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UROLOGY - ORIGINAL ARTICLE

Evaluation of fine particles in surgical smoke from an urologist's operating room by time and by distance

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Abstract

Introduction Electrocautery, harmonic scalpel tissue dissection and other surgical techniques can generate surgical smoke with high proportion of 'fine particles' ($PM_{2.5}$) <2.5 μm, which is known to have adverse effects on human health. The high-risk zone for $PM_{2.5}$ during surgeries by time and by distance has not been well evaluated.

Methods The study included open superficial, open abdominal, open pelvic, laparoscopic and transurethral urology surgeries, five of each. A particle counter was placed at three different distances from the incision site, and the real-time $PM_{2.5}$ concentration was displayed after each cut. Air Quality Index (AQI) revised by the US Environmental Protection Agency and the calculated inhalation dose were used to evaluate the severity of $PM_{2.5}$.

Results In superficial, abdominal and pelvic surgeries, the peak $PM_{2.5}$ concentration may reach 245.7, 149.4 and 165.1 μg/m³ 3–6 s after a single cut 40 cm from the incision site. By the time, AQI usually turns to 'unhealthy' or 'very unhealthy.' In laparoscopic surgeries, 40 cm from the trocar, the air quality reached 'hazardous' in 3 s after opening of the trocar valve with a peak concentration of

517.5 μg/m³. In transurethral surgeries, the AQI 40 cm away from the resectoscope is generally at moderate level. In each surgery, the chief surgeon may inhale most of the $PM_{2.5}$, while the assistant will inhale less than half the dose, and the scrub nurse may inhale nearly none. The use of wall suction may induce a 48–65 % decrease in fine particle inhalation.

Conclusions During surgeries, the concentration of $PM_{2.5}$ could reach a very unhealthy status, especially for the chief surgeon who is the nearest to the incision site. Surgical smoke evacuation in the first few seconds of a cut is essential; however, using smoke evacuators such as a wall suction alone may not be enough.

Keywords Surgical smoke · Fine particle · Air quality · $PM_{2.5}$

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Introduction

Electrocautery, harmonic scalpel tissue dissection and other equipments which can generate surgical smoke are widely used in the era of urology. Surgeons are exposed to surgical smoke not only from open surgeries, but also from laparoscopic surgeries [1], transurethral resection of bladder tumors (TURBT) and transurethral resection of the prostate (TURP) [2]. Surgical smoke is usually composed of chemicals, blood and tissue particles, viruses and bacteria, bringing potential harmfulness to the health of operating room personnel [3]. Large amount of carbon monoxide and carcinogenic compounds such as acrylonitrile, hydrogen cyanide, formaldehyde and benzene were found in surgical smoke [4]. It is also said that HPV may be transmitted by surgical plume, making its infectiousness of great concern [5]. However, compositions of surgical

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smoke vary, and it is hard to evaluate its harmfulness without a unified factor.

Particulate matter <2.5 μm ($PM_{2.5}$) was mainly demonstrated as one of the main environmental air pollutants [6]. Interestingly, surgical smoke may simply be a wisp of $PM_{2.5}$. Weld et al. mentioned that 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). The mean size of small particles was 68.3 nm and of the larger ones was 994 nm [7]. The horrible thing of $PM_{2.5}$ is that they can directly reach the small airways and alveoli, thus leading to local inflammatory response, activation of prothrombotic factors, development of atherosclerosis and cardiovascular diseases [8]. Meta-analysis showed that $PM_{2.5}$ is associated with increased hospitalization and mortality due to cardiopulmonary disease [9]. Though the concept of $PM_{2.5}$ made it easier to estimate the harmfulness of surgical smoke, we still need to know at what time and at what distance should we be most aware of them.

In the current study, we tried to analyze the amount of $PM_{2.5}$ generated in different urology surgeries by time and by distance.

Methods

Surgery types and patients

We conducted a prospective study to analyze $PM_{2.5}$ generated through open surgeries, laparoscopic surgeries and transurethral surgeries. Our department is a cancer center, so all of the patients involved are suspected to have malignant tumors. We chose three subtypes of surgeries due to surgery depth for the open surgery group: inguinal lymph node dissection for penile cancer (superficial surgeries), partial nephrectomy (abdominal surgeries) and radical prostatectomy (pelvic surgeries). Laparoscopic partial nephrectomy was chosen for the laparoscopic surgery group. Transurethral surgeries included TURBT. For each types of surgeries mentioned above, five patients were analyzed. All procedures were performed in the same laminar airflow operating room. The study was approved by the institutional review board of our medical institution. All the patients submitted a written informed consent.

