Experimental study on specialized ventilation system of airborne infection isolation room

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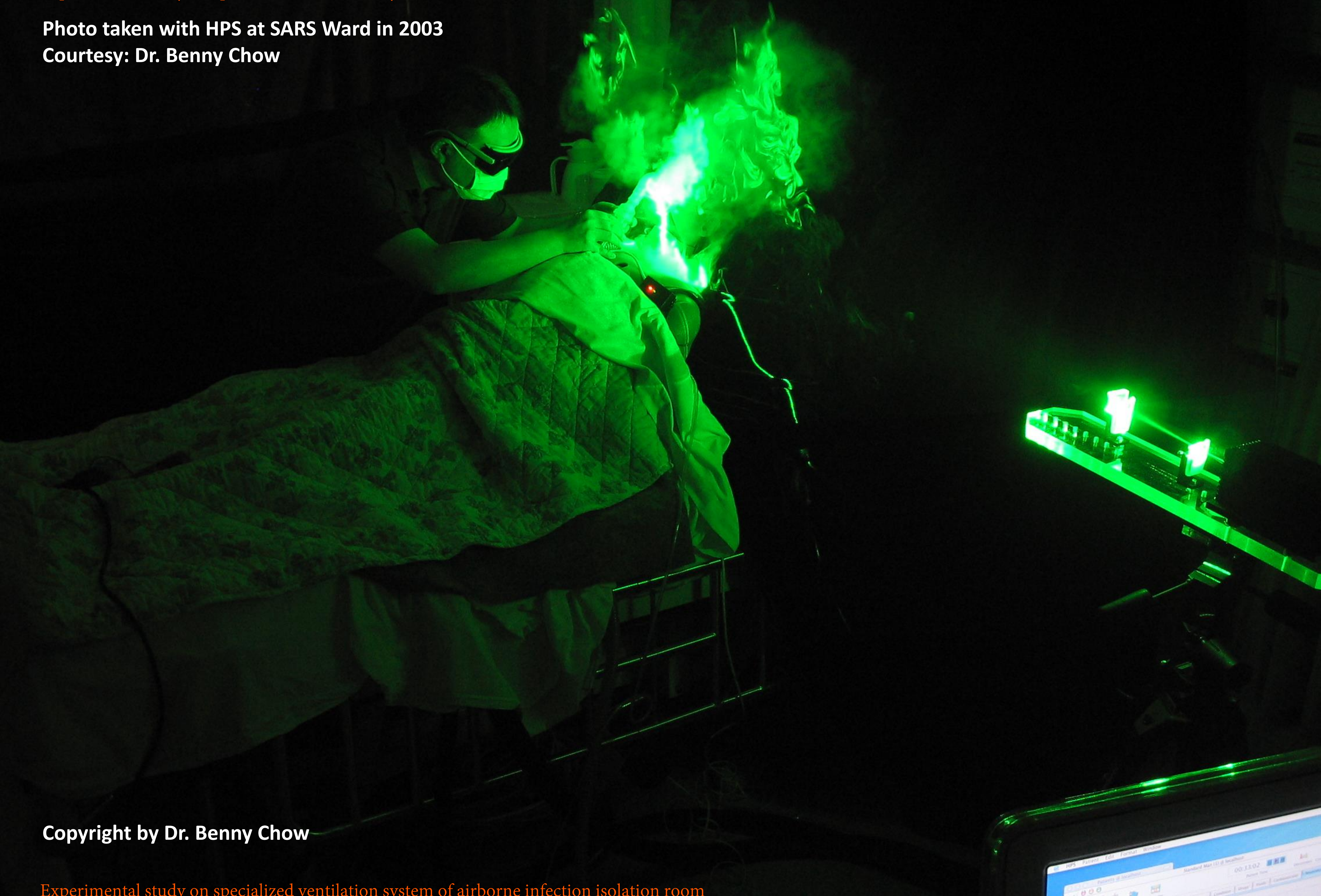
Photo taken with HPS at SARS Ward in 2003
Courtesy: Dr. Benny Chow
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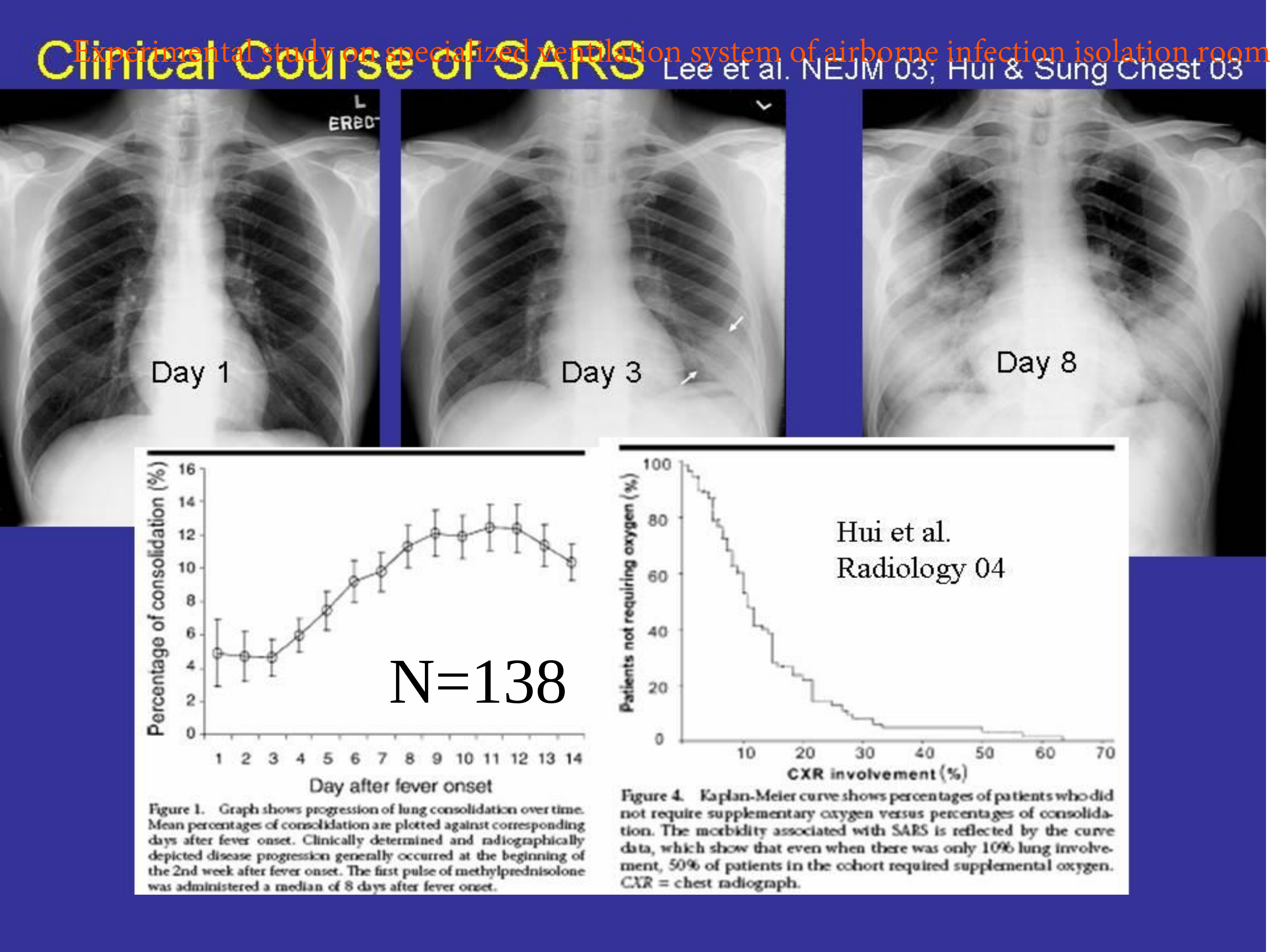
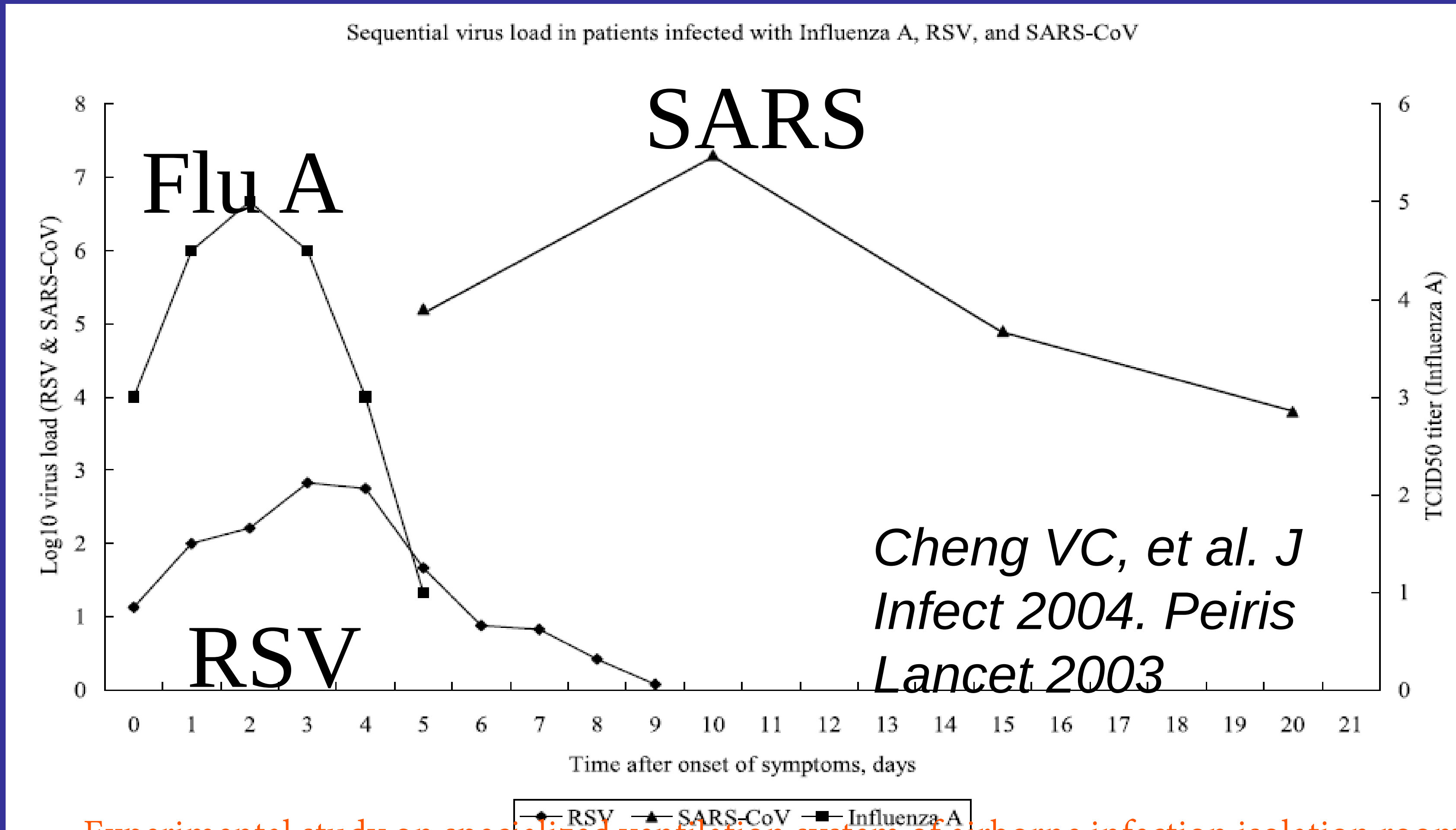


Among 8,096 cases of SARS globally, 1,706(~21%) were HCWs. SARS patients ill & yet highly infectious esp in 2nd week of illness.



358 Pitzer et al. *Am J Epidemiol* 2007;166:355–363

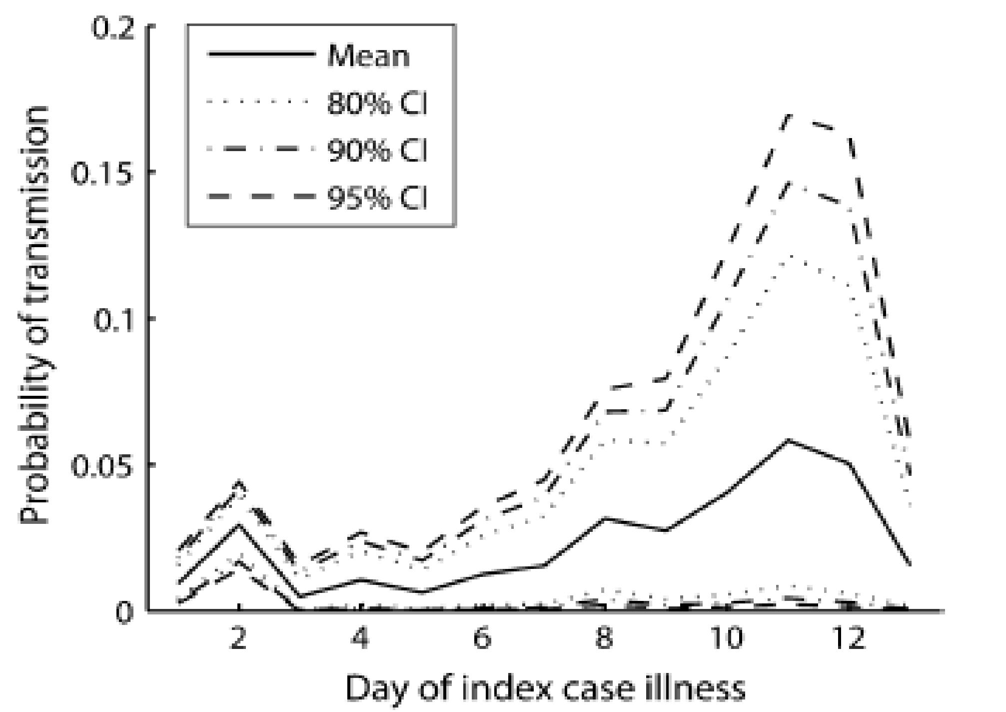


FIGURE 1. Probability of transmission of severe acute respiratory syndrome (SARS) according to day of index case illness during the 2003 SARS epidemic in Hong Kong, China. The solid line represents the estimated mean transmission probability, while the dotted, dash-dotted, and dashed lines represent the 80%, 90%, and 95% credible intervals (CIs), respectively.

