

# Effect of electrosurgery in the operating room on surgeons' blood indices: a simulation model and experiment on rabbits

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## Abstract

**Objective:** This study aimed to examine the content of surgical smoke in the operating room, and the health effects of exposure to surgical smoke on surgeons.

**Methods:** We measured the content of surgical smoke in the operating room. The effect of exposure to surgical smoke on surgeons was examined using rabbits. Surgical smoke distribution was simulated to study the route of spread of surgical smoke. The effect of an evacuator was also evaluated.

**Results:** In the operating room during electrosurgery, there was a high-content zone of surgical smoke ( $1.5 \times 10^{-2}\%$ , carbon monoxide;  $3.0 \times 10^{-2}\%$ , carbon dioxide). In rabbit experiments, all groups that were exposed to surgical smoke showed significantly higher carboxyhemoglobin levels than did controls. Exposure to a high content of surgical smoke had a greater effect on blood indices than working continuously in the operating room.

**Conclusions:** During electro-laparotomy, carbon monoxide in the high-content and low-content zones is higher than the United States Environmental Protection Agency's limit. Carboxyhemoglobin levels may be  $> 10\%$  with continuous operations over a week in the high-content zone in the operating room. Even with an evacuator, surgeons' blood indices can still be affected by surgical smoke.

## Keywords

Operating room, surgical smoke, smoke exposure, blood indices, carbon monoxide content, electrosurgery, laparotomy

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## Introduction

The electrosurgical unit was invented in 1927,<sup>1</sup> but over the last 2 decades, electrosurgery has become more popular worldwide.<sup>2</sup> The advantages of an electrosurgical unit are high cutting speed, positive hemostatic effects, ease of operation, and safety. Consequently, the percentage of surgeons who perform electrosurgery has considerably increased.<sup>2-5</sup>

The electrosurgical unit relies on a current passing through tissue to produce heat to complete separation and coagulation.<sup>3</sup> Previous studies have simulated the temperature field during tissue cutting with an electrosurgical unit by ANSYS.<sup>4</sup> These studies showed that the tip temperature of the knife was 214.4°C at 20 W of power, 301.7°C at 60 W, 436.6°C at 70 W, and higher than 500°C at 80 W.

During electrosurgery, a high temperature at the tip of the knife pyrolyzes the tissue and produces large volumes of high-temperature surgical smoke. Many studies have analyzed surgical smoke.<sup>6-10</sup> There are several harmful components in surgical smoke (especially carbon monoxide [CO]) that endanger the health of all staff in the operating room. At the same time, the work load of surgeons is higher than ever. Surgeons may work an entire day in the operating room and are forced to be in contact with surgical smoke every day during the working week.<sup>10</sup> However, few reports have studied the distribution of surgical smoke in the operating room during electrosurgery to help surgeons avoid concentrated zones of surgical smoke.<sup>11</sup> There have been even fewer studies on the health effects of exposure (continuous working or working with 1-day intervals, i.e., gd/gd-alt) to surgical smoke for surgeons.<sup>11</sup>

This study aimed to examine the distribution of surgical smoke in operating rooms. We also investigated the effect of exposure (gd/gd-alt) to surgical smoke in high-/low-

concentration zones for surgeons using a statistical method based on rabbit experiments. We established a mathematical model to clarify the concentration regions of surgical smoke and to study the effect of an evacuator. These results will help surgeons protect themselves by standing in the correct location in an operating room and by making reasonable operating schedules.

