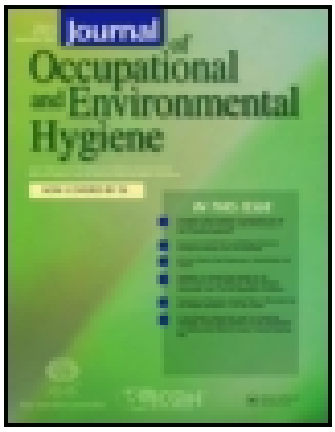

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Application of a two-zone model to estimate medical laser generated particulate matter exposures

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ABSTRACT

We estimated particulate matter exposures for two simulated medical laser procedures using a near-field/far-field model. Size-specific mass emission rates obtained from a laboratory-based emission chamber study were used with estimated room size, air exchange rate and interflow between zones to demonstrate the potential exposure range. Modeled steady-state concentrations for the near-field ranged between 80 and 2140 μg/m^3 and between 40 and 1650 μg/m^3 in the far-field. Results indicate concentrations in the simulated scenarios are similar to those obtained from limited field assessments conducted in hospital operating rooms. Since new medical laser technologies and applications continue to grow, modeled occupational exposures of medical laser generated particulate matter can be useful in better understanding these exposures in the clinical environment, and to inform control strategies.

Word count: 123

INTRODUCTION

Lasers now impact a wide range of medical specialties, and new technologies and clinical applications continue to grow. Medical laser generated air contaminants (LGAC) created at the point of laser-tissue interaction have been shown to cause dose-dependent respiratory inflammatory response in laboratory animals [1-3], and may contain viable bacteria and viruses, including human papilloma virus[4-8], though it is unclear if they remain infectious[9-13].

In a previous study, we built a laboratory-based emission chamber system to measure size-specific particulate matter emission rates during simulated medical laser procedures on porcine tissue [14, 15]. We calculated mass emission rates for a range of laser operational parameter settings[15], and used the emission rates to inform a two-zone model to estimate exposures to laser generated particulate matter (LGPM). Modeling the particulate matter concentrations may be useful in determining exposure levels in clinical settings and in assessing the effectiveness of controls in place for the protection of health care professionals.

METHODS

Two-zone model

We utilized a two-zone model that has been applied to solvents [16-19] and respirable particulate matter [20]. The model accounts for imperfect air mixing within a room, and the observation that workers in close proximity to the source generally experience higher exposures than workers further from the source [16]. As a result, the room is divided into two zones. The near-field zone includes the emission source, namely the procedure site and includes the laser

operator, and the far-field zone includes the remainder of the room volume. Air is assumed perfectly mixed within each zone, and exchange between zones occur at rate β (m^3/min). Mechanical ventilation removes air from the far-field zone.

The two-zone model is written[21]:

$$V_{NF}dC_N = Gdt + \beta C_{FF}dt - \beta C_{NF}dt \quad (1)$$

$$V_{FF}dC_F = \beta C_{NF}dt \text{ ï } [\beta + Q]C_{FF}dt \quad (2)$$

Where, V_{NF} and V_{FF} are the volumes (m^3) of the near (NF) and far-field (FF), respectively, C_{NF} and C_{FF} are the particle mass concentrations (mg/m^3), G is the mass emission rate (mg/min), β is the airflow rate between the two fields (m^3/min), Q is the supplied/exhaust net airflow rate in the room (m^3/min), and t is time (min). The inter-zone airflow, β, is one-half the product of the estimated free surface area (FSA, m^2) of the near-field zone and random air speed (s, m/s)[21], such that β is dependent upon the specified geometry of the near-field. Though the exposure of interest is LGPM, the model neglects particle loss due to gravitational settling. This is reasonable because only respirable particles are considered, and these particles settle slowly relative to the time-scale of the exposure duration.