NPPV – Independent Risk Factor for Nosocomial Outbreak

Why Did Outbreaks of Severe Acute Respiratory Syndrome Occur in Some Hospital Wards but Not in Others?

Ignatius T. Yu,[1,2] Zhan Hong Xie,[4] Kelvin K. Tsoi,[1] Yuk Lan Chiu,[1] Siu Wai Lok,[1] Xiao Ping Tang,[5] David S. Hui,[3] Nelson Lee,[3] Yi Min Li,[4] Zhi Tong Huang,[6] Tao Liu,[7] Tze Wai Wong,[2] Nan Shan Zhong,[4] and Joseph J. Sung[1,3]

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Background. Most documented "superspreading events" of severe acute respiratory syndrome (SARS) occurred in hospitals, but the underlying causes remain unclear. We systematically analyzed the risk factors for nosocomial outbreaks of SARS among hospital wards in Guangzhou and Hong Kong, China.

Methods. A case-control study was conducted. Case wards were hospital wards in which superspreading events of SARS occurred, and control wards were wards in which patients with SARS were admitted, but no subsequent nosocomial outbreaks occurred. Information on environmental and administrative factors was obtained through visits to the wards and interviews with ward managers or nursing officers. Relevant information about host factors was abstracted from the medical records. Logistic regression analyses were used to identify the major risk factors for superspreading events.

Results. Eighty-six wards in 21 hospitals in Guangzhou and 38 wards in 5 hospitals in Hong Kong were included in the study. Six risk factors were significant in the final multiple-logistic regression model: minimum distance between beds of ⩽1 m (odds ratio [OR], 6.94; 95% confidence interval [CI], 1.68–28.75), availability of washing or changing facilities for staff (OR, 0.12; 95% CI, 0.02–0.97), whether resuscitation was ever performed in the ward (OR, 3.81; 95% CI, 1.04–13.87), whether staff members worked while experiencing symptoms (OR, 10.55; 95% CI, 2.28–48.87), whether any host patients (index patient or the first patient with SARS admitted to a ward) required oxygen therapy (OR, 4.30; 95% CI, 1.00–18.43), and whether any host patients required bi-level positive airway pressure ventilation (OR, 11.82; 95% CI, 1.97–70.80).

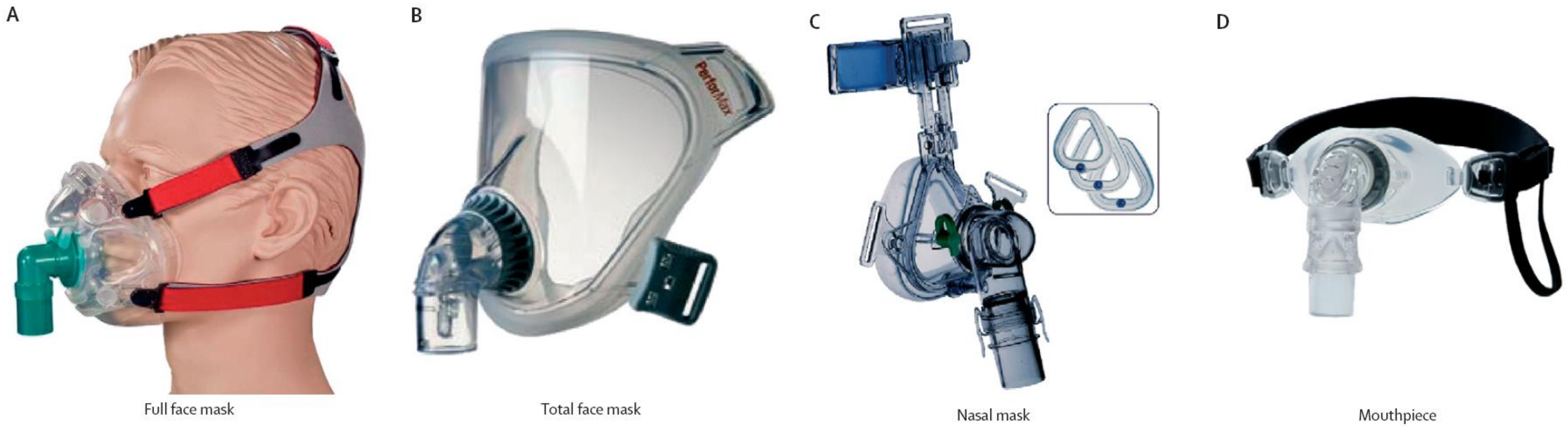
Conclusions. Our results revealed that factors that were associated with the ward environment and administration were important in nosocomial outbreaks of SARS. The lessons learned from this study remain very important and highly relevant to the daily operation of hospital wards if we are to prevent nosocomial outbreaks of other respiratory infections in the future.

Yu, Ignatius T. Xie, Zhan Hong; Tsoi, Kelvin K. et al. (2007). "Why Did Outbreaks of Severe Acute Respiratory Syndrome Occur in Some Hospital Wards but Not in Others?", Clinical Infectious Diseases. 44 (8), pp. 1017-1025.

NPPV – Independent Risk Factor for Nosocomial Outbreak

	Guangzhou		Hong Kong		Overall	
Type of factor, factor	OR (95% CI)	*P*	OR (95% CI)	*P*	OR (95% CI)	*P*
Environmental or administrative factors						
Minimum distance between beds of ≤1 m	**11.77 (1.54–90.13)**	.02	10.28 (0.58–182.10)	.11	**6.94 (1.68–28.75)**	.008
Washing or changing facilities for staff	…	>.15	…	>.15	0.12 (0.02–0.97)	.05
Never used exhaust fan	4.16 (0.98–17.72)	.05	…	>.15	…	>.15
Performance of resuscitation	…	>.15	…	>.15	**3.81 (1.04–13.87)**	.04
Staff working while experiencing symptoms	**11.18 (1.99–62.81)**	.006	**19.27 (1.12–332.48)**	.04	**10.55 (2.28–48.87)**	.003
Host factors						
Requiring oxygen therapy	**10.14 (1.70–60.37)**	.01	…	>.15	**4.30 (1.00–18.43)**	.05
Use of BIPAP ventilation	6.67 (0.90–49.23)	.06	…	>.15	**11.82 (1.97–70.80)**	.007
Systemic symptoms	12.71 (0.70–232.03)	.09	…	>.15	…	>.15

Figure: The summary of the major risk factors associated with the nosocomial outbreak in medical ward environments (Yu 2007).



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Nosocomial Infection (hospital-acquired)

"Even with the current stringent design and practice guidelines, nosocomial (hospital-acquired) infection of healthcare workers (HCWs) and inpatients continues to occur. What might be the limitations in current isolation ward designs?"

Source: https://medstudentinmoz.wordpress.com/page/2/

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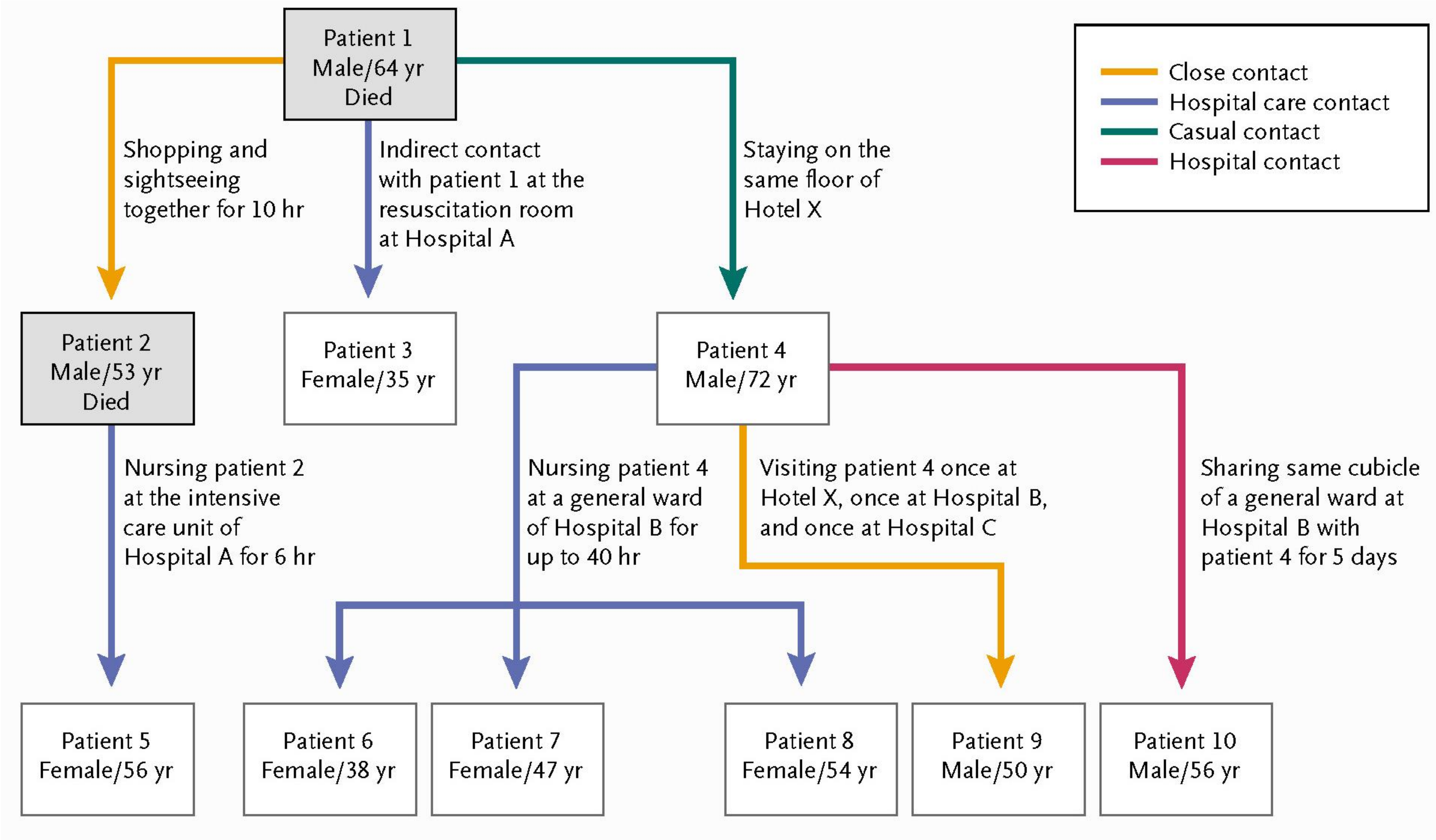
Nosocomial Infection (hospital-acquired)



Source: Tsang, K.W. et al. “A Cluster of Cases of Severe Acute Respiratory Syndrome in Hong Kong.” New England Journal of Medicine 348, no. 20 (May 15, 2003): 1977–85.