## Methods

### *Measurement of surgical smoke in an actual operating room*

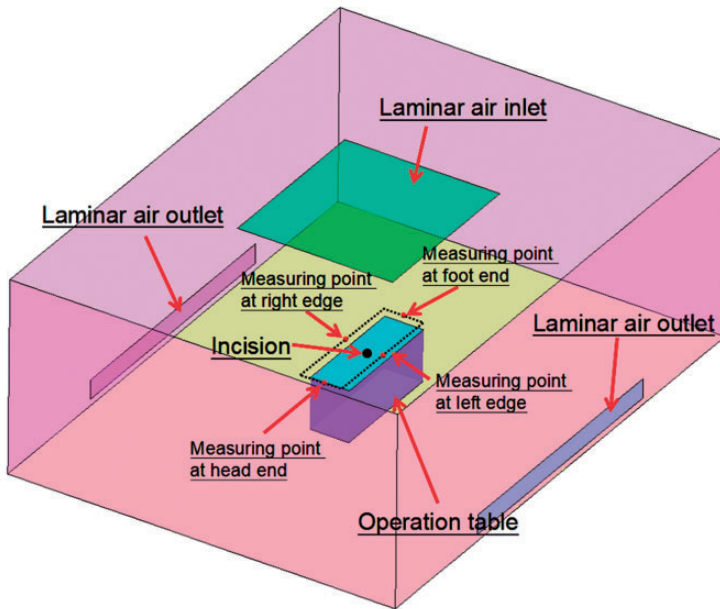
We measured the distribution of surgical smoke to examine the effect of surgical smoke on surgeons who are continuously working in the operating room. CO content at certain positions in the operating room was measured with a portable CO detector (SKY8000 CO detector; Shenzhen Unitec Technology Co., Ltd., Shenzhen, China) during electrosurgery. The measurement positions were at the four corners of the operating table at a height of 1 m from the floor (Figure 1).

### *Rabbit experiments*

Using measured data of surgical smoke during surgery, the effect of surgical smoke on blood indices of surgeons continuously working in the operating room was studied by experiments on rabbits. Rabbits were exposed to gas that contained CO, carbon dioxide (CO<sub>2</sub>), oxygen (O<sub>2</sub>), and nitrogen (N<sub>2</sub>) for certain time intervals. This procedure simulated surgical smoke exposure during electrosurgery.

The animal use protocol was reviewed and approved by the Animal Ethical and Welfare Committee (AEWC) of Wuhan University of Science and Technology, China.

*Experimental conditions.* The simulation cabin was a hexahedral airtight Perspex cabin



**Figure 1.** Measuring points in the operating room

with a volume of  $2 \text{ m}^3$ . The input gas flow rate was  $18 \text{ m}^3/\text{h}$ , the temperature and humidity were  $25 \pm 2^\circ\text{C}$  and  $70\% \pm 10\%$ , respectively, and five rabbits were kept in each cabin.

$\text{CO}$  and  $\text{CO}_2$  were distributed and imported into the simulation cabin through intake using a precise gas distributing facility. The chemical analysis of gas in the cabin was tested with a gas chromatograph (Agilent 7890B; Agilent Technologies Inc., Wilmington, DE, USA).

**Experimental methods.** The animals used in these experiments were male Japanese rabbits, weighing 2 to 3 kg. Eighty rabbits were randomly divided into the following five groups: normal control (NC), daily low-level surgical smoke exposure (L-gd), daily high-level surgical smoke exposure (H-gd), low-level surgical smoke exposure with a 1-day interval (L-gd-alt), and high-level surgical smoke exposure with a 1-day interval (H-gd-alt). For the NC group, the rabbits

were fed in the simulation cabin with imported fresh air for 5 days. For the L-gd and H-gd groups, the rabbits were fed in separate simulation cabins with imported low-content or high-content surgical smoke for 8 hours per day for 5 days. For the L-gd-alt and H-gd-alt groups, the rabbits were fed in separate stimulation cabins with imported low-content or high-content surgical smoke for 8 hours per day with a 1-day interval for 5 days.

**Measurement of blood indices.** Ear arterial blood (0.8 mL) was collected with a sterile syringe from each rabbit before and after surgical smoke exposure. Each blood sample was injected into a sample tube containing heparin. Each sample was then shaken and immediately placed on ice. The blood gas indices of each sample were measured with an iStat-300 blood gas detector (iStat-300G; Abbott, Chicago, IL, USA) 30 minutes after sampling, and carboxyhemoglobin (HbCO) levels were

measured with a spectrophotometer (722S spectrophotometer; Shanghai Instrument Electric Analytical Instrument Co., Ltd. Shanghai, China) after sampling.

**Statistical methods.** Measured indices of each group were compared using the program SPSS for Windows, Version 13.0 (SPSS Inc., Chicago, IL, USA). The measured results for pH, O<sub>2</sub> saturation, O<sub>2</sub> content, and HbCO levels are shown as the mean  $\pm$  standard deviation. Statistical calculations were performed using the independent sample t-test and two-way analysis of variance. Statistical results with a *p* value of  $< 0.05$  were considered as significant.