A two-zone model was preferred over a well-mixed box model, owing to the proximity of workers to the source. We considered alternative two-zone models, such as the Advanced Reach

Tool[22], but found that more structured tool does not have the necessary input options consistent with this exposure scenario, including the emission rate of the material to the environment, room volumes, and air exchange rates that we preferred for our model. The Advanced Reach Tool is also targeted toward industrial material handling processes, not the generation of fine fumes.

Modeled environment

We considered clinical treatment and operating rooms as the site of medical laser procedures, and used the *Guidelines for Design and Construction of Hospital and Outpatient Facilities* from the Facility Guidelines Institute to estimate room size and ventilation rates. Simulated treatment rooms were assumed to have volume 22.5 m^3 and receive 6 air exchanges per hour (ACH), and simulated operating rooms were assumed to have volume 170 m^3 and receive 15 ACH[23]. The maximum distance between the operator and the point source was assumed to be 1 m. As a result, the near-field was represented by a cube with radius length aspect 0.5 m, which gives V_{NF} = 1 m^3 and FSA = 5 m^2 [24].

Inter-zone air exchange rate, β, was calculated as follows. To our knowledge random air speed in treatment and operating rooms has not been measured. The United Kingdom Department of Health recommends operating room air speeds of 6 to 18 m/min to ensure control of aerosolized bacteria[25]. These air speed rates are high relative to those observed by Baldwin and Maynard (1998) in offices, warehouses and industrial sites, where the geometric mean value was 3 m/min and mean value (85^{th} percentile) was 18 m/min[26]. We assumed random air speeds of 3 or 6 m/min for the treatment room, and 6 or 18 m/min for the operating room. As a result,

estimates for β in the treatment room were 7.5 and 15 m^3/min and in the operating room were 15 and 45 m^3/min.

Mass emission rates

We previously determined size-specific particle emission rates during the lasing of porcine tissue in a simulated medical laser procedure [15]. Particle count emission rates were converted to mass emission rates for particles with aerodynamic diameters <10 μm (Table II)[15]. Briefly, particle counts measured in aerodynamic diameter were converted to mass by calculating the average terminal settling velocity at each measured size range, and calculating the particle mass for the corresponding settling velocity [15]. Overlap in collection diameters between particle counters were adjusted by subtracting the AeroTrak® emission rates between 0.3 and 1 μm from emission rates collected using the P-Trak® and the size range was adjusted accordingly for analysis. We used mass emission rates of 3709 μg/min and 1830 μg/min in our model (Table II), corresponding to setting 1 and setting 2, respectively.

An important variable in determining exposure during laser clinical procedures is the laser on-time, which depends upon patient and operator characteristics, as well as the procedure itself. An examination of the relevant literature did not find any mention of the extent of laser use during procedures, but a web search found some facial laser treatments described to last between 30 and 60 minutes[27, 28]. Anecdotally, a dermatologist described that members of her team perform 6 clinical laser procedures each day, on average. Each procedure lasts 5 to 45 minutes (average 10 minutes), and lasers are operated approximately 95% of the procedure duration (Dr.

Melanie Kingsley, personal communication, July, 23 2014). In other specialties, medical laser use may be less frequent or be operated for smaller proportions of the procedure duration. For our model, we assumed continuous medical laser use for 15 minutes, and we included steady-state concentration as a worst-case scenario.

RESULTS

Estimated concentrations of respirable LGPM were determined after 5, 10 and 15 minutes of continuous laser operation, and at steady-state conditions (Table III). In the operating room scenario, near-field steady state concentrations of respirable LGPM varied between 80 and 340 μg/m^3, compared to 940 and 2140 μg/m^3 in the treatment room scenario (Table III). Steady-state concentrations of LGPM were lower in the far-field than in the near-field, and varied in the simulated operating room between 40 and 90 μg/m^3, and between 810 and 1650 μg/m^3 in the simulated treatment room. Concentration ratios between the near and far-field were between 4:1 and 1:1. For a given emission rate, 1830 or 3709 μg/min, larger room volume and higher air exchange rate (e.g., operating room) and larger β were associated with lower concentrations of LGPM in the near-field. Steady state conditions were achieved within 15 minutes in the simulated operating room with assumed continuous emission, but continued to rise in the simulated treatment room. Particulate mass concentrations in the two simulated scenarios were vastly different even though the difference in the emission rates was small.