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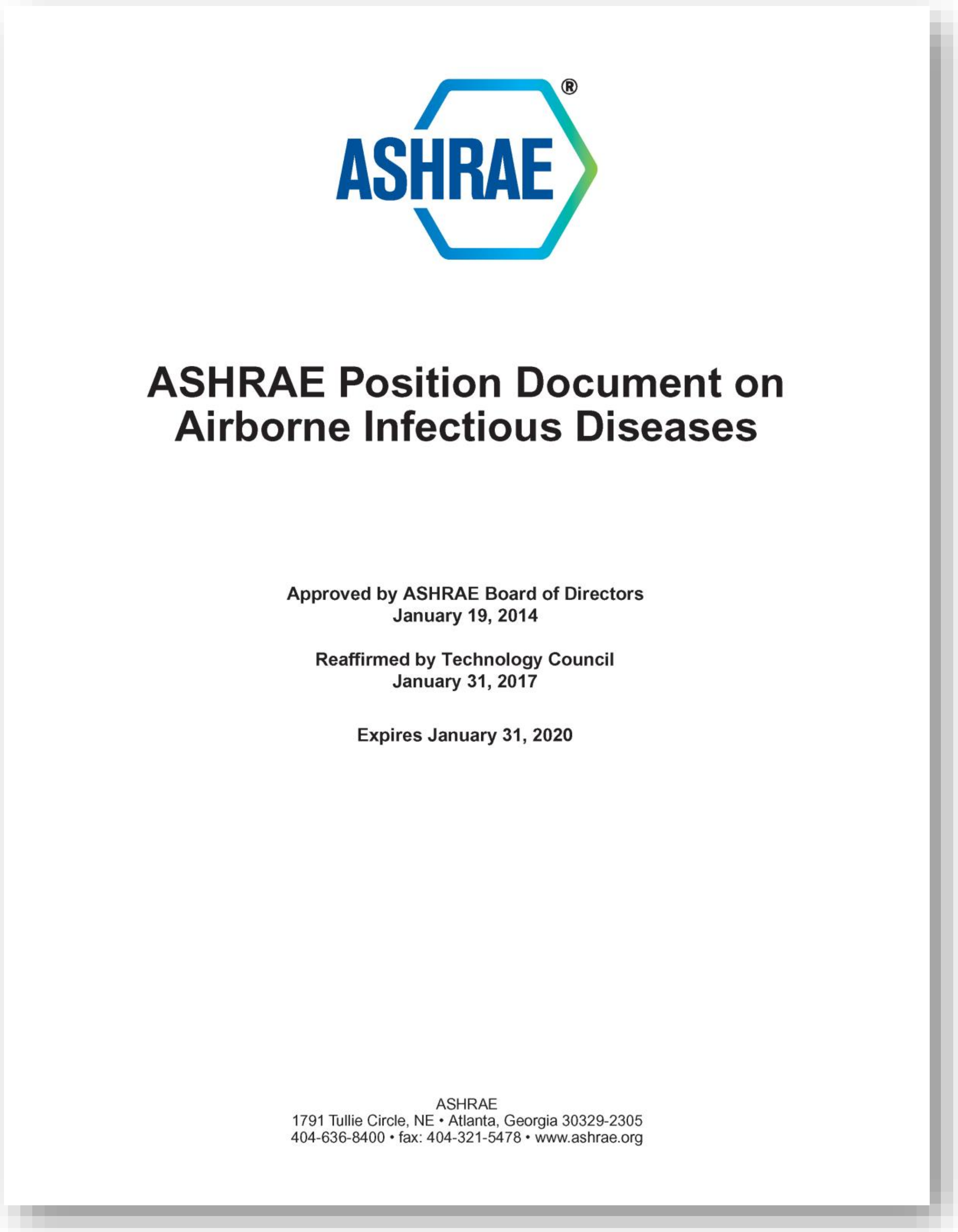
Nosocomial Infection (hospital-acquired)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ASHRAE Position Document on Airborne Infectious Diseases

Approved by ASHRAE Board of Directors
January 19, 2014

Reaffirmed by Technology Council
January 31, 2017

Expires January 31, 2020

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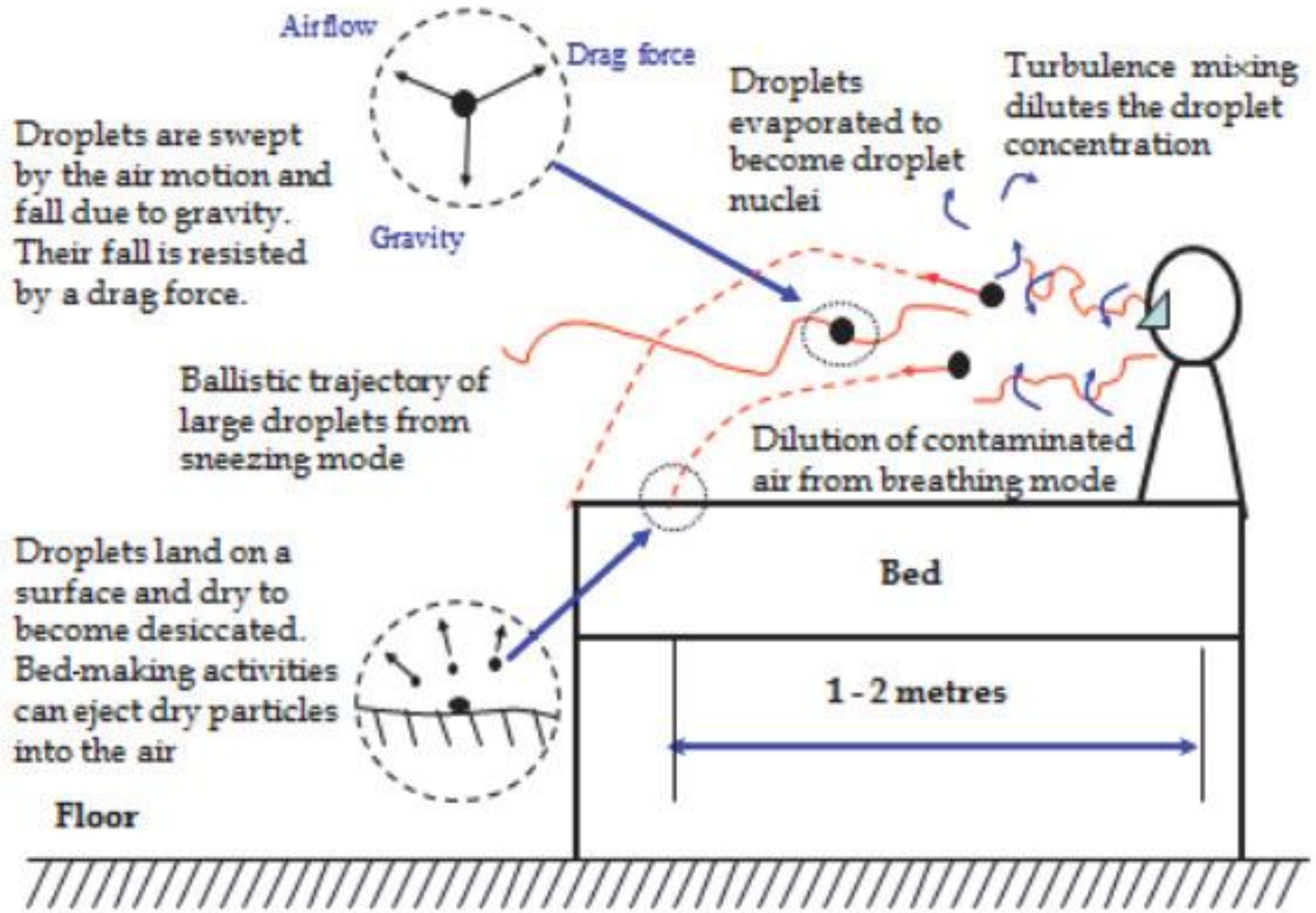

Source: ASHRAE Position Document on Airborne Infectious Diseases (2017)

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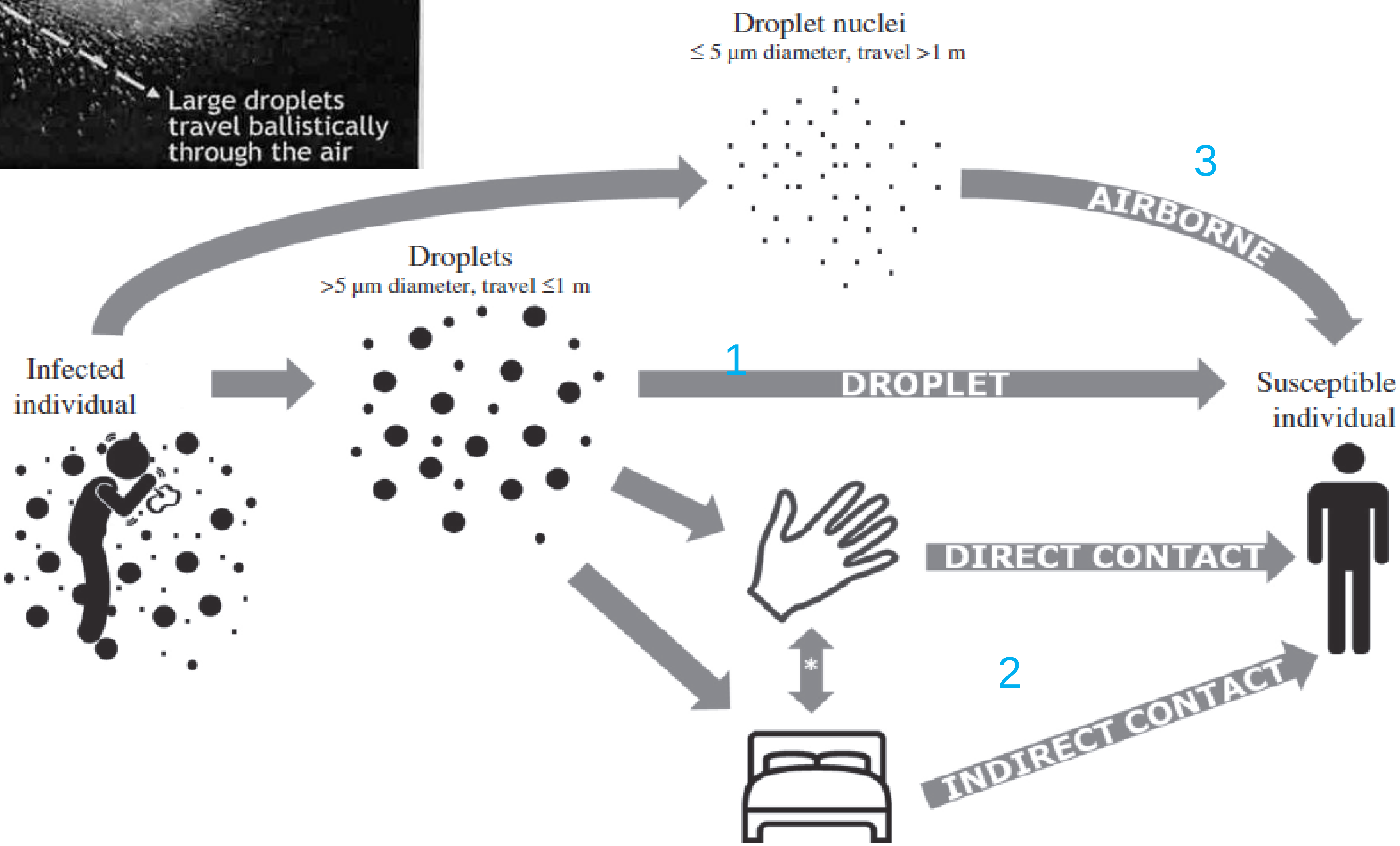
Otter JA, et al. J Hosp Infect 2015



* Transmission routes involving a combination of hand & surface = indirect contact.

Figure 1. Transmission routes: droplet, airborne, direct contact, and indirect contact. (Indirect contact: routes involving a combination of hand and surface.) Definitions of 'droplet' and 'droplet nuclei' are from Atkinson *et al.*[5]

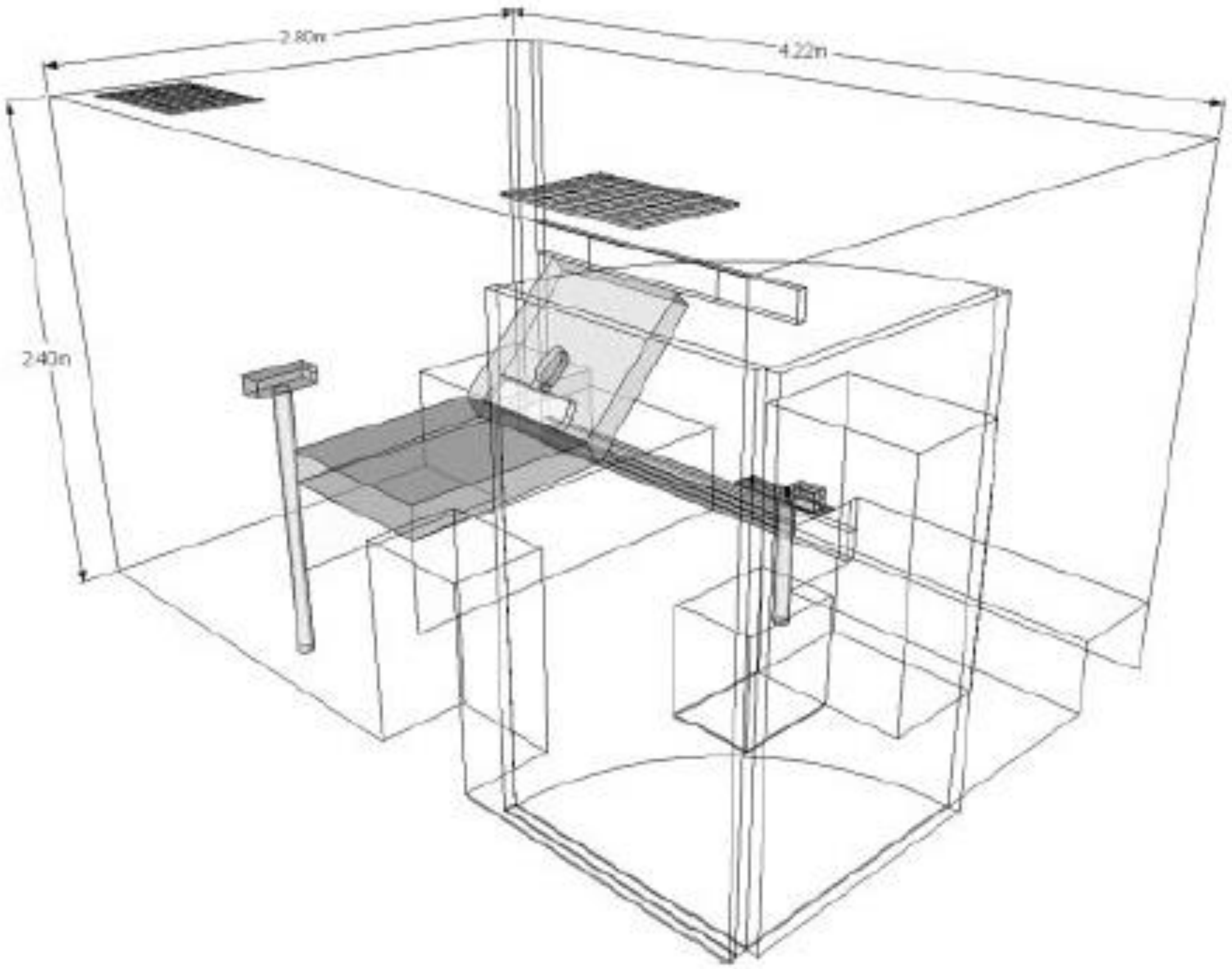


FIGURE 1. The room dimension and equipment layout inside the negative pressure isolation room. The room measured 4.22 m (depth) by 2.80 m (width) by 2.4 m (height). The camera and laser device were positioned along the sagittal plane and the coronal plane of the head of patient, respectively. Two fresh air diffusers as air inlet were mounted on the ceiling. The negative pressure of the isolation room was provided by the air exhausts positioned at the bottom of the bed.