### *Mathematical simulation of surgical smoke distribution in the operating room*

On the basis of the rabbit experiment data, which clarified the effect of surgical smoke on blood indices of surgeons working

continuously in the operating room, a mathematical model was constructed using the FLUENT 15.0 program (Ansys Inc., Canonsburg, PA, USA). This model was established to determine the distribution route of surgical smoke during surgery for better protection of surgeons. In addition, a geometric model of an operating room was created. The conditions of the simulation model were estimated on the basis of the actual flow rate of surgical smoke from an electro-knife tip with a constant temperature and cutting speed. The parameters of the model are shown in Table 1.

The governing equations of this model included the continuity equation, Navier–Stokes equations, the *k*- $\epsilon$  turbulence model, and the dynamic model of particles. The flow and mixture of surgical smoke were estimated using the multiphase mixture model in FLUENT 15.0.

The boundary conditions of the mathematical model were as follows. (1) The inlet

**Table 1.** Parameters for a simulation model for surgical smoke distribution in an operating room

Items	Value
Size of the operating room (L $\times$ W $\times$ H), m	8 $\times$ 6 $\times$ 3
Inlet of laminar air flow (L $\times$ W), m	2.4 $\times$ 2.6
Position of the laminar air flow inlet	Center of the ceiling
Size of the outlet of laminar air flow (L $\times$ W), m	4 $\times$ 0.3
Number of laminar flow outlets	2
Position of laminar air flow outlets	Lower part of two walls
Inlet velocity of laminar air flow, m/s	0.096
Temperature of laminar air flow at the inlet, °C	27
Heat transfer in the walls	Conduction
Outdoor temperature, °C	30
Size of the operating table (L $\times$ W $\times$ H), m	1.8 $\times$ 0.8 $\times$ 0.8
Incision position of the electro-knife	Center on the surface of the operating room
Temperature at the electro-knife incision, °C	300
Flow rate of surgical smoke at the incision, m <sup>3</sup> /s	2 $\times$ 10 <sup>-5</sup>
Chemical analysis of surgical smoke at the incision	CO: 5%, CO <sub>2</sub> : 10%, O <sub>2</sub> : 15%, N <sub>2</sub> : 70%
Pipe diameter of the evacuator (MEGA DYNE ZIP PEN, ETHICON), m	0.022
Outflow of the evacuator, m <sup>3</sup> /s	1.83 $\times$ 10 <sup>-4</sup>

L: length; H: height; W: width; CO: carbon monoxide; CO<sub>2</sub>: carbon dioxide; O<sub>2</sub>: oxygen; N<sub>2</sub>: nitrogen

of laminar air flow was set as the velocity inlet. (2) The outlet of laminar air flow was set as the pressure outlet, with a pressure of 0 pa. (3) The incision at the center of the operating table surface was set as the inlet of surgical smoke. (4) The velocity distribution at the four walls of the operating room was estimated with wall function. (5) Heat transfer of the walls of the operating room was set as the third boundary condition. (6) The ceiling and floor of the operating room were adiabatic.

The operating room was divided into  $3 \times 10^5$  grids. The simulation was performed using the finite volume method, where the model algorithm was the Pressure Implicit Split Operator method and the discrete scheme was the second order upwind difference scheme.

**Results**

*Measurement data in an actual operating room*

During laparotomy with an electro-knife (power 40 W), the CO content of four points in an actual operating room was measured. Simulation results of surgical smoke in the operating room showed that CO content at both sides at the edge of the middle part of the operating table (0.014%–0.015%) was much higher than that at the head or foot part of the operating table (0.0049%–0.0050%) (Table 2). At each location, actual measurements were recorded four times and the mean of these measurements was reported (Table 2). We found that the center region of the operating table had the highest content of surgical smoke. This region was called the high-content zone (HCZ) for surgical smoke. The mean gas contents in this region were  $1.5 \times 10^{-2}\%$  for CO,  $3.0 \times 10^{-2}\%$  for CO<sub>2</sub>, and 20% for O<sub>2</sub>. The regions near the operation table’s foot and head end had the second highest content of surgical smoke. These regions were called the