Instruments and measurement strategy

Dylos 1700 (Dylos, California, USA): this instrument uses a laser light scattering technique to measure the number of particles. The instrument draws air through an inlet (4 × 6 cm) in the casing of the device using a small fan.

Particle counts are expressed as a concentration per 0.01 cu ft of sampled air with the upper limit of the device memory 65,536 particle counts per 0.01 cu ft (0.283 l). The formula used to calculate adjusted measurement of $PM_{2.5}$ mass (μg/m^3) was as follows: $y = 1.57 \times 10^{-7} \times x^2 + 4.16 \times 10^{-3} \times x + 0.65$ [10], where x is the number of particles counted by the Dylos 1700 (per 0.01 cu ft) and y is the adjusted measurement of $PM_{2.5}$ mass (μg/m^3). Dylos is able to produce an instant measurement of $PM_{2.5}$, so we were able to record the amount change of surgery smoke particles generated per second.

Dissection and resection during open and laparoscopic surgeries were carried out using bipolar electrocautery units (FORCE 300, Valleylab, Boulder, CO, USA), and the power setting was 40 W. TURBT was performed using a 22F resectoscope, and a standard tungsten cutting loop, and the electrosurgical generator (AUTOCON, Karl Storz, GmbH) was set to 150 W for cutting and vaporization.

For open surgeries, the inlet of Dylos was placed at three different distances (40, 60 and 120 cm) from the incision site, near the breathing zone of surgical personnel, to imitate the position of the operator (40 cm), the assistant (60 cm) and the scrub nurse (120 cm). Every cut should last for 2–3 s, and the measuring of $PM_{2.5}$ should be started and continued for 15 s right after the cut. The $PM_{2.5}$ was measured with and without a wall suction for surgical smoke evacuation [11]. For laparoscopic surgeries, the inlet of Dylos was placed at three different distances (40, 60 and 120 cm) from the trocar outlet at the horizontal level of 170 cm, to imitate the position of the operator, the assistant and the scrub nurse. The valve of the trocar was opened for 3 s to release surgical smoke as long as the smoke impacts the surgeon's vision of the surgical site. For transurethral surgeries, the inlet of Dylos was placed at 40 cm away from the resectoscope at the horizontal level of 130 cm to imitate the position of the operator, and the measurement should be started and continued for 15 s as soon as we pull out the resectoscope for specimen collecting or irrigation solution exchanging. For each patient, the measurement is triplicated. We also measured the background $PM_{2.5}$ when a surgery started.

We used the Air Quality Index (AQI, The National Ambient Air Quality Standards for Particle Pollution; Web site: http://www.epa.gov/airquality/particlepollution/2012/decfsstandards.pdf) for $PM_{2.5}$ revised by the US Environmental Protection Agency (EPA) to evaluate how clean or polluted the air is. For example, the AQI converts concentrations for fine particles to a number on a scale from 0 to 500, different scores in the scale refers to different qualities of the air, such as 'good,' 'moderate' and 'unhealthy for sensitive groups.' The AQI breakpoints are outlined in the table below:

AQI category	PM$_{2.5}$ breakpoints (µg/m^3)
Good	0.0–12.0
Moderate	12.1–35.4
Unhealthy for sensitive groups	35.5–55.4
Unhealthy	55.5–150.4
Very unhealthy	150.5–250.4
Hazardous	250.5–350.4
	350.5–500

Statistical analysis

The instant PM$_{2.5}$ value of each procedure was recorded and plotted in linear graphs. Inhalation dose for each cut were calculated by exposure concentration and inhalation rate: $D = \int_{t1}^{t2} C(t) \cdot IR(t) \cdot dt/60$ [12], where D stands for the inhalation dose, µg; $C(t)$ is the real-time exposure concentration, µg/m; $t1$ and $t2$ stand for the start and end time of exposure, respectively, s; and $IR(t)$ is the respiratory rate, m^3/min. The mean respiratory rate for adults with light intensity activity level is 1.2×10^{-2} m^3/min, respectively [13]. The mean ± standard deviation amount of inhalation dose of PM$_{2.5}$ was calculated, and the Student t test was performed to test the differences between them. The accumulation of PM$_{2.5}$ dose according to time from the cut was calculated in percentages. We compared the inhalation dose of PM$_{2.5}$ in different procedures and different conditions (distance, with or without the use of wall suction). All analyses were performed using SPSS 17.0 software. P values were two-tailed and considered significant when <0.05.