Exhaled Air and Aerosolized Droplet Dispersion During Application of a Jet Nebulizer*

(CHEST 2009; 135:648–654)

David S. Hui, MD, FCCP; Benny K. Chow, MPh; Leo C. Y. Chu, MBChB; Susanna S. Ng, MBChB; Stephen D. Hall, PhD; Tony Gin, MD; and Matthew T. V. Chan, MD

Table 1—*Three Different Lung Settings of HPS Applied in this Study**

Settings	Normal Lung Condition	Mild Lung Injury	Severe Lung Injury
Oxygen consumption, mL/min	200	300	500
Lung compliance, mL/cm H_2O	70	35	10
Respiratory rate, breaths/min†	12	25	40
Tidal volume, mL†	700	300	150

*From Kuhlen et al[16] and Light.[17]

†Respiratory rate and tidal volume were adjusted by the HPS program to achieve primarily the target oxygen consumption and lung compliance.

Jet nebulizer (negative pressure isolation ward)

(*Hui DS, Chow Benny, et al. Chest 2009;135:648-54)*

Main Topics for Today

1. Verify the **ventilation performance** based on the detailed indoor airflow environment of existing isolation wards for both renovation and new construction hospitals;
2. Examine the **distinctive patient exhaled airflow patterns**, from different oxygen delivery interventions for patient with different lung breathing conditions and oxygen flow rate settings, as modeled by a human patient simulator (HPS);
3. Investigate the dynamic airflow interaction between **patient exhaled air plumes** as induced by common clinical oxygen administration and the indoor airflow environment of an AII room.

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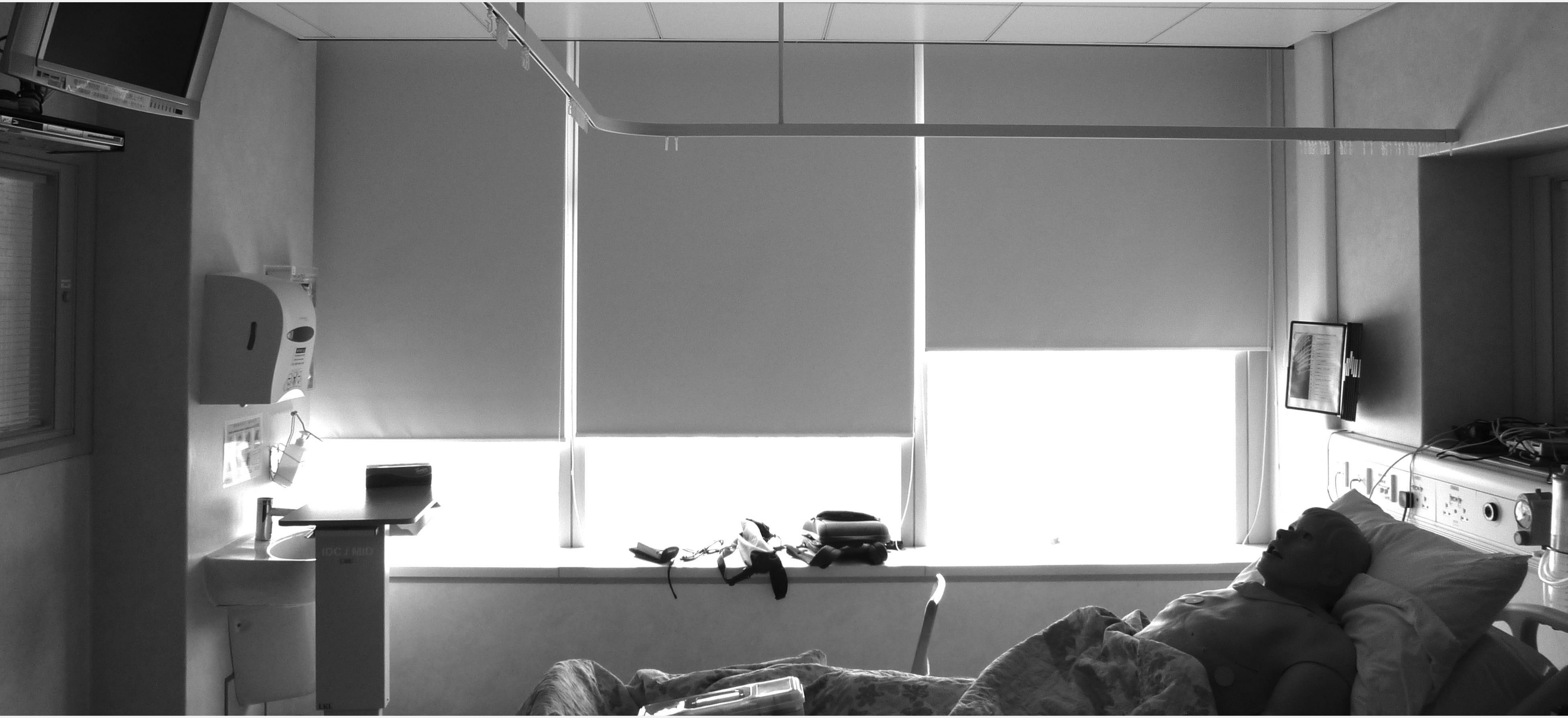
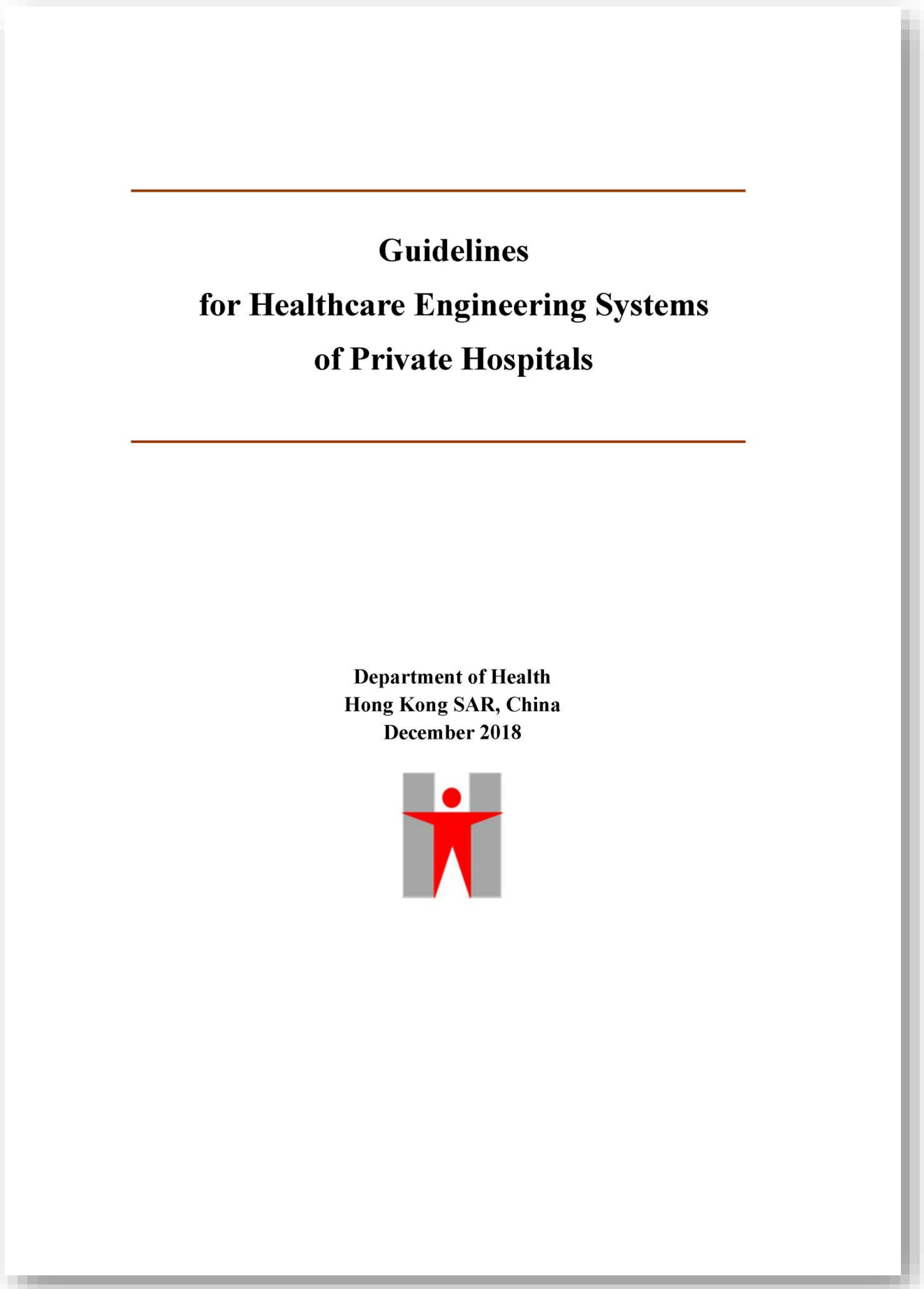
ISOLATION WARD DESIGN



Ventilation Design for Health Care Facilities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Department of Health
Hong Kong SAR, China
December 2018

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Ventilation Design for Health Care Facilities

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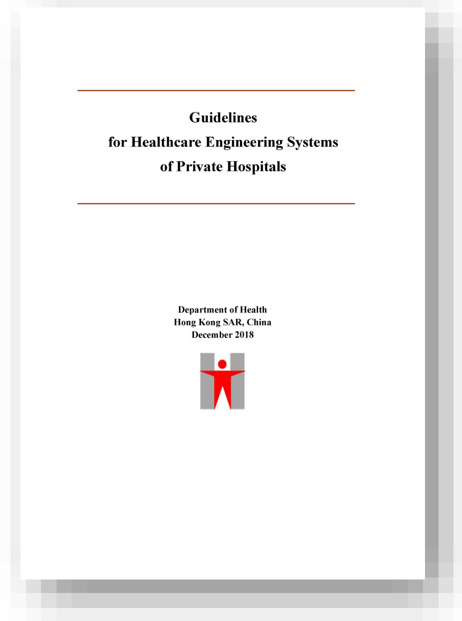
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Ventilation Design for Health Care Facilities

2.2 Design and Installation

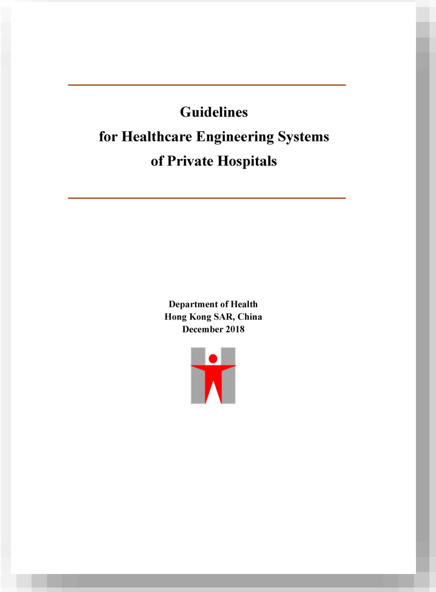
2.2.1 The design and installation of the specialised ventilation systems are of internationally acceptable healthcare standards such as ANSI/ASHRAE/ASHE Standard 170 – "Ventilation of Health Care Facilities" of the US, or Health Technical Memorandum (HTM) 03-01 – "Specialised ventilation for healthcare premises" of the UK, or equivalent.

2.2.2 In specialised ventilation areas, including but not limited to airborne infection isolation (AII) rooms, protective environment (PE) rooms, operating theatres/rooms and aseptic preparation clean rooms, the ventilation systems provide appropriate pressure relationship, air change rate, filtration efficiency, temperature and relative humidity, and air movement generally from clean to less clean areas. (Detailed guidelines on the specialised ventilation requirements are provided in Annex 2A.)