DISCUSSION

Two field-studies have measured LGPM concentrations during simulated clinical laser procedures in hospital operating rooms. Albrecht et al (2005) lased porcine liver for 5 minutes with a CO_2 laser at 20 W and with a beam diameter between 0.6 and 1.2 mm. The simulated procedure was performed in a hospital OR with a volume of 109.5m^3 and 19 ACH, similar to our simulated OR. Measurements were taken at eye-level in the near-field, and at the periphery of the OR (far-field) for the duration of the lasing experiment (5 minutes) and for an additional 25 minutes using a real-time dust particle collector. Respirable LGPM concentrations of 590-1,690 µg/m^3 and 160-340 µg/m^3 were measured in the near-field and far-field, respectively, during lasing. Particulate matter concentrations in the near and far-field returned to near background levels 10 minutes after the procedures ended[29]. Tanpowpong and Koytong (2002) also performed a simulated clinical laser procedure ï lasing a specimen with a CO_2 laser evaporator for two hours in an otolaryngology OR ï and measured LGPM. The OR had limited air movement and contained a single exhaust fan and an air-conditioner; the room size was not described. A laser diode portable dust monitor was used to measure one hour averages of PM concentration, placement of the monitor was not mentioned. The highest average PM_{10} concentrations were measured during the second hour of laser vaporization procedures (PM_{10} = 246 µg/m^3) and was three times greater than operating room background and 35 times greater than concentrations in an adjacent office[30]. Our simulated OR (Table III) was more similar to the field study sites than the simulated treatment room. Our simulated room concentrations in the near-field were between 170 ï 340 µg/m^3 and between 40-90 µg/m^3 in the far-field, below concentrations reported by Albrecht et al. (2005), but within the level reported by Tanpowpong and Koytong (2002).

While the most involved laser procedures occur in surgical ORs, many new outpatient procedures have been developed that are performed in ambulatory surgical centers or clinical treatment rooms. Like ORs, ventilation guidelines exist for such facilities[23]. However, it is likely that laser procedures are performed in private practice office settings, where general exhaust ventilation is minimal. These conditions are likely to result in occupational exposures to respirable LGPM as large, or larger, than estimates here for treatment rooms (Table III).

The modeled mass concentrations of LGPM were low relative to exposure guidelines like the ACGIH Threshold Limit Value of 3 mg/m^3 respirable particulate not otherwise classified (PNOC) as an 8-hour TWA (Table III). The protective relevance of the TLV to LGPMs, however, is unknown. Risks to health from LGPM may not be compared to PNOC due to the large mass of fine and ultrafine particles and the presence of biologically viable material[31, 32]. As particle size decreases, the percent of surface molecules increases exponentially, leading to increased surface reactivity and ultimately greater biological activity than particles with greater diameter. The high penetration of the smallest particles deeper into the respiratory system, and movement directly into vital organs[33] may lead to increased toxicity, oxidative stress, and cellular dysfunction when compared to larger diameter particles[34]. Biological viability is also a concern due to demonstrated infection to healthcare professionals after performing laser procedures: While the aerosolization of viable material has been demonstrated, the infectiousness of such material has not been confirmed[10, 35-37]. Currently, no standards have been published for occupational exposures to ultrafine particles or infectious biological materials.