Results

The characteristics of the patients and the surgery types they had undergone are shown in Table 1. PM$_{2.5}$ was measured in 25 surgeries; these operations took place between November 2013 and March 2014 at Fudan University Shanghai Cancer Center, China. Each type of surgeries was consecutively selected, the mean age of the patients was nearly 60 years old, and most patients had a normal body mass index (BMI). Background PM$_{2.5}$ was measured when a surgery started in the operating room, and the value was nearly 5 µg/m^3, which is quite same for all of the surgeries.

The instant PM$_{2.5}$ value of each procedure was recorded and plotted in linear graphs as shown in Fig. 1. The concentration of PM$_{2.5}$ varies at different distances from the incision site. In superficial surgeries, the operator (40 cm) may inhale 2.47 µg PM$_{2.5}$ at every single cut, while the assistant (60 cm) may inhale 1.18 µg, and the scrub nurse (120 cm) may only inhale about 0.19 µg PM$_{2.5}$. The similar phenomenon can also be seen in other open surgeries. In laparoscopic surgeries, the operator may inhale 4.33 µg PM$_{2.5}$, while the assistant and the scrub nurse may inhale 1.21 µg and 0.08 µg PM$_{2.5}$.

Concentrations for PM$_{2.5}$ and their relation with AQI are shown in Table 2. The AQI of the air 40 cm from the incision site usually turns to 'unhealthy' or 'very unhealthy' 3–6 s after a single cut, and the peak PM$_{2.5}$ concentration may reach 245.7, 149.4 and 165.1 µg/m^3 for superficial, abdominal and pelvic surgeries. In laparoscopic surgeries, the AQI 40 cm facing the trocar reached 'hazardous' in 3 s after we open the trocar valve with a peak concentration of 517.5 µg/m^3. However, in transurethral surgeries, the AQI 40 cm away from the resectoscope is generally at moderate level.

Figure 2 shows the accumulation of PM$_{2.5}$ dose (40 cm away from the incision site or trocar) calculated in percentages. It took 5.1, 5.8 and 6.6 s for the inhalation dose to reach 80 % after a single cut in superficial, abdominal or pelvic surgeries. In laparoscopic surgeries, it took 3.7 s for the inhalation dose to reach 80 %.

We measured PM$_{2.5}$ with and without a wall suction for surgical smoke evacuation (Fig. 3). In open surgeries, wall suction is used and the concentration of PM$_{2.5}$ and the