2.2.3 Where gaseous anaesthetic agents are used, appropriate gas administration devices and exhaust systems are in place, and relevant requirements on occupational safety are observed.

2.2.4 Outdoor air intakes for air handling units are situated away from vehicle staging areas, exterior designated smoking area, cooling towers and all exhaust and vent discharges.

2.2.5 The discharges from general extract systems are placed at a suitable location to minimise the recirculation of discharged air back into the building. In addition, the discharges from AII rooms and local exhaust ventilation systems are preferably vertical and at sufficient height above roof level. (Detailed guidelines on the exhaust discharge requirements are provided in Annex 2B.)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1. **Airborne Infection Isolation (AII) Rooms (Isolation Ward),**
2. **Protective Environment (PE) Rooms,**
3. **Operating Theatres (OT)**

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Ventilation Design for Health Care Facilities

Annex 2A

Specialised Ventilation Requirements

1. Specialised ventilation areas are ventilated according to the following requirements :

	Function of Space	Pressure Relationship to Adjacent Areas	Min. Outdoor ACH	Min. Total ACH	All Room Air Exhausted Directly to Outdoors	Air Recirculated by Means of Room Units[1]	Design Relative Humidity %	Deign Temp. ^{0}C	Min. Filter Efficiency
1	Operating theatre / room (OT/OR)	Positive	4	20	NR	No	20-60	20-24	MERV-14
2	Airborne Infection Isolation (AII) room	Negative	2	12	Yes	No	Max 60	21-24	MERV-14
3	Protective Environment (PE) room	Positive	2	12	NR	No	Max 60	21-24	HEPA

Note:

NR – no requirement

1 Recirculating devices with high-efficiency particulate air (HEPA) filters may be used in existing facilities to achieve the required room ACH, provided the specified minimum outdoor ACH is supplied.

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Ventilation Design for Health Care Facilities

2. Airborne Infection Isolation (AII) rooms

2.1 AII rooms are sealed to provide a minimum differential pressure of -2.5 Pa across the envelope.

2.2 AII rooms have a permanently installed device and / or mechanism to constantly monitor the differential air pressure between the room and the corridor. A local visual means is provided to indicate whenever negative differential pressure is not maintained.

2.3 Exhaust air grilles in the patient room are located directly above the patient bed, on the ceiling or on the wall near the head of the bed.

3. Protective Environment (PE) rooms

3.1 PE rooms are sealed to provide a minimum differential pressure of +2.5 Pa across the envelope.

3.2 PE rooms have a permanently installed device and / or mechanism to constantly monitor the differential air pressure between the room and the corridor. A local visual means is provided to indicate whenever positive differential pressure is not maintained.

3.3 Supply air diffusers are located above the patient bed and return/exhaust grilles are located near the patient room door.

4. Operating theatres/rooms (OTs/ORs)

4.1 OTs/ORs are maintained at a positive pressure with respect to all adjoining spaces at all times.

4.2 A pressure differential is maintained at a valve of at least +2.5 Pa.

4.3 Each room has individual temperature control.

Airborne Infection Isolation

Negative Pressure -2.5Pa

Differential Air Pressure Monitor

Exhaust air grilles location

Protective Environment

Positive Pressure +2.5Pa

Differential Air Pressure Monitor

Supply Air Diffusers Location

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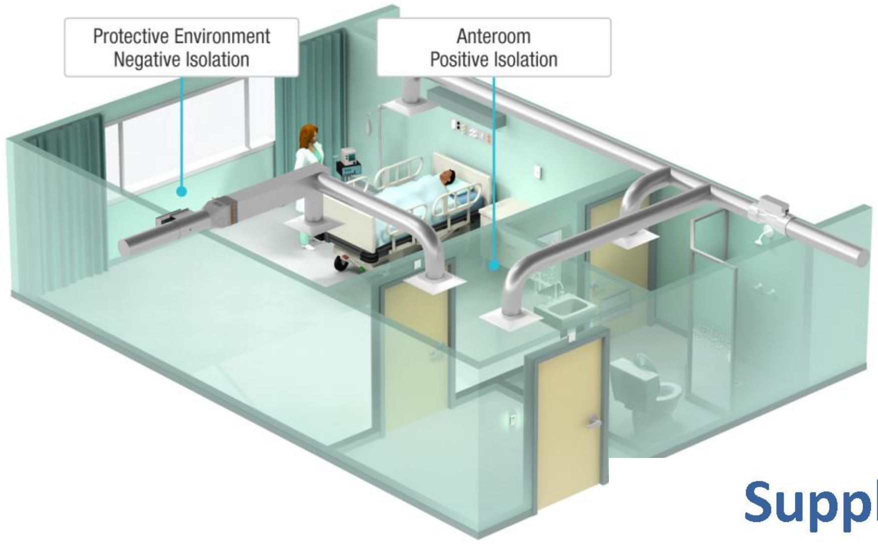
Ventilation Design for Health Care Facilities



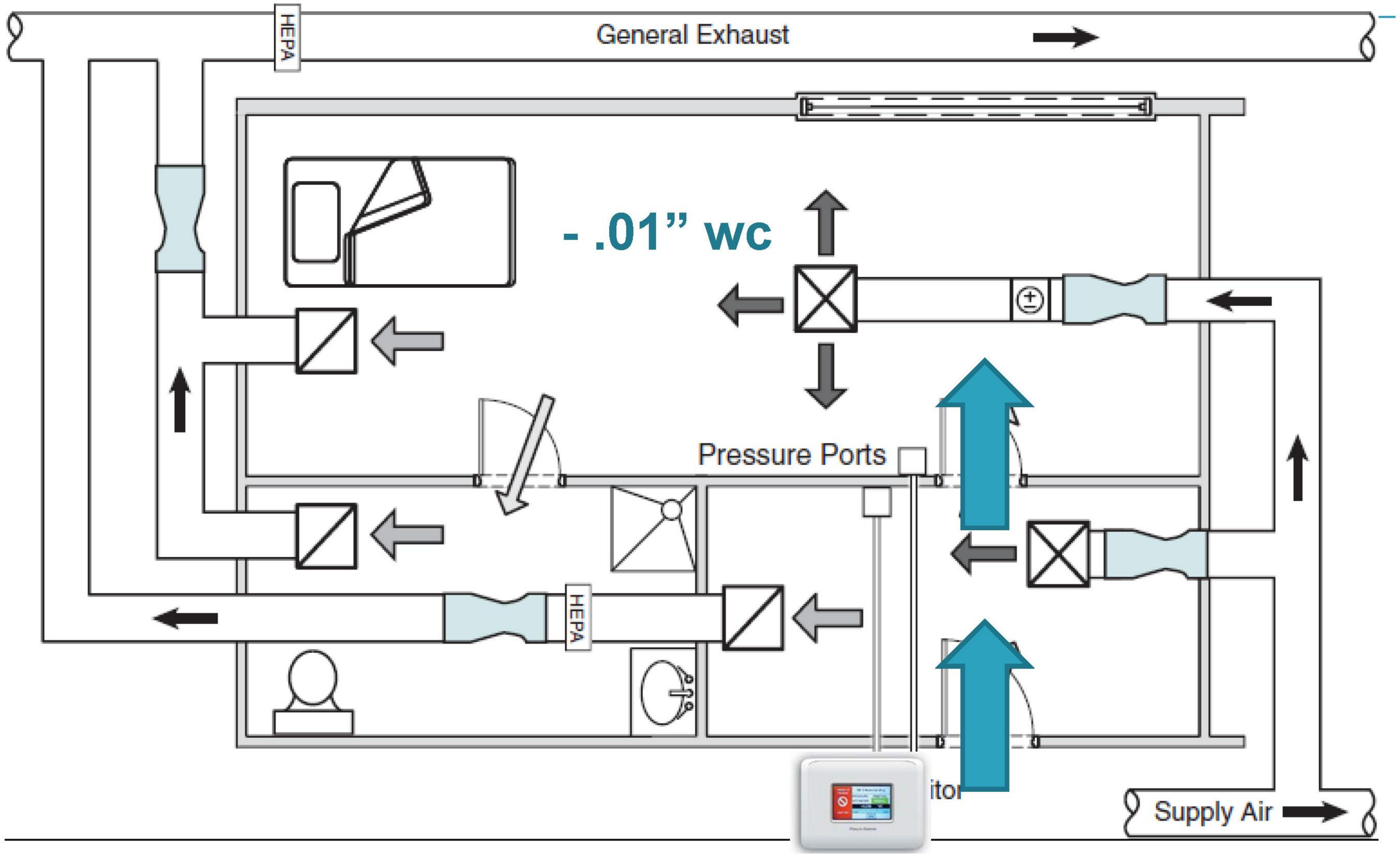
Airborne Infection Isolation

Negative Pressure -2.5Pa

Differential Air Pressure Monitor

Exhaust air grilles location

Supply / Exhaust Tracking Pairs



Source: ASHRAE Madison Chapter (Don MacDonald, Phoenix Controls)

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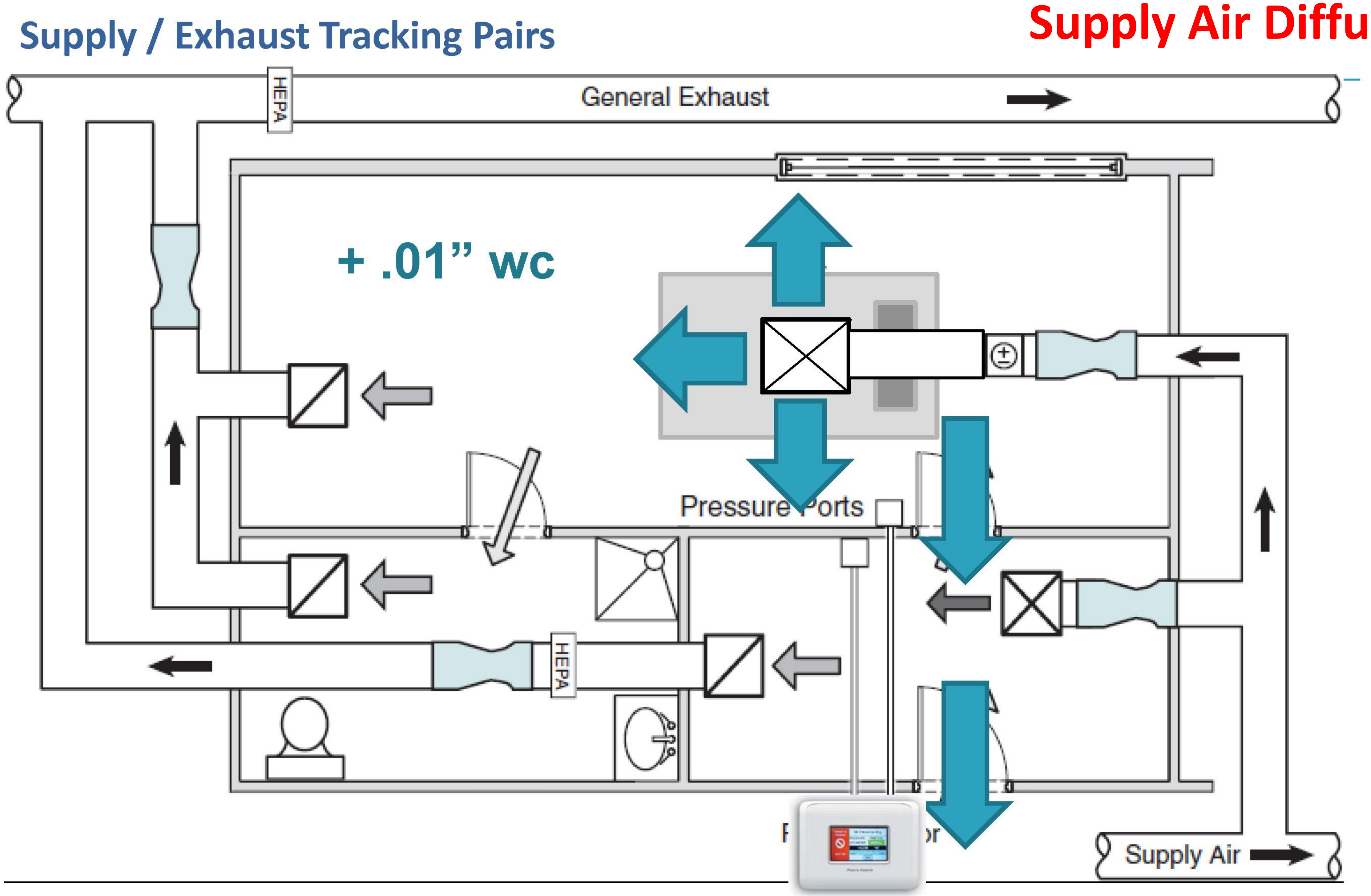
Ventilation Design for Health Care Facilities