Modeling LGPM provides means by which to estimate exposures in clinical settings. Since clinical environments and laser operational parameters are diversifying, and changing with new treatments and delivery methods, modeling provides an efficient method to estimate exposure with limited empirical data. However, the lack of publications with sufficient data to compare the accuracy of our modeling and measurement methods is a limitation. To further improve and validate the model, future efforts will involve expanding the measurement of emission rates to additional wavelengths and other operational parameters to model additional exposure scenarios, and comparing modeled results with real-time sampling data from medical laser procedures. Expansion and validation of the model will strengthen its value as a tool in exposure assessment, and in developing control strategies that can be tailored depending on the expected activity, distance from the point source, and room conditions.

CONCLUSION

We modeled an estimated range of occupational exposures to LGPM for health care professionals involved in medical laser procedures. Our results were within the range of concentrations measured in limited field studies conducted in hospital operating rooms. However, laser technologies continue to be developed and applications of medical lasers continue to grow. We plan to investigate new devices and applications to estimate potential exposures for LGPM emission and validate modeled results, as new technologies may produce emission rates that are dependent on unique operational parameters.

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Table I. Description of Clinical CO_2 Laser Settings for Two Procedures Described in the Literature

Procedure	Parameter	Levels	Author references
Rhinophyma	Power	10 to 20 W	Madan et al., 2009 [38] and Lomeo et al., 1997 [39]
	Beam Diameter	2 to 3 mm (defocused)	
	Pulse Repetition Freq.	0.1 mm (focused) Continuous mode	
Onychocryptosis	Power	4 to 5 W	Serour, 2002 [40] and Ozawa et al., 2005 [41]
	Beam Diameter	1 to 2 mm	
	Pulse Repetition Freq.	Continuous mode	

Table II. Mass Emission Rate by Size Range for Two Medical CO_2 Laser Operational Parameter Settings

Particle Size Bins (μm)	Setting 1[a]			Setting 2[b]		
	Particles/min	μg/min	% mass	Particles/min	μg/min	% mass
0.02-0.3	$3.6*10^{11}$	3529.2	95.1	$1.5*10^{11}$	1518.1	83.0
0.3-0.5	$1.3*10^{9}$	79.8	2.2	$1.3*10^{9}$	80.1	4.4
0.5-1.0	$1.6*10^{8}$	53.2	1.4	$2.7*10^{8}$	91.5	5.0
1.0-3.0	$3.6*10^{6}$	23.1	0.6	$5.8*10^{6}$	37.3	2.0
3.0-5.0	$2.6*10^{5}$	10.2	0.3	$9.7*10^{5}$	37.5	2.1
5.0-10.0	$5.2*10^{4}$	13.7	0.4	$2.5*10^{5}$	65.6	3.6
Total	$3.6*10^{11}$	3709	100	$1.5*10^{11}$	1830	100

[a]Setting 1: power: 12 W, beam diameter: 0.5 mm, pulse repetition frequency (PRF): 5 Hz and [b]Setting 2: Power: 5 W, beam diameter: 2 mm, PRF: 5 Hz. Utilizing a Ultra MD™ 40 CO_2 laser system.

Table III. Concentrations of Respirable LGAC Particulates (μg/m^3) Estimated in the Near-field (NF) and Far-field Zones (FF) of Operating and Treatment Rooms.

Mass Emission Rate (μg/min)	**Time Elapsed (min)**	**Operating Room**				**Treatment Room**			
		β = 15 m^3/min		**β = 45 m^3/min**		**β = 7.5 m^3/min**		**β = 15 m^3/min**	
		NF	**FF**	**NF**	**FF**	**NF**	**FF**	**NF**	**FF**
1830	5	150	30	70	30	550	310	430	310
Setting 1	10	160	40	80	40	750	510	630	510
	15	160	40	80	40	870	630	750	630
	SS[a]	170	40	80	40	1060	810	940	810
3709	5	310	60	140	60	1110	630	880	640
Setting 2	10	330	80	160	80	1520	1040	1280	1040
	15	330	90	170	90	1770	1280	1520	1280
	SS[a]	340	90	170	90	2140	1650	1900	1650

[a]Steady-state concentration of particulate matter at specified room conditions