Table 1 Summary of the general characteristics of the patients and operations

Operation				Patient		
Surgery type	Operation time (mean, min)	Blood loss (mean, ml)	Wall suction used	Age (mean, years)	Gender (male/female)	BMI (mean)
Inguinal lymph node dissection	75 ± 19	10 ± 2	Yes	65 ± 7.1	5/0	22.4 ± 3.5
Partial nephrectomy	96 ± 33	185 ± 33	Yes	55 ± 10.06	2/3	23.6 ± 1.8
Radical prostatectomy	121 ± 28	155 ± 44	Yes	62 ± 9.6	5/0	23.5 ± 2.1
Laparoscopic partial nephrectomy	115 ± 35	120 ± 20	No	53 ± 5.3	4/1	23.1 ± 1.9
Transurethral surgeries	15 ± 5	5 ± 0	No	65 ± 7.04	3/2	23.7 ± 2.0
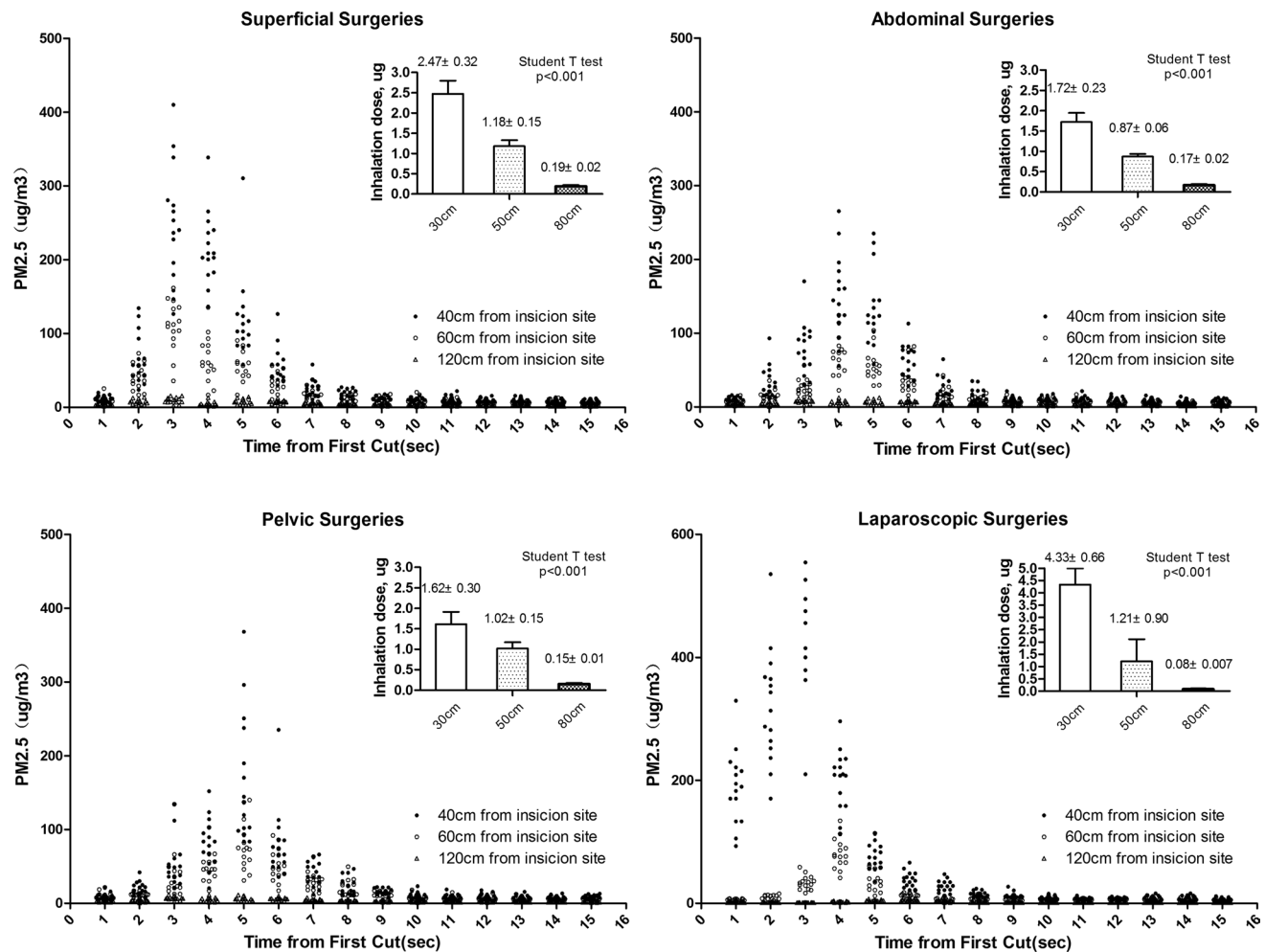
Fig. 1 Instant PM$_{2.5}$ value of each procedure and of different distances from the incision site

inhalation dose are shown in Fig. 3. With the use of wall suction, inhalation dose decreased from 2.47 to 1.29 μg (48 % off) in superficial surgeries, 1.72–0.84 μg (52 % off) in abdominal surgeries and 1.61–0.57 μg (65 % off).