Protective Environment

Positive Pressure +2.5Pa

Differential Air Pressure Monitor

Supply Air Diffusers Location



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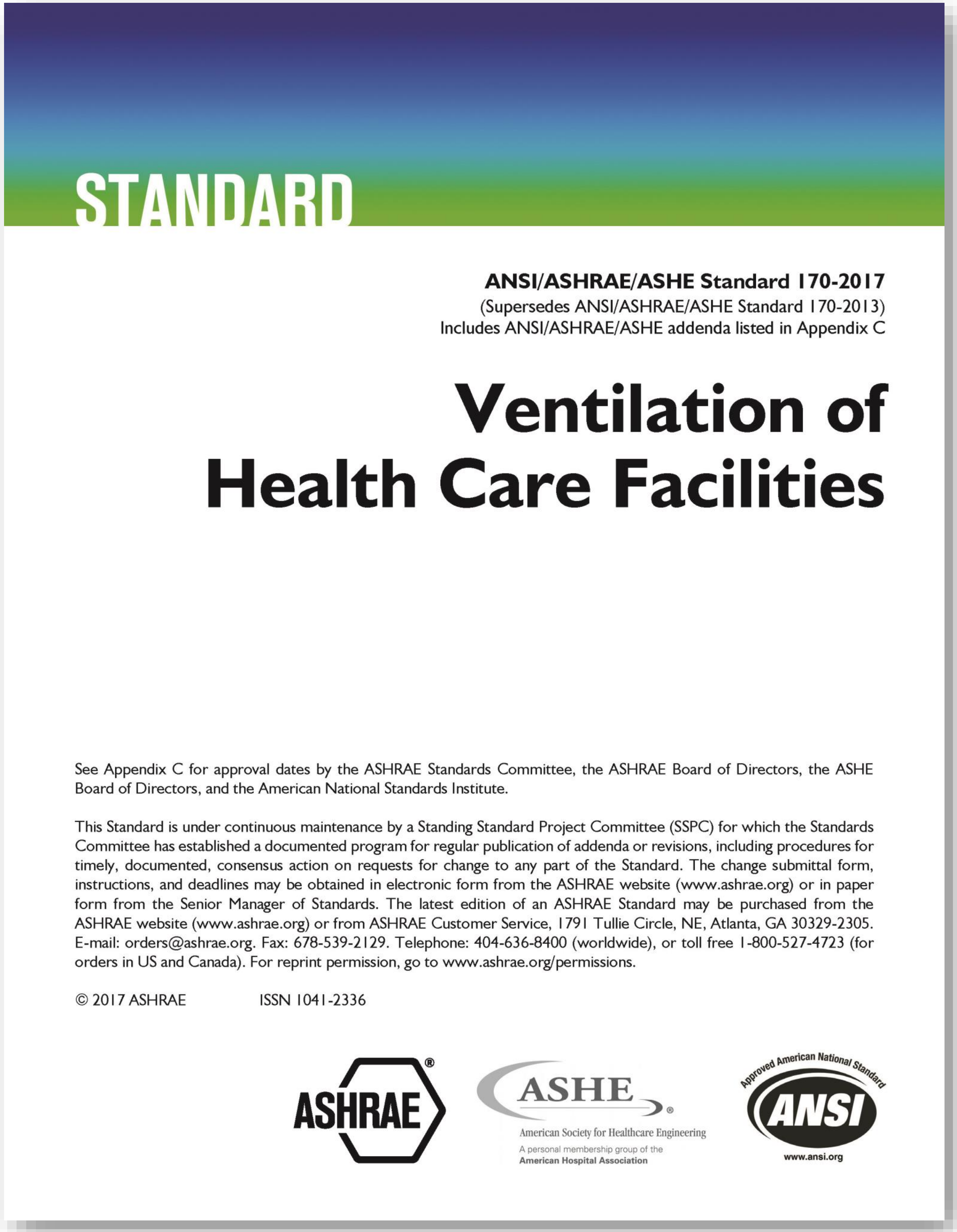

STANDARD

ANSI/ASHRAE/ASHE Standard 170-2017
(Supersedes ANSI/ASHRAE/ASHE Standard 170-2013)
Includes ANSI/ASHRAE/ASHE addenda listed in Appendix C

Ventilation of Health Care Facilities

See Appendix C for approval dates by the ASHRAE Standards Committee, the ASHRAE Board of Directors, the ASHE Board of Directors, and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE website (www.ashrae.org) or in paper form from the Senior Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

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ASHRAE Standard 170-2017

(Supersedes ASHRAE Standard 170-2013) Includes ANSI/ASHRAE/ASHE addenda listed in Appendix C

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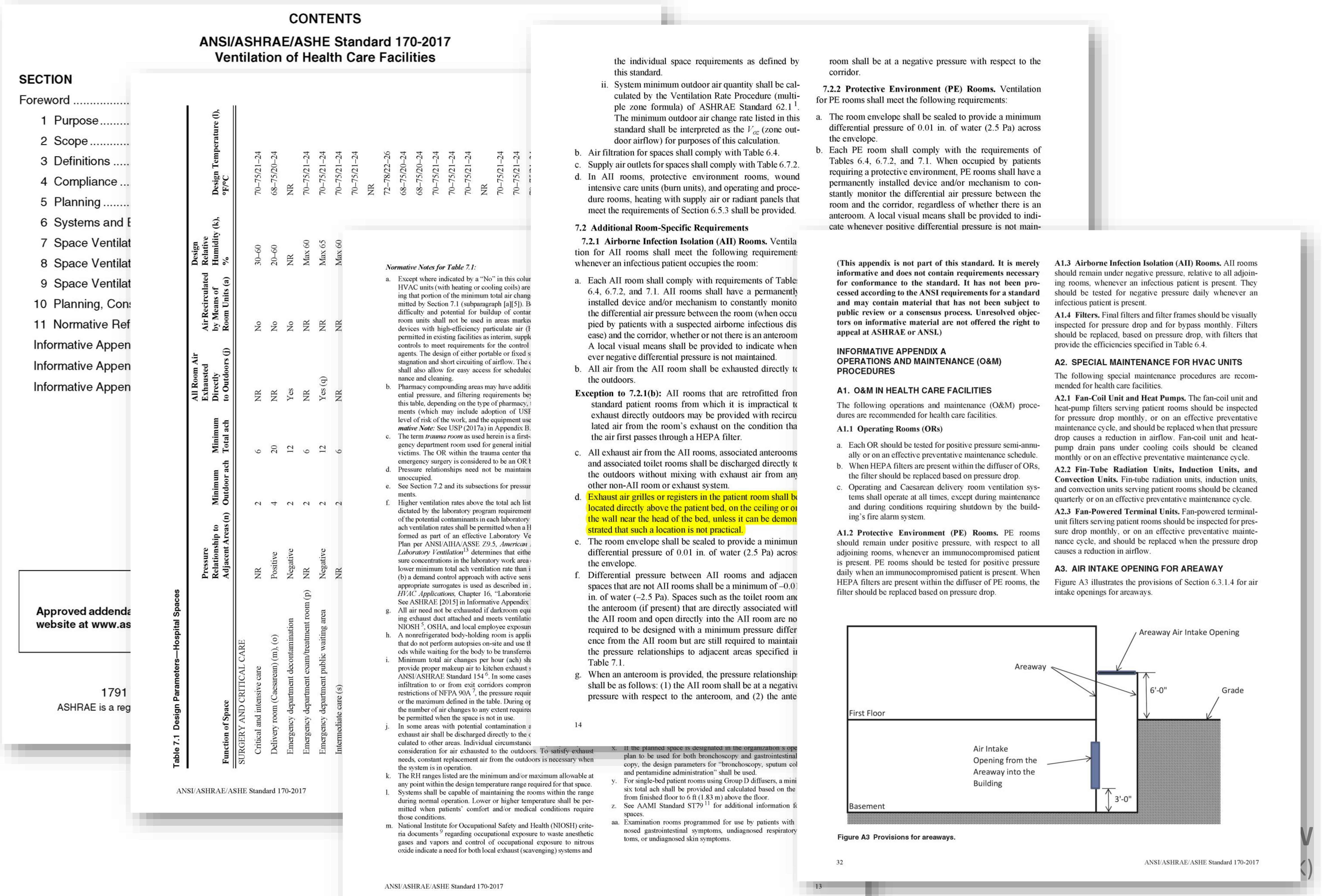
Ventilation Design for Health Care Facilities



Isolation System in a Hospital

Level 1 - Administrative Control

Such as proper triage of patients, detecting infections early and, separating infectious patients from others (WHO 2007; CDC 2007); Adequate staff training and patients education; Effective communication with all relevant departments.

Level 2 - Environmental and Engineering Controls

Include cleaning of the environment, spatial separation, ventilation of spaces

Level 3 - Personal Protection

Have personal protective equipment (PPE), including, masks, respirators, gowns, gloves, eye protection, etc.

Figure: Three levels of isolation precautions controls as stipulated at WHO.

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Negative Pressure Isolation Ward

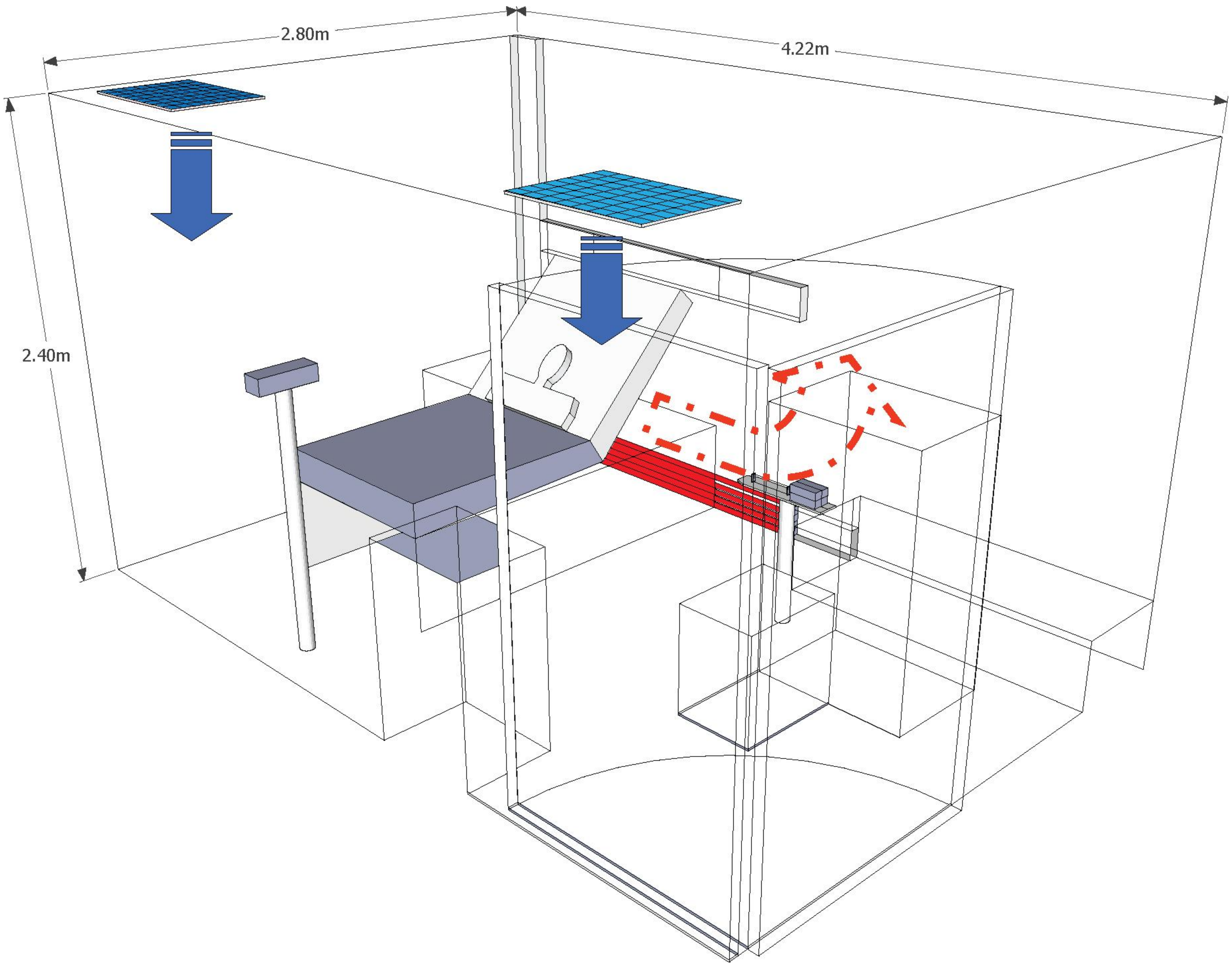

Figure: Downward ventilation system provides negative pressure to isolation room B of PWH. (Source : Benny Chow)

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Negative Pressure Isolation Ward