**Table 2.** Measurement of surgical smoke at four points in the operating room

Point	Height, m	CO			CO <sub>2</sub>			O <sub>2</sub>		
		Measurement results, %	Simulation results, %	Difference, %	Measurement results, %	Simulation results, %	Difference, %	Measurement results, %	Simulation results, %	Difference, %
Center point of the head end of the operating table	1	$5.1 \times 10^{-3}$	$5.0 \times 10^{-3}$	2	$9 \times 10^{-3}$	$9.1 \times 10^{-3}$	1	20.3		
Center point of the foot end of the operating table	1	$4.8 \times 10^{-3}$	$4.9 \times 10^{-3}$	2	$1.1 \times 10^{-2}$	$1.0 \times 10^{-2}$	9	20.4		
Center point of the right edge of the operating table	1	$1.6 \times 10^{-2}$	$1.5 \times 10^{-2}$	6	$2.9 \times 10^{-2}$	$2.8 \times 10^{-2}$	3	20.1		
Center point of the left edge of the operating table	1	$1.5 \times 10^{-2}$	$1.4 \times 10^{-2}$	7	$3.1 \times 10^{-2}$	$3.2 \times 10^{-2}$	3	20.2		

CO: carbon monoxide; CO<sub>2</sub>: carbon dioxide; O<sub>2</sub>: oxygen

low-content zone (LCZ) for surgical smoke. The mean gas contents in this regions were  $5 \times 10^{-3}\%$  for CO,  $1.0 \times 10^{-2}\%$  for CO<sub>2</sub>, and 20% for O<sub>2</sub>. The differences between simulation data of the mathematical model and actual measurement results ranged between 1% and 9%. Therefore, the simulation model was verified and could be used to analyze the distribution of surgical smoke in an operating room.

### Rabbit experiments

We examined two levels of CO and CO<sub>2</sub> content, and the experimental conditions for each group are shown in Table 3.

As shown in Table 4, there were no significant differences in all measured blood indices before exposure to surgical smoke between the exposure groups (L-gd/H-gd/L-gd-alt/H-gd-alt) and the NC group. However, after exposure to surgical smoke, there were some significant differences between the groups. The L-gd group had significantly higher HbCO levels after exposure to surgical smoke compared with the NC group ( $p < 0.01$ ). The H-gd group showed significant changes in all measured blood indices after exposure (all  $p < 0.01$ ). The L-gd-alt group had significantly higher HbCO levels than did the NC group ( $p < 0.01$ ). The H-gd-alt group showed significantly different

pH, HbCO levels, and O<sub>2</sub> content after smoke exposure compared with the NC group (all  $p < 0.05$ ). Comparison of mean post-exposure HbCO levels among the groups showed that HbCO levels ranked as follows: H-gd group > H-gd-alt group > L-gd group > L-gd-alt group. The mean post-exposure HbCO level in the H-gd group was twice as high as that in the L-gd group. The mean post-exposure HbCO level in the H-gd group was 4.5 times higher than that in the L-gd-alt group. Moreover, the mean post-exposure HbCO level in the H-gd group was 1.3 times higher than that in the H-gd-alt group. The mean HbCO index in the H-gd-alt group was 24% lower than that in H-gd group. The mean HbCO index in the L-gd-alt group was 56% lower than that in the L-gd group.

Two-way ANOVA showed that exposure to high or low surgical smoke content in the operating room significantly affected all blood indices (all  $p < 0.01$ ). However, working with a 1-day interval only significantly affected HbCO and O<sub>2</sub> saturation (both  $p < 0.01$ , Table 5).

### Simulation results of the mathematical model

As shown in Figure 2, many observations were observed from the mathematical

**Table 3.** Experimental conditions for each rabbit group

Group	Case number	Experimental condition		
		CO and CO <sub>2</sub> content in the simulation cabin		Mode of exposure
		CO, %	CO <sub>2</sub> , %	
NC	20	0	0	No exposure
L-gd	20	$5.0 \times 10^{-3}$	$1.0 \times 10^{-2}$	Continuous exposure
H-gd	20	$1.5 \times 10^{-2}$	$3.0 \times 10^{-2}$	Continuous exposure
L-gd-alt	20	$5.0 \times 10^{-3}$	$1.0 \times 10^{-2}$	Exposure with a 1-day interval
H-gd-alt	20	$1.5 \times 10^{-2}$	$3.0 \times 10^{-2}$	Exposure with a 1-day interval

CO: carbon monoxide; CO<sub>2</sub>: carbon dioxide; O<sub>2</sub>: oxygen; NC: normal control; L-gd: daily low-level surgical smoke exposure H-gd: daily high-level surgical smoke exposure; L-gd-alt: low-level surgical smoke exposure with a 1-day interval; H-gd-alt: high-level surgical smoke exposure with a 1-day interval. n = 4 rabbits in each group