Discussion

Many studies have evaluated the composition and concentration of surgical smoke. However, few studies have investigated PM$_{2.5}$ produced during surgeries. In the current study, we verified the amount of PM$_{2.5}$ that surgical staffs may be involved with in five types of urology surgeries. The main finding of the article is that in most of the surgeries, the concentration of PM$_{2.5}$ of a single smoke plume could become very unhealthy for involved surgeons. In open superficial surgeries, for example, the chief surgeon may inhale 2.47 μg of PM$_{2.5}$ in 15 s after a single cut. Generally speaking, one will inhale such amount of particular matter only if he stands in an air-polluted area with a

55 μg/m^3 PM$_{2.5}$ for the same time length, and this level of PM$_{2.5}$ is much higher than the short-term fine particle standard (35 μg/m^3) which was issued by the US EPA [14]. On the other hand, the real-time concentration of PM$_{2.5}$ will reach a peak level about 3–6 s after a single cut. At this period of time, PM$_{2.5}$ may become 'very unhealthy' or even 'hazardous' (Table 2). Luckily, while the distance to the incision site increases, the concentration and inhalation dose of PM$_{2.5}$ decrease rapidly; the assistant will inhale less than half the dose compared with the chief surgeon, while the scrub nurse may inhale nearly none. Data also showed that the accumulation dose of PM$_{2.5}$ can reach 80 % usually at the sixth second for open surgeries and at the fourth second for laparoscopic surgeries (Fig. 2). We then measured PM$_{2.5}$ with a wall suction for surgical smoke evacuation. This simple and widely used device can easily capture surgical smoke and reduce the concentration of PM$_{2.5}$.

In 2004, the first American Heart Association scientific statement concluded that exposure to particulate matter air pollution contributes to cardiovascular

**Table 2** Mean PM$_{2.5}$ and correlated AQI category at different surgeries at the position of the operator

Time from first cut(s)	Superficial surgeries		Abdominal surgeries		Pelvic surgeries		Laparoscopic surgeries		Transurethral surgeries	
	PM$_{2.5}$ value (μg/m^3)	AQI	PM$_{2.5}$ value (μg/m^3)	AQI	PM$_{2.5}$ value (μg/m^3)	AQI	PM$_{2.5}$ value (μg/m^3)	AQI	PM$_{2.5}$ value (μg/m^3)	AQI
1	11.8	G	10.0	G	9.7	G	188.5	VU	9.7	G
2	65.8	U	33.1	M	19.5	M	319.1	H	13.1	M
3	245.7	VU	79.3	U	53.6	USG	517.5	H	22.6	M
4	215.7	VU	149.4	U	82.0	U	201.6	VU	23.7	M
5	119.2	U	134.4	U	165.1	VU	74.6	U	25.2	M
6	55.9	U	64.3	U	79.4	U	38.6	USG	21.7	M
7	25.4	M	24.6	M	39.8	USG	27.5	M		18.9
8	18.2	M	15.8	M	22.0	M	15.0	M	20.5	M
9	11.8	G	10.6	G	15.3	M	12.8	M	11.4	G
10	9.6	G	10.7	G	10.8	G	9.0	G	9.2	G
11	10.3	G	10.0	G	9.0	G	8.2	G	8.9	G
12	9.1	G	8.7	G	9.0	G	8.5	G	8.7	G
13	9.4	G	8.5	G	7.5	G	8.7	G	7.9	G
14	8.2	G	6.7	G	7.7	G	9.0	G	8.8	G
15	7.8	G	7.4	G	8.3	G	6.6	G	6.9	G

G good, *M* moderate, *USG* unhealthy for sensitive groups, *U* unhealthy, *VU* very unhealthy, *H* hazardous

morbidity and mortality [6]. Further studies extended the findings that exposure to PM$_{2.5}$ over a few hours to weeks can trigger cardiovascular disease-related mortality and nonfatal event [15]. In Europe, the multicenter European Study of Cohorts for Air Pollution Effects (ESCAPE) project was held to investigate air pollutants and their associated disease. The results of ESCAPE concluded that exposure to air pollutants, especially PM$_{2.5}$ may increase natural-cause mortality (HR = 1.07 per 5 μg/m^3 increase) [16], incidence of lung cancer (HR = 1.18 per 5 μg/m^3 increase) [17], acute coronary events (HR = 1.13 per 5 μg/m^3 increase) [18] and low birthweight (HR = 1.18 per 5 μg/m^3 increase) [19]. Generally speaking, in those large epidemiology studies, PM$_{2.5}$ was measured in the outdoor atmosphere. The anthropogenic sources of outdoor PM$_{2.5}$ include motor vehicle emissions, tire fragmentation, road dust and other industrial combustion, while the natural sources include wood burning, soil, pollens and molds. In contrast, surgical smoke is usually composed of hydrocarbons, nitriles, fatty acids, phenols, blood and tissue particles, viruses and bacteria, quite different from the outdoor atmosphere. How much harm surgical PM$_{2.5}$ will do to surgeons is still unknown. However, we cannot conclude that surgical PM$_{2.5}$ is not harmful simply because they are not traffic emissions. Multiple studies of air pollutants have been held in different cities to help isolate the pollutants that may be more responsible for the health effects, and consistent positive findings with PM$_{2.5}$ instead of other certain particles were found [15].