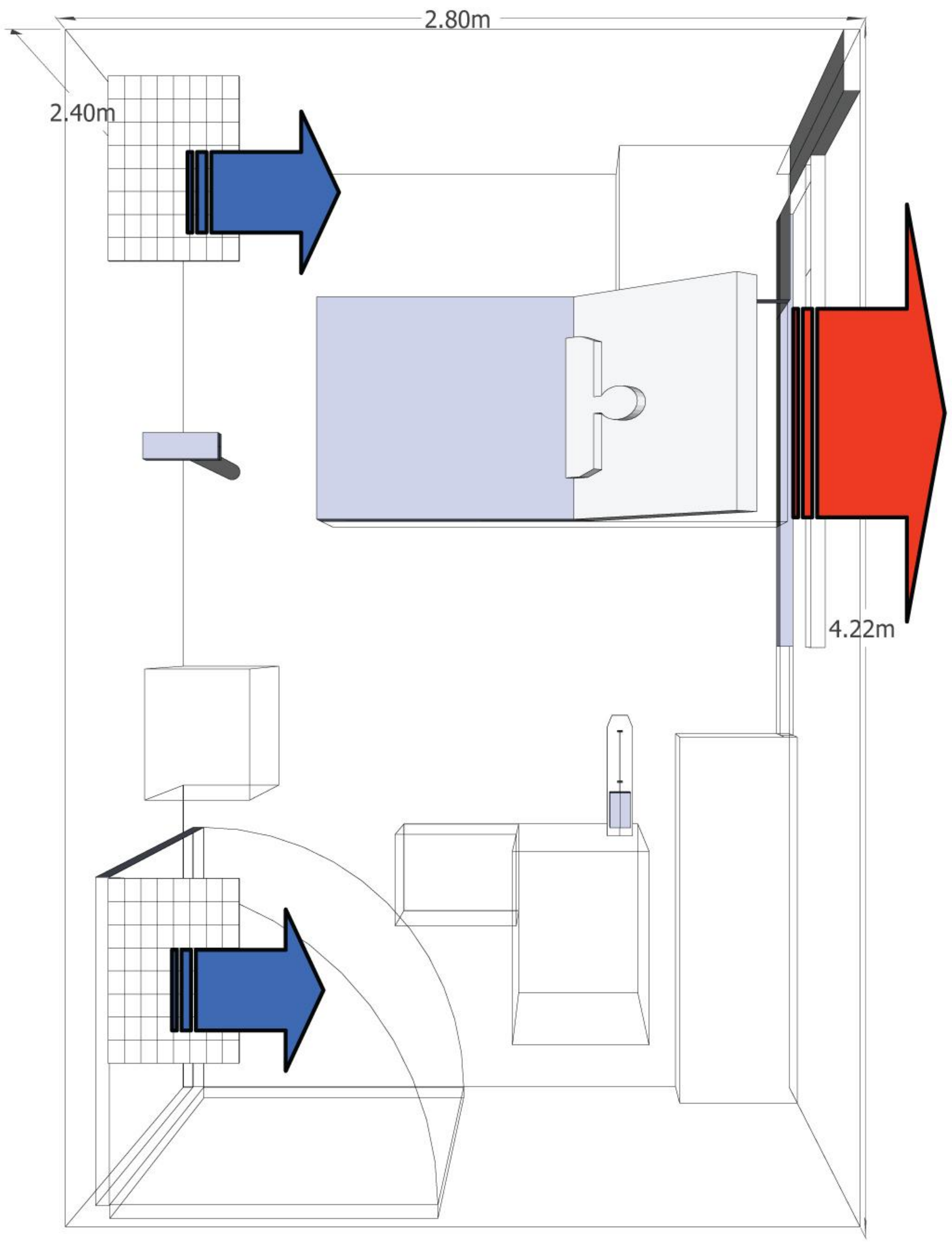

Figure: Downward ventilation system provides negative pressure to isolation room B of PWH.

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Experimental study on specialized ventilation system of airborne infection isolation room

Main Design Principles for an Isolation Room

1. The AII room should be at least **2.5 Pa** (0.01-inch water gauge) **Negative Pressure** with respect to adjacent spaces, between patient rooms and the double door anteroom to prevent air leaking outward;
2. The **Dilution Ventilation Rate** should be at least 6 ACH for existing facilities and **12 ACH** for new facilities;
3. The AII room can be constructed with or without an anteroom. An **anteroom** can act as an airlock space and is recommended to store personal protective equipment (PPE);
4. **Outdoor fresh air intakes** shall be located at not less than 7.6 m horizontally from **all exhaust outlets**. The exhaust shall be discharged above roof level. Avoid direct exhaust towards operable windows, walkways, public areas, and parking areas;

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Main Design Principles for an Isolation Room

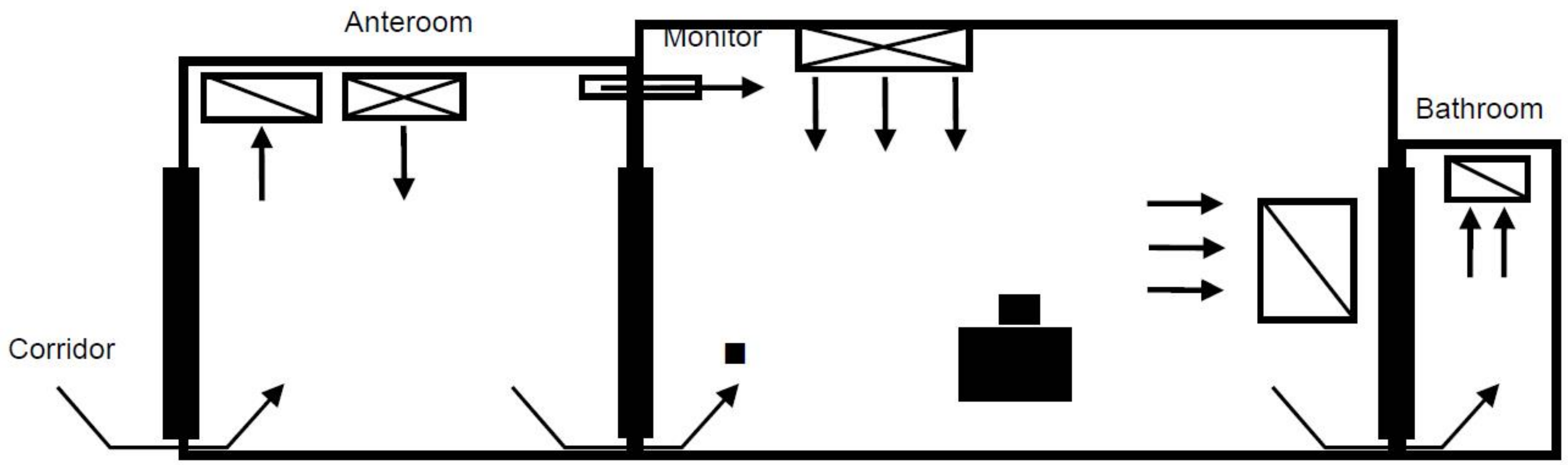

Figure: Sectional view of the conceptual of airflow diagram of AII room with anteroom (CDC 2003)

[engineering features]	**Airborne Infection Isolation room (AII)**	**Operating Theatres (OT)**	**Protective Environment (PE)**
Air pressure	Negative	Positive	Positive
Pressure differentials in relation to the adjacent areas	> -2.5 Pascal (i.e. 0.01 inch water gauge)	Positive	> +2.5 to +8 Pascal
Room air changes per hour (ACH)	Minimum 6 ACH (for existing facilities); > 12 ACH (for renovation or new construction)	> 15 ACH	> 12 ACH
Sealed	Yes	Yes	Yes
Filtration efficiency of supply air	As per local hospital policy	> 90%	HEPA filter at 99.97% at 0.3µm
Filtration efficiency of exhaust air	Not required if direct exhaust air to the outside; or HEPA filter at 99.97% at 0.3 µm for re-circulated air	Not required if exhaust air to outside; or HEPA filters should be installed for re-circulated air	Not required
Recirculation	No, unless HEPA filters are installed	Yes	Yes
Clean to dirty airflow	All towards patient and exhausted	For supply across patient and exhausted	From supply across patient and exhausted

Figure: The summary of the engineering control specification for AII room, operating theatres and protective environment issued by the Center for Health Protection (CDC 2003; WHO 2009; CHP 2007)

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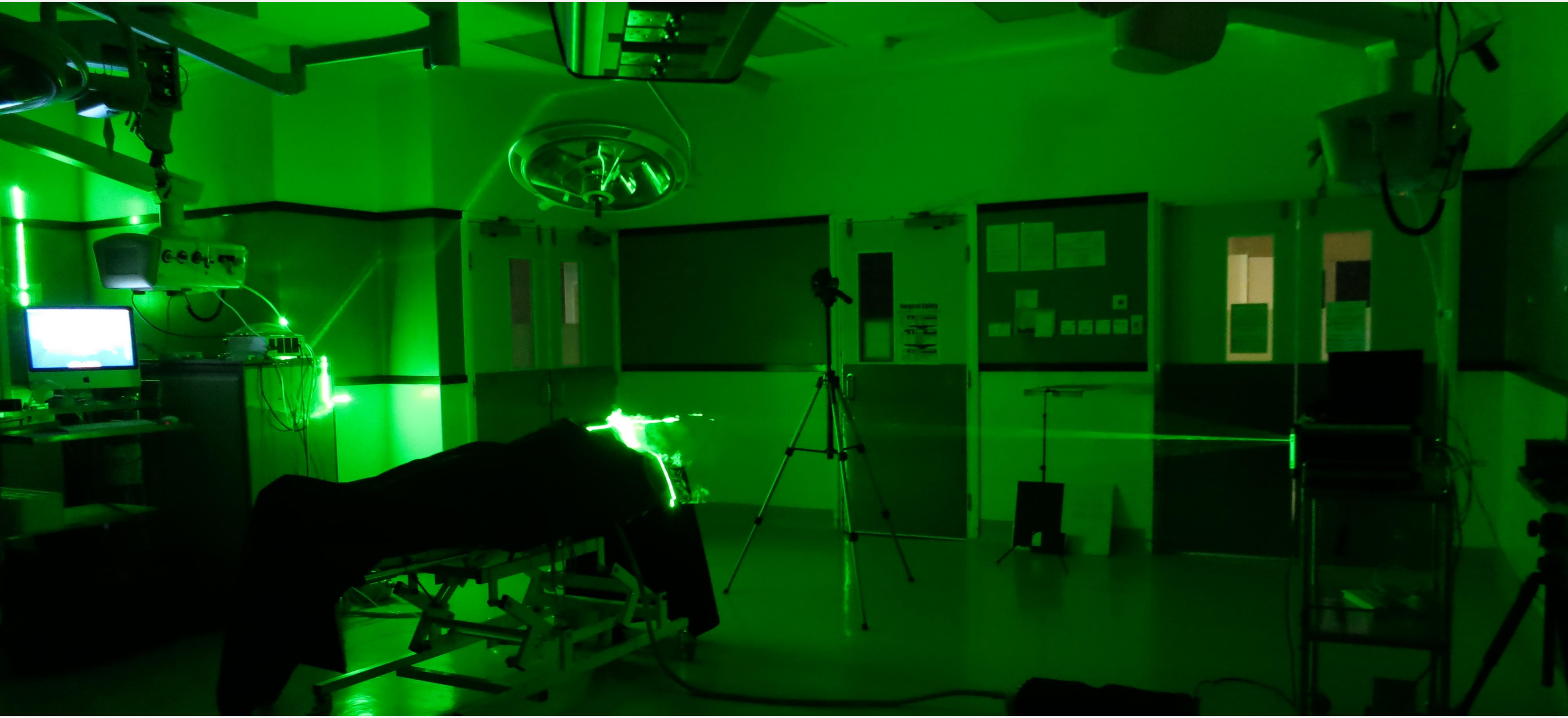
ON-SITE MEASUREMENT



Isolation Room A at PMH

Figure: Isolation Room A at PMH showing a spacious single bed patient room with an anteroom as airlock between corridor and patient room.

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Clinical Settings & Human-centred Design

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Isolation Room A at PMH

Figure: Fully glazed air-tight, auto-swing door (left) and the ultraviolet germicidal irradiation (UVGI) lamp mounted on the top of patient bed (right) for isolation room A at PMH.

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Isolation Room A at PMH

Figure: Spacious single bed patient room of isolation room A at PMH, with air supply diffusers mounted on the ceiling at the end of the patient bed and floor level exhaust underneath the head of the patient bed.

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(ASHRAE-HKC/Med.CUHK)

Isolation Room B at PMH

Figure: The more congested isolation room B at PWH, with air supply diffusers mounted on the ceiling at the foot of the patient bed and floor level exhausts underneath the head of the patient bed.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Common Oxygen Therapies

Mask Types	Technical Comments	Visual Appearance of Masks
Simple (Hudson) Mask Brand: Well Lead Model: Oxygen mask, Adult elongated [www.welllead.com.cn]	1. Most commonly used oxygen mask; 2. Cannot control O_2%; it depends on O_2flow rate, mask fit and patient IPAP; 3. Performance: 4L/min, oxygen is around 35%; up to 14L/min, oxygen is around 65%.	
Venturi Mask Brand: Salter Labs Model: Accu-Flow Venturi System (Adult) [www.salterlabs.com]	1. Design to deliver accurate O_2 concentration (24%, 28%, 31%, 35%, 40%) with five individual diluter jets; 2. Operate with Venturi principle; 3. Combination of oxygen flow rate and the diluter jets determine the O2 concentration.	

Figure: The illustrations of the common oxygen masks and its laser flow visualization in a negative pressure isolation room.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Common Oxygen Therapies

Mask Types	Technical Comments	Visual Appearance of Masks
Nasal Cannula Mask Brand: Airlife Model: Nasal Oxygen Cannula Cat. 001325 [www.cardinal.com]	1. Deliver supplementary oxygen directly to patient via nostrils directly; 2. The oxygen flow rate ranges from 1 to 6 L/min; can deliver 28% to 44% oxygen; 3. Allow patient to receive high volume of oxygen therapy accurately.	
Jet Nebulizer Brand: (Salter Labs Model: Nebulizer adult, REF 8924 [www.salterlabs.com]	1. Nebulizes 3cc in less than 10 minutes; Shortened treatment times; 2. Nebulizes in horizontal or vertical position; Allow patient to be in a comfortable position for treatment; 3. Larger surface area provided by unique convex cone design.	

