiwan) 45 cm away from the source to measure the noise level in the hearing zone.

Control methods

The square-shaped air curtain (30 cm x 30 cm) consists of four cross-flow fans (SHD30290A12, Gulf Electrics Co., Ltd, Taiwan). The air curtain was placed 60 cm above the surgical table and fixed with four clamp stands. Air Velocity Meter (model 9535-A, TSI Inc., MN, USA) was used to measure the air curtain's wind velocity profile at three different heights, as shown in Fig. 3, left panel. The three heights were 0 cm, 30 cm, and 60 cm above the surgical table. At each level, 25 points were measured. The air curtain's removal efficiency was compared with a commercial smoke evacuation pencil. The smoke evacuation pencil flow rate was controlled at 40 LPM using the mass flow controller (Model MCR-50SLPM-D/5M, Alicat, AZ, USA).

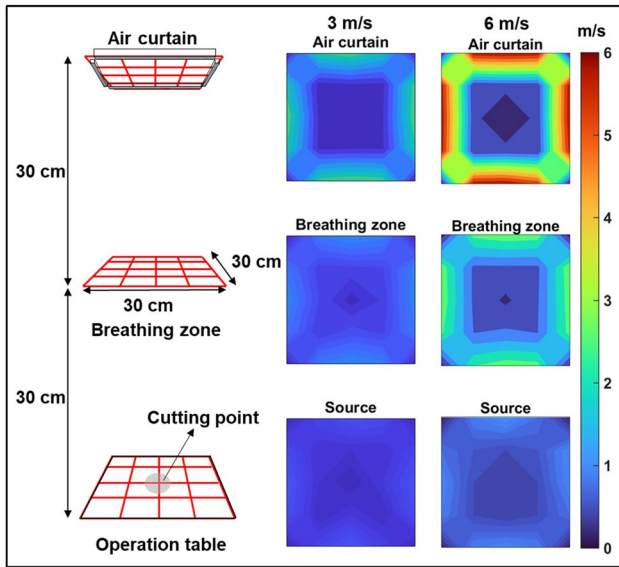


Fig. 3 Wind velocity profile of air curtain at three levels (air curtain outlet, breathing zone, and source) with two different outlet flow velocities: 3 m/s and 6 m/s

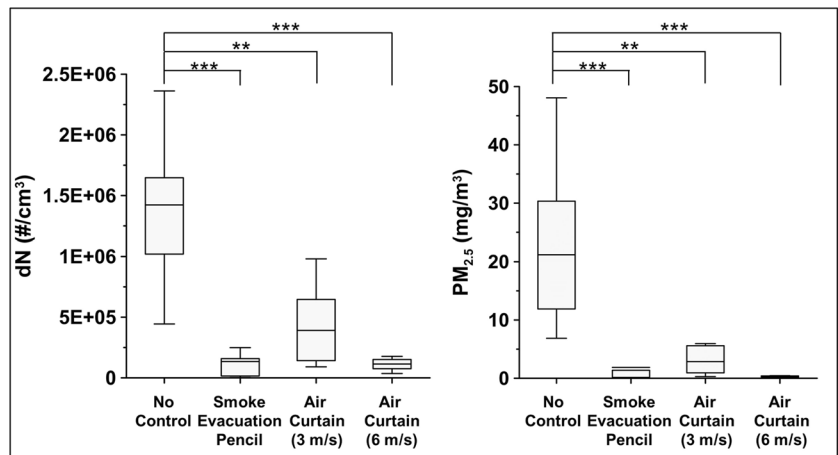
Removal Efficiency (RE)

The removal efficiency (RE) under different conditions can be defined as

$$RE(\%) = \left(1 - \frac{C_{with\ control}}{C_{without\ control}} \right) \times 100\% \tag{1}$$

where $C_{with\ control}$ and $C_{without\ control}$ were the measured particle mass or number concentrations with different control methods and without control, respectively.

Fig. 4 Boxplot of particle number and mass concentration measurements in the breathing zone under different control methods. The top and bottom edges of the boxes represent the 25th and 75th percentiles, the central line marks the median. Bars outside the box represent the 1.5 times interquartile range (** $p < 0.001$, *** $p < 0.05$)



Results and discussion

Air curtain's wind velocity profile and noise level under different settings

Wind velocity profiles were obtained and shown in Fig. 3 (right panel) for the low-velocity and high-velocity air curtains. The airflow velocity decreased with increasing distance from the outlet. The velocity measured at 30 cm and 0 cm above the surgical table for the low-velocity air curtain was around 1 and 0.5 m/s, respectively. For the high-velocity air curtain, the velocity measured at 30 cm and 0 cm above the surgical table was around 2.5 m/s and 1 m/s, respectively.