**Table 4.** Blood indices after surgical smoke exposure

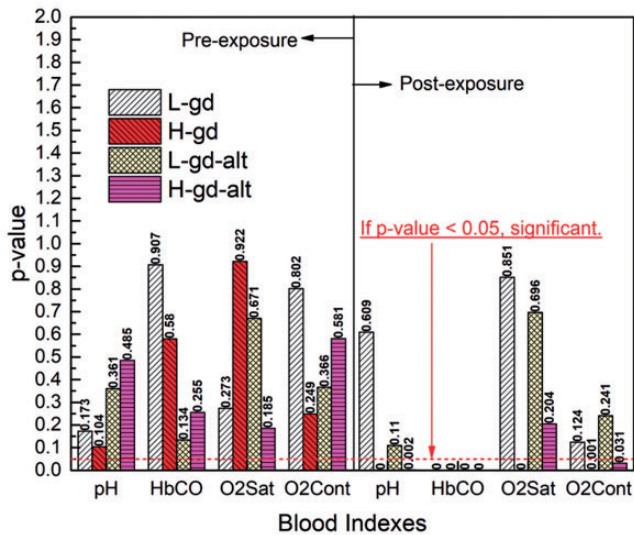
Group	Parameter	Case number	pH		HbCO, %		O <sub>2</sub> Sat, %		O <sub>2</sub> Cont, %	
			Pre-exposure	Post-exposure	Pre-exposure	Post-exposure	Pre-exposure	Post-exposure	Pre-exposure	Post-exposure
NC	$\bar{x} \pm s$	20	7.322±0.022	7.325±0.011	0.51±0.21	0.56±0.31	96.52±0.55	96.34±1.03	20.27±0.14	20.23±0.18
L-gd	$\bar{x} \pm s$	20	7.333±0.029	7.329±0.030	0.52±0.25	5.49±0.40	96.35±0.41	96.29±0.50	20.26±0.12	20.14±0.16
	<i>p</i>	/	-1.388	-0.516	-0.117	-43.665	1.113	0.189	0.252	1.571
H-gd	$\bar{x} \pm s$	20	7.334±0.026	7.291±0.036	0.907	<i>p</i> < 0.001**	0.273	0.851	0.802	0.124
	<i>t</i>	/	-1.663	4.116	-0.558	-42.611	0.098	5.457	1.172	3.674
	<i>p</i>	/	0.104	<i>p</i> < 0.001**	0.58	<i>p</i> < 0.001**	0.922	<i>p</i> < 0.001**	0.249	0.001**
L-gd-alt	$\bar{x} \pm s$	20	7.330±0.033	7.333±0.019	0.60±0.12	2.57±0.32	96.58±0.31	96.43±0.42	20.23±0.17	20.16±0.17
	<i>t</i>	/	-0.925	-1.635	-1.533	-20.393	-0.428	-0.394	0.916	1.19
	<i>p</i>	/	0.361	0.11	0.134	<i>p</i> < 0.001**	0.671	0.696	0.366	0.241
H-gd-alt	$\bar{x} \pm s$	20	7.326±0.012	7.297±0.036	0.45±0.12	8.84±1.13	96.79±0.71	95.96±0.81	20.29±0.09	20.10±0.17
	<i>t</i>	/	-0.706	3.316	1.156	-31.51	-1.35	1.293	-0.556	2.241
	<i>p</i>	/	0.485	0.002**	0.255	<i>p</i> < 0.001**	0.185	0.204	0.581	0.031*

\*\**p* < 0.01, \**p* < 0.05; HbCO: carboxyhemoglobin; O<sub>2</sub>Sat: oxygen saturation; O<sub>2</sub>Cont: oxygen content; NC: normal control; L-gd: daily low-level surgical smoke exposure H-gd: daily high-level surgical smoke exposure; L-gd-alt: low-level surgical smoke exposure with a 1-day interval; H-gd-alt: high-level surgical smoke exposure with a 1-day interval;  $\bar{x} \pm s$ : mean ± standard deviation. n = 4 rabbits in each group