Figure: The illustrations of the common oxygen masks and its laser flow visualization in a negative pressure isolation room.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Common Oxygen Therapies

Mask Types	Technical Comments	Visual Appearance of Masks
NPPV Mask Brand: Respironic Model: Image 3 full face mask, Lot. 040219/ 1004884 [www.respironics.com]	1. Exhalation device NOT INCLUDED; 2. "Whisper Swivel" exhalation port was attached, which caused a large scale diffused contamination around the patient head; 3. Entrainment valve included.	
NPPV Mask Brand: Respironic Model: Comfort Full 2 full face mask, Lot. 070105/1004873 [www.respironics.com]	1. Exhalation device - "Quiet Diffuser" - Three rows of tiny ports creating a strong directional air jet projected towards the end of patient bed; 2. Entrainment valve type - provides quick access to room air if pressure is less than 3cm H_2O.	

Figure: The illustrations of the common oxygen masks and its laser flow visualization in a negative pressure isolation room.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

INSTRUMENTS

Airflow Visualization – Laser Imaging System

Figure: Set-up of Spectra Physic OEM 532nm DPSS of the Laser Imaging System (LIS).

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(ASHRAE-HKC/Med.CUHK)

Airflow Visualization – Laser Imaging System

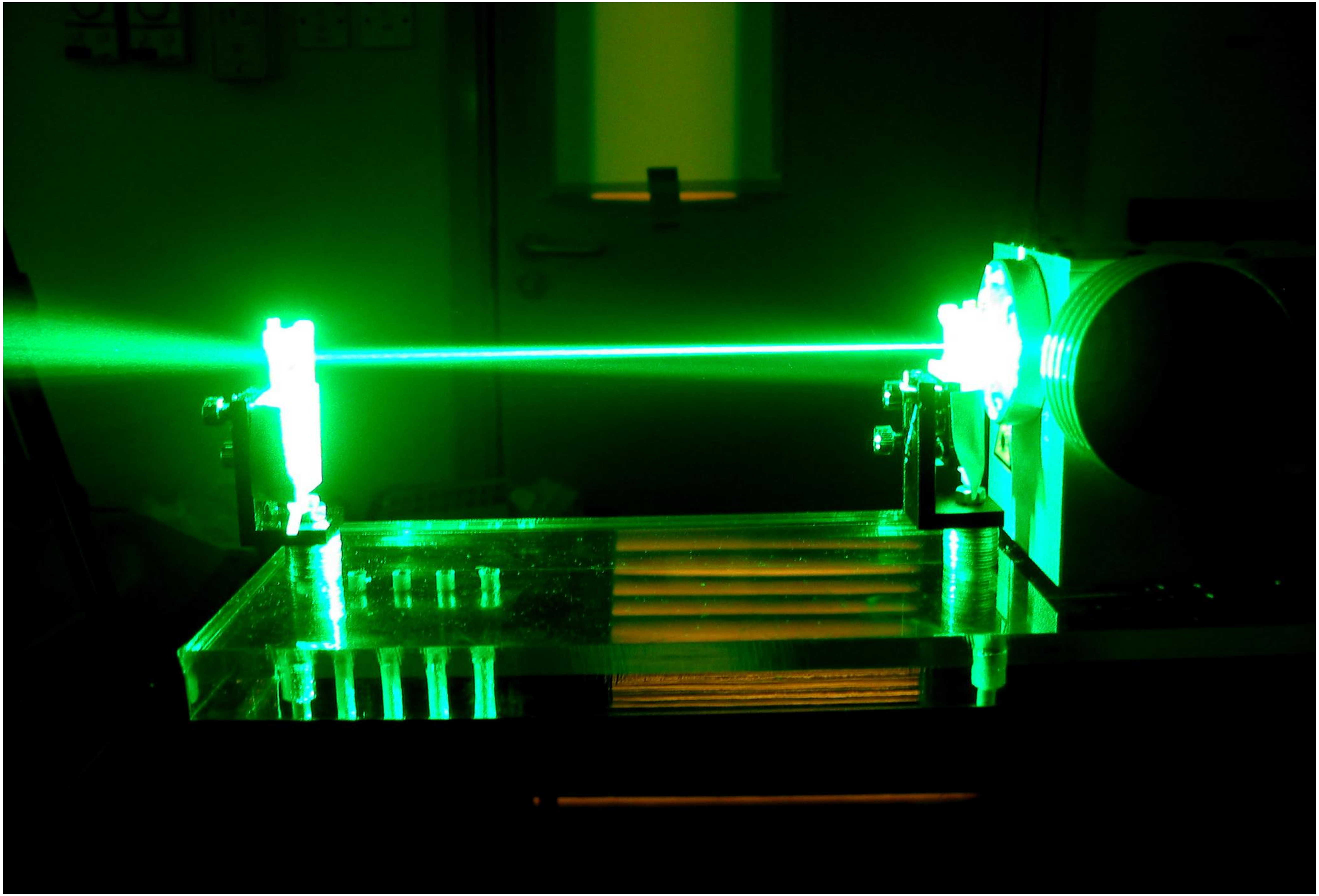

Figure: Powerful laser beam and light sheet was generated from Nd:YAG DPSS laser system passing through an optical system developed for this study.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Image Capture and Frame Extraction

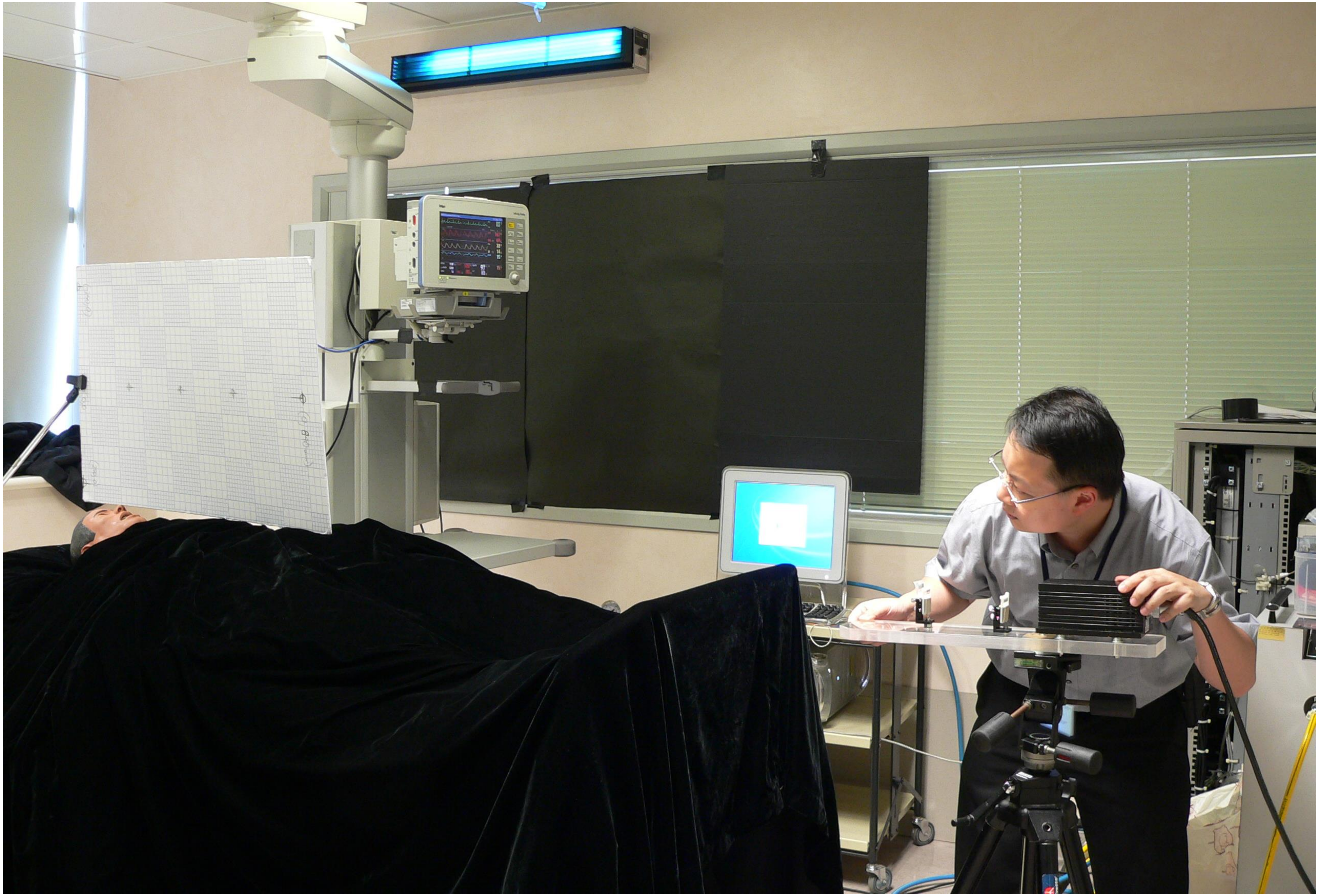

Figure: Calibrating the low-powered LIS with the dimension grid mounted on the median sagittal plane of the mannequin.

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Experiments on Jet Nebulizer

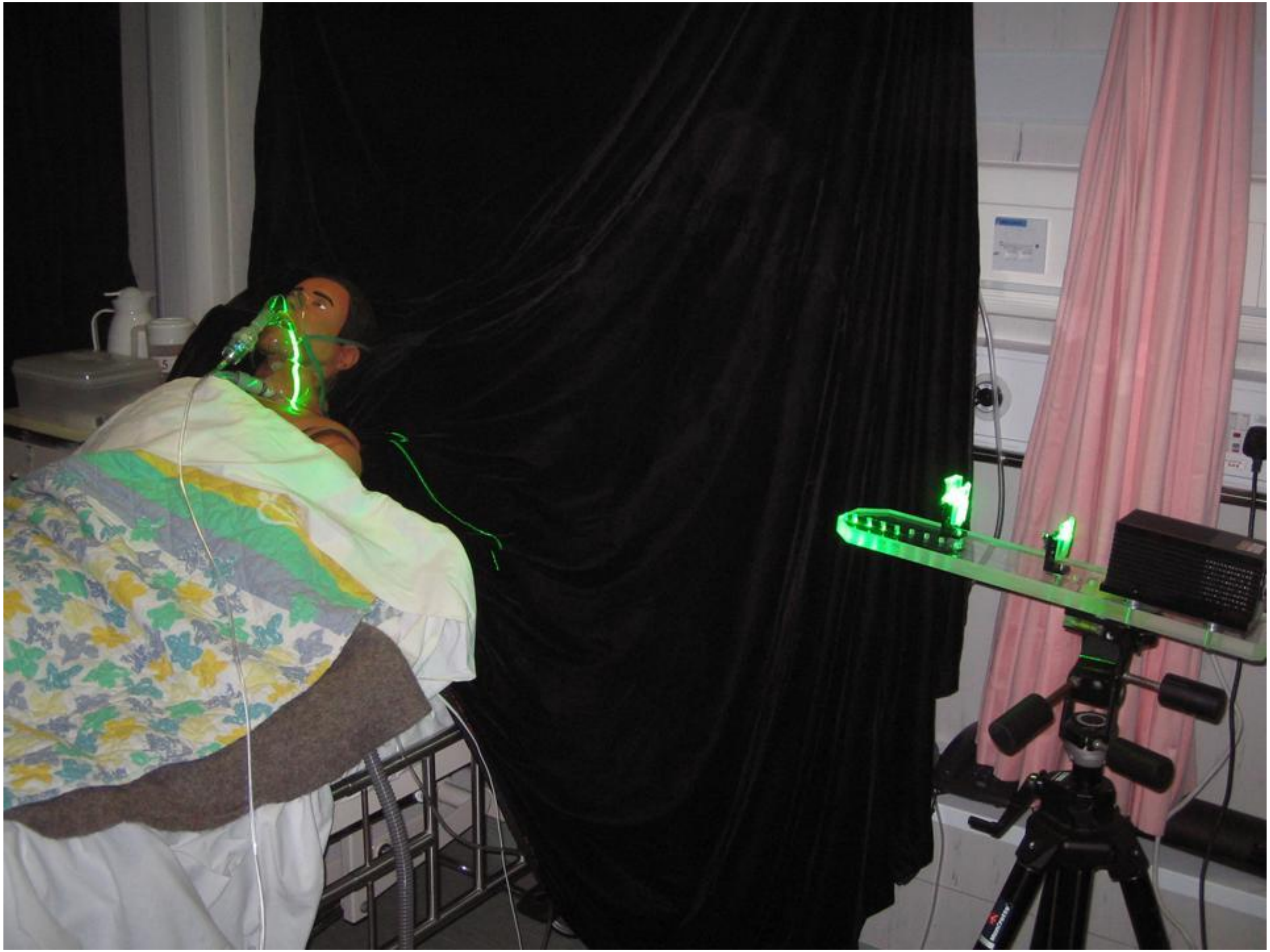

Figure: A jet nebulizer was attached to a HPS with a LST laser light sheet in the transverse plane.

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(ASHRAE-HKC/Med.CUHK)

Experiments on Jet Nebulizer