The measured noise levels for no control, the smoke evacuation pencil, the low-velocity air curtain, and the high-velocity air curtain were 50 dBA, 65 dBA, 57 dBA, and 58 dBA, respectively. Note that the noise level of the air curtain is lower than that of the commercial smoke evacuation pencil.

The high-velocity air curtain shows similar particle removal efficiency and less noise (57–58 dBA) compared to the smoke evacuation pencil (65 dBA). Another study shows that the noise level reaches up to 69 dBA when using smoke evacuators (Seipp et al. 2018). High noise levels can distract the medical personnel working in the operating room (Keller et al. 2016). Thus, further improvement of the noise reduction design of the air curtain is warranted.

Surgical smoke concentration and size distribution

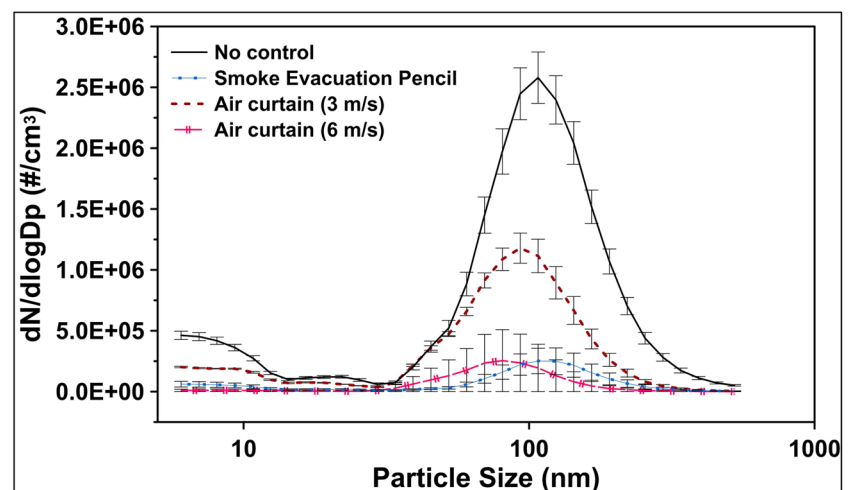
Figure 4 shows the boxplot of particle number and mass concentrations in the breathing zone with different surgical smoke control methods. The highest concentrations and largest variations in the breathing zone were seen under

no control setting, where the average particle number and mass concentrations were about $1.45 \times 10^6 \text{ #/cm}^3$ and 21.19 mg/m^3 , respectively. The average particle number and mass concentrations using the smoke evacuation pencil were $1.35 \times 10^5 \text{ #/cm}^3$ and 1.86 mg/m^3 , respectively. Furthermore, the average particle number and mass concentrations for the low-velocity air curtain were $3.91 \times 10^5 \text{ #/cm}^3$ and 2.87 mg/m^3 , respectively. In contrast, the average particle number and mass concentrations for the high-velocity air curtain were $1.14 \times 10^5 \text{ #/cm}^3$ and 0.35 mg/m^3 , respectively.

Figure 5 shows the particle number concentrations and size distributions under different surgical smoke control methods. The count median diameter (CMD) for no control, the smoke evacuation pencil, the low-velocity air curtain, and the high-velocity air curtain were 107.50 nm, 107.50 nm, 93.10 nm, and 80.60 nm, respectively. Note that at a higher velocity, the air curtain has a smaller CMD since there was more dry air delivered to the surgical smoke that can reduce the particle size.

Surgical smoke control methods such as air curtain and smoke evacuation pencil effectively help reduce medical personnels' particle exposure. The large variations in the observed particle number concentration, mass concentration, and standard deviation in settings without any control can be attributed to the turbulence flow affecting the dispersion of the particles in the operating room—this phenomenon is also seen in other studies (Karjalainen et al. 2018; Lee et al. 2018; Buggisch et al. 2020). Another reason is the day-to-day differences in the porcine tissue used. We observed the least variation in particle number and mass concentration with the high-velocity air curtain. This shows that, regardless of the high variation in the surgical smoke concentration generated during electrosurgery, the high-velocity air curtain is still able to reduce its concentration.