In the ESCAPE study, PM$_{2.5}$ consistently associated with natural-cause mortality even if the author adjusted the model with traffic variables [16]. So the size/morphology of surgical particle matters may be their major characteristic, for they are a 'group' of particles which can reach the small airways and alveoli just the same as PM$_{2.5}$ from the atmosphere, thus causing systemic inflammation, systemic oxidative stress, thrombosis and coagulation. On the other hand, chemicals present in surgical smoke include carbon monoxide, acrylonitrile, hydrogen cyanide, formaldehyde and benzene. Some of those are carcinogenic and can have independent and potentially synergistic or antagonistic effects with each other and with PM$_{2.5}$ [4].

In 2007, Spearman et al. did a survey on surgical staffs, found that most people were concerned about exposure to surgical smoke and felt that precautions were inadequate. However, the author mentioned that the use of smoke extraction equipment is very limited [20]. Usually, in order to avoid surgical smoke pollution, we can use local exhaust ventilations (such as wall suction or smoke evacuator) and respiratory protections (such as surgical mask or N95 or other National Institute for Occupational Safety and Health (NIOSH)-approved respirator). In a survey done in 2012, we noticed that wall suction may be the most widely used for surgical smoke control [11]. In our institute, we use wall suction for smoke evacuation and we do observed a 48–62 % decrease in surgical PM$_{2.5}$ exposure. Thus, for procedures that produce only nuisance levels of smoke, wall suction is entirely adequate. For respiratory
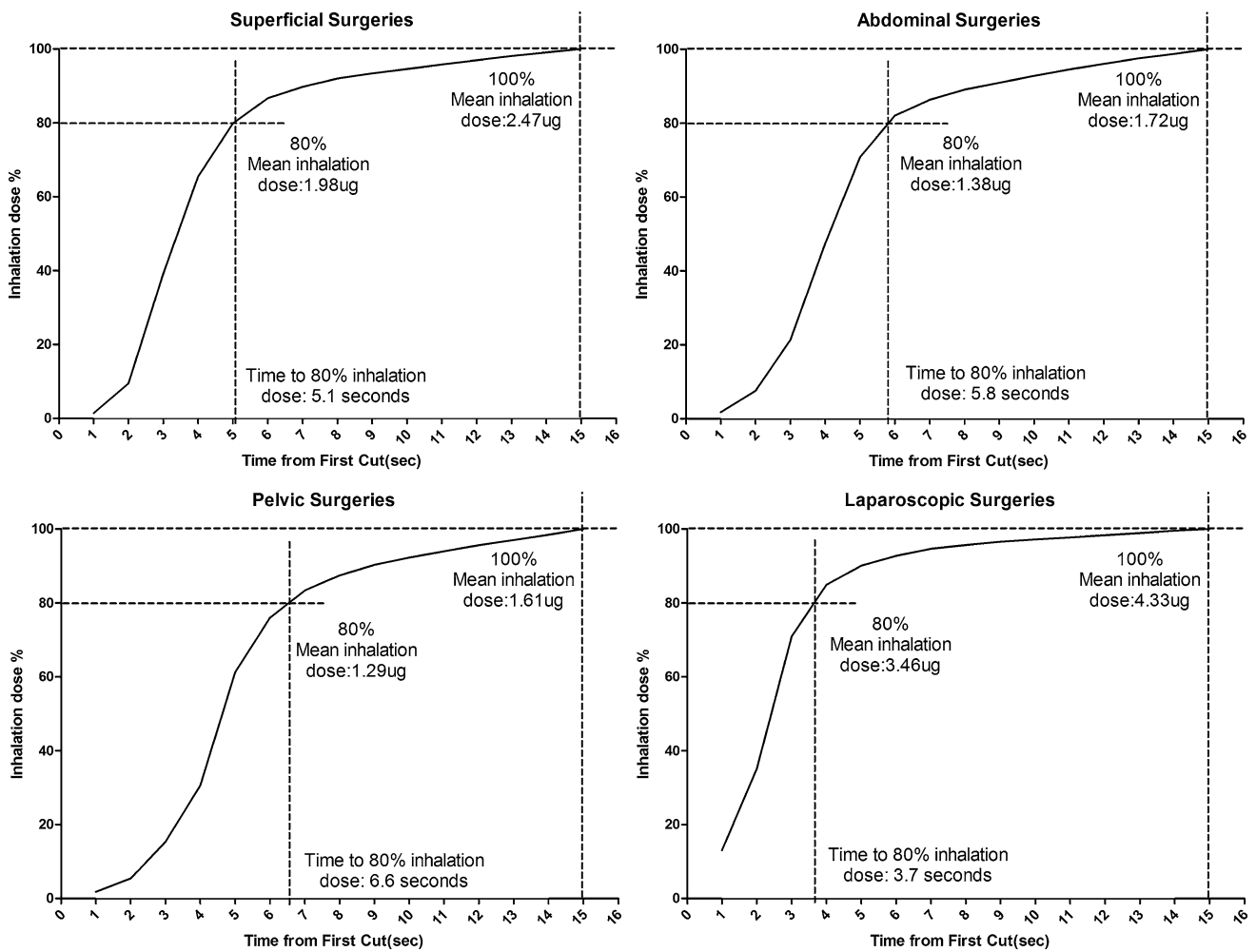
Fig. 2 Accumulation of PM$_{2.5}$ dose calculated in percentages
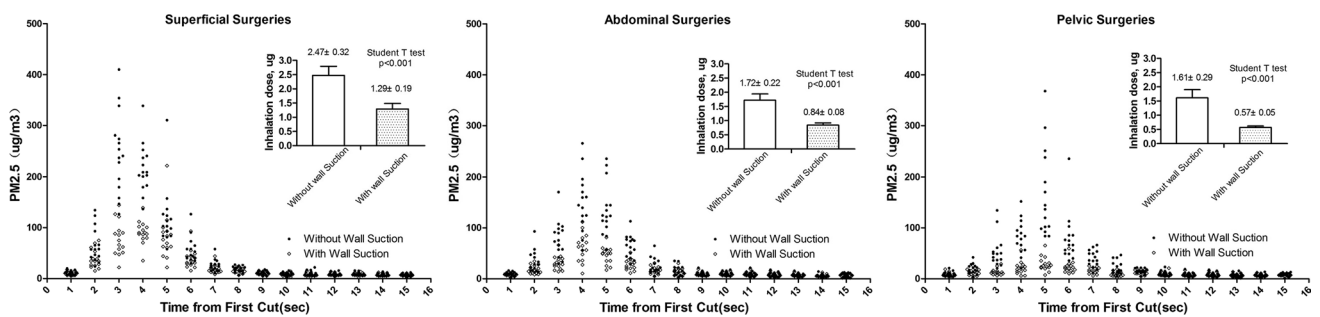
Fig. 3 PM$_{2.5}$ with and without a wall suction for surgical smoke evacuation