**Table 5.** Two-way analysis of variance results of experimental data

Source	Dependent variable	Freedom	F	Significance
Surgical smoke content: high or low	pH	2	19.868	$p < 0.001^{**}$
	HbCO	2	1888.461	$p < 0.001^{**}$
	O <sub>2</sub> Sat	2	48.489	$p < 0.001^{**}$
	O <sub>2</sub> Cont	2	8.071	0.001 <sup>**</sup>
Working mode: gd or gd-alt	pH	1	0.403	0.527
	HbCO	1	217.921	$p < 0.001^{**}$
	O <sub>2</sub> Sat	1	13.426	$p < 0.001^{**}$
	O <sub>2</sub> Cont	1	3.417	0.067

\*\* $p < 0.01$ . gd: daily surgical smoke exposure; gd-alt: surgical smoke exposure with a 1-day interval; HbCO: carboxyhemoglobin; O<sub>2</sub>Sat: oxygen saturation; O<sub>2</sub>Cont: oxygen content



**Figure 2.** Distribution of surgical smoke in the operating room (laparotomy, electro-knife power: 40 W)

model. First, surgical smoke was driven upward because of natural convection and a large volume of gas from a high-temperature incision. Additionally, laminar air flow from the ceiling pushed the upwelling surgical smoke downward. Furthermore, the surgical smoke spread around the operating table during electro-surgery. In the center of the operating room, the highest concentration of surgical smoke was directly above the incision, 1.5

m from the floor, and 0.5 m from the surface of the operating table. Therefore, the zone within  $< 0.5$  m in height and 0.5 m around the incision in a horizontal direction was deemed the zone with a high content of surgical smoke. In this area, the CO content ranged from  $0.5$  to  $2.0 \times 10^{-2}\%$  (HCZ, A zone in Figure 2). Surgical smoke spread out around the operating table. Most smoke flowed to the two walls with laminar air outlets, while a small amount of surgical



smoke flowed to the two other walls without outlets. This subset of smoke was recirculated and remained in the operating room. The zone < 2.1 m from the wall without an air outlet had a low level of surgical smoke, with a CO content that ranged from 1.5 to  $5 \times 10^{-3}\%$  (LCZ, B zone in Figure 2). The region outside the HCZ and LCZ was minimally contaminated by surgical smoke, with a CO content  $< 1 \times 10^{-4}\%$  due to laminar air flow in the operating room. This area was named the non-contaminated zone (NCZ).

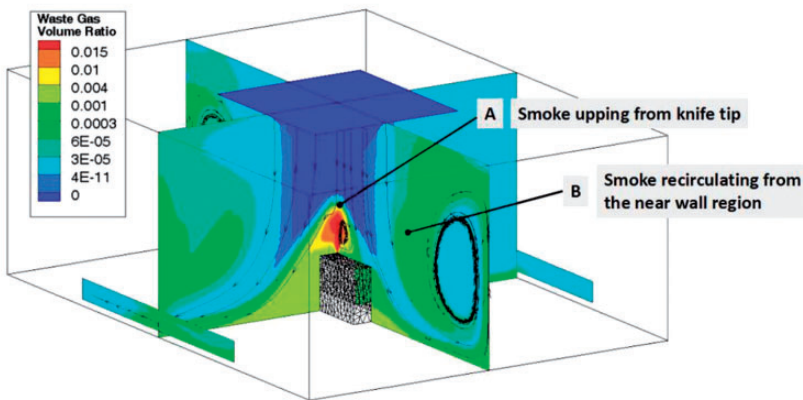
With an evacuator, the plume height of surgical smoke was decreased and the range of the HCZ was reduced (Figure 3). However, the range of the LCZ was enlarged. This occurred because the plume of surgical smoke was driven to one side of the operation table by the evacuator, and was easily blown over by down flow from the roof in the operating room. The evacuator had no effect on the NCZ.

**Discussion**

During laparotomy with a 40 W power electro-knife, the CO content in the HCZ of the operating room ranged from 50 to 200 ppm. This content is much greater than the 9 ppm upper limit for an 8-hour

exposure set by the Unites States Environmental Protection Agency (EPA).<sup>12</sup> The CO content in the LCZ ranged from 15 to 50 ppm, which was also greater than the EPA upper limit. The CO content in the NCZ was less than 1 ppm, which was within the EPA upper limit. Therefore, surgeons should avoid the HCZ and the LCZ in the operating room during laparotomy with an electro-knife. Standing inside the NCZ is recommended for surgeons performing electrosurgery.