Fig. 5 Particle size distribution measurements in the breathing zone under different control methods; the error bars represent one standard error of the average



Surgical smoke removal efficiency

Figure 6 shows the particle removal efficiency of different surgical smoke control methods. All methods reduce particle number and mass concentration in the breathing zone by over 70% and 85%, respectively. The particle number removal efficiencies were 88.52%, 70.79%, and 91.29% for the smoke evacuation pencil, low-velocity air curtain, and high-velocity air curtain, respectively. The respective $\text{PM}_{2.5}$ removal efficiencies were 90.92%, 85.38%, and 97.99%.

The results indicated that the high-velocity air curtain has the highest particle number and mass concentration removal efficiencies among the three surgical smoke control methods. The smoke evacuation pencil used in this study has particle number and mass concentration removal efficiencies of 88.52% and 90.92%, respectively. This removal efficiency is higher than another study also using smoke evacuation pencil, which shows the particle number

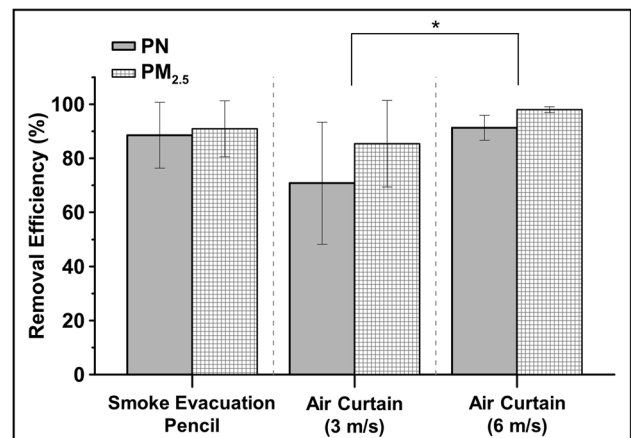


Fig. 6 Particle number and $\text{PM}_{2.5}$ removal efficiencies in the breathing zone; the error bars represent one standard deviation. (* $p < 0.01$)

and mass concentration removal efficiencies to be around 66 % (Lee et al. 2018). These differences could be attributed to the higher flow rate (40 LPM vs. 35 LPM) used in this study. Other reasons may include differences in the operating room setting and the brand of smoke evacuation pencils.

In terms of cost-efficiency, the initial cost of the standalone smoke evacuator is more than \$1500, not including the cost of replacement filters and maintenance (Chapman et al. 2017). The commercial smoke evacuation pencil is less expensive, costing around \$30 (Neill and Golda 2017), but it is not reusable. The cost for the air curtain used in this study is less than \$200, and it is reusable, showing it to be a cost-effective tool to help reduce surgical smoke concentration. Furthermore, the air curtain can also be used with the current LEV or commercial smoke evacuation pencil for added efficiency in removing surgical smoke.

Nevertheless, some limitations still exist with this study. The first is that this study's current air curtain model is not yet integrated with the surgical light and still requires a clamp stand. The second limitation is that the air curtain formed by the four cross-flow fans cannot fully contain the surgical smoke. More improvements are needed to increase the sealing efficiency and reduce the noise generated by the air curtain. More air curtain parameters, such as height and flow velocity, are needed to be optimized in future research.

Conclusion

Air curtains can help reduce the surgical smoke concentration in an operating room. This economically-feasible method will generate lower noise levels than the commonly-used local exhaust ventilation. Furthermore, applying the air curtain underneath the surgical light will be a more user-friendly design for operating room staff. The next-generation air curtain will be integrated with the surgical light to save even more space. Finally, more research is needed to find the air curtain's optimal design (e.g., size, shape, and fan performance). The air curtain is a promising tool for surgical smoke reduction that can benefit operating room personnel.

Acknowledgments The authors thank the experimental support from Mr. Wei-An Wang and Mr. Di-Zhong Lin. Special thanks to Paul Spence for proof reading the article. We greatly acknowledge the support from the Laboratory Animal Center, College of Medicine, National Cheng Kung University, Tainan, Taiwan.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Xuan-Huy Ninh and Hung-Yu Tzeng. The first draft of the manuscript was written by Xuan-Huy Ninh and Hung-Yu Tzeng. All authors commented on previous versions of the manuscript. All authors have read and approved the final version of the manuscript for publication.

Funding This research was financially supported by the Taiwan Ministry of Science and Technology under the grants MOST 110-2221-E-006-098- and MOST 111-2221-E-006-029 -. This research was also supported in part by Higher Education Sprout Project, Ministry of Education to the Headquarters of University Advancement at National Cheng Kung University(NCKU) under grant D112-F2507. T.W. Wong acknowledges funding from the Center of Applied Nanomedicine, National Cheng Kung University from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE).

Data availability The datasets used during the current study are available from the corresponding author on request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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