protections, the literature indicated that only 'N95 or other NIOSH-approved respirator' choice ensures some measure of protection [11]. Truthfully, we investigated that regular surgical masks (used in our institute) are nearly useless in reducing PM$_{2.5}$ (data not shown).

Conclusions

During surgeries, the concentration of PM$_{2.5}$ could reach a very unhealthy status, especially for the chief surgeon who is the nearest to the incision site. Surgical smoke evacuation

in the first few seconds of a cut is essential; however, using smoke evacuators such as a wall suction alone may not be enough. Surgeons and other OR personnel should be aware of the potential health hazards and should take proper measures to minimize their exposure to surgical $PM_{2.5}$.

Author contributions Hong-Kai Wang, Fei Mo and Hai-Liang Zhang had full access to all of the data in the study and took responsibility for the integrity of the data and the accuracy of the data analysis. Hong-Kai Wang, Fei Mo, Chun-Guang Ma, Bo Dai, Guo-Hai Shi, and Yao Zhu involved in acquisition of data. Hai-Liang Zhang involved in study concept and design. Hong-Kai Wang wrote the manuscript. Supervision: Ding-Wei Ye and Hai-Liang Zhang conceived of the study and participated in its design and coordination.

Compliance with ethical standards

Conflict of interest All authors declare no competing financial interests.

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