If surgeons were to continuously stand in the HCZ throughout their work days, their pH, HbCO levels, O<sub>2</sub> saturation, and O<sub>2</sub> content would likely be abnormal. In our rabbit experiments, the mean HbCO level in rabbits that remained in the HCZ for 5 days was 20.7 times higher than that in rabbits without exposure to surgical smoke. If surgeons were to stand in the HCZ with a 1-day interval between work days, their pH, HbCO levels, and O<sub>2</sub> content indices would still likely be abnormal. The average HbCO level of rabbits that were exposed to high levels of surgical smoke daily or with an interval day was greater than 8.8% in our study. A previous study showed that rats that were exposed to a side stream of cigarette smoke had a mean HbCO level of 8.5%.<sup>13</sup>



**Figure 3.** Distribution of surgical smoke in the operating room with an evacuator

If surgeons were to continuously stand in the LCZ throughout their work days, their HbCO levels would likely be abnormal. In our study, the mean HbCO levels of rabbits that remained in the LCZ for 5 days was 9.8 times higher than that in rabbits without exposure to surgical smoke. If surgeons were to stand in the LCZ with a 1-day interval between work days, their HbCO levels would still likely be abnormal. The average HbCO level in rabbits that were exposed to surgical smoke equivalent to the LCZ zone daily or daily with an alternate interval was greater than 2.57%. A previous study showed that the mean HbCO level in individuals who smoke cigarettes in the long term was 2.93%.<sup>14</sup>

Our mathematical model showed that, when exposed to surgical smoke with a 1-day interval, HbCO levels were decreased by 24% when standing in the HCZ and HbCO levels were decreased by 56% when standing in the LCZ compared with continuous exposure day after day. Therefore, surgeons who maintain a 1-day interval between electrosurgeries can protect against harmful effects of surgical smoke. If CO levels in the HCZ and LCZ in an operating room are higher than the upper limit for 8-hour exposure as set by the US EPA,<sup>12</sup> exposure to CO may result in tissue hypoxia, which is harmful to health.<sup>15-18</sup>

The World Health Organization recommends an HbCO level of 2% for indoor air quality. HbCO levels > 2% can cause ST-segment changes and decreased time to angina.<sup>19-21</sup> In our study, all five surgical smoke exposure groups had HbCO levels higher than 2.5%. This finding indicates that staying in the HCZ and LCZ in the operating room is harmful to surgeons. The commonly accepted blood HbCO thresholds for the diagnosis of CO poisoning is 10% in smokers and 5% in non-smokers.<sup>22</sup> Therefore, individuals with HbCO levels > 10% may have headaches and feel weak. The mean HbCO level for

the H-gd group was 11.61%. This finding suggests that surgeons who work all day every weekday in the HCZ of an operating room should rest immediately to allow their HbCO levels to recover.

Our study showed that working at a region with a high content of surgical smoke in the operating room could be more harmful to surgeons than working continuously in the operating room for several days. Surgeons should stand in the correct location in the operating room during electro-surgery and manage their operating schedule to avoid health hazards from surgical smoke exposure.

The present study showed that an evacuator could reduce the range of the HCZ for surgical smoke using mathematical model simulation. However, an evacuator could also enlarge the LCZ for surgical smoke in the operating room during surgery because it causes blowing over of the plume of surgical smoke. Therefore, even with an evacuator, blood indices of surgeons who continuously work in the operating room for 1 week could be affected by surgical smoke.

## Conclusions

Our mathematical model shows that, during electro-surgery, there is a highly contaminated zone within 0.5 m around the heated tip of an electro-knife and a low contaminated zone within 2.1 m from the two walls without a laminar air outlet. In these zones, CO levels are above the United States EPA upper limit for an 8-hour exposure. Our rabbit experiments show that exposure to surgical smoke results in high HbCO levels. Exposure to the highly contaminated zone of surgical smoke for 5 continuous days significantly affects pH, HbCO levels, O<sub>2</sub> saturation, and O<sub>2</sub> content. Exposure to surgical smoke also leads to a mean HbCO level > 2%, which is the World Health Organization guideline for

indoor air quality. Continuous exposure to a high level of surgical smoke leads to a mean HbCO level above the threshold for diagnosis of CO poisoning. Surgeons should stand in the correct location in the operating room during electrosurgery and manage their operating schedule to avoid health hazards from surgical smoke exposure.

### Authors' contributions

All authors conducted the study and contributed to writing and general formatting of the manuscript. All authors read and approved the final manuscript.



### Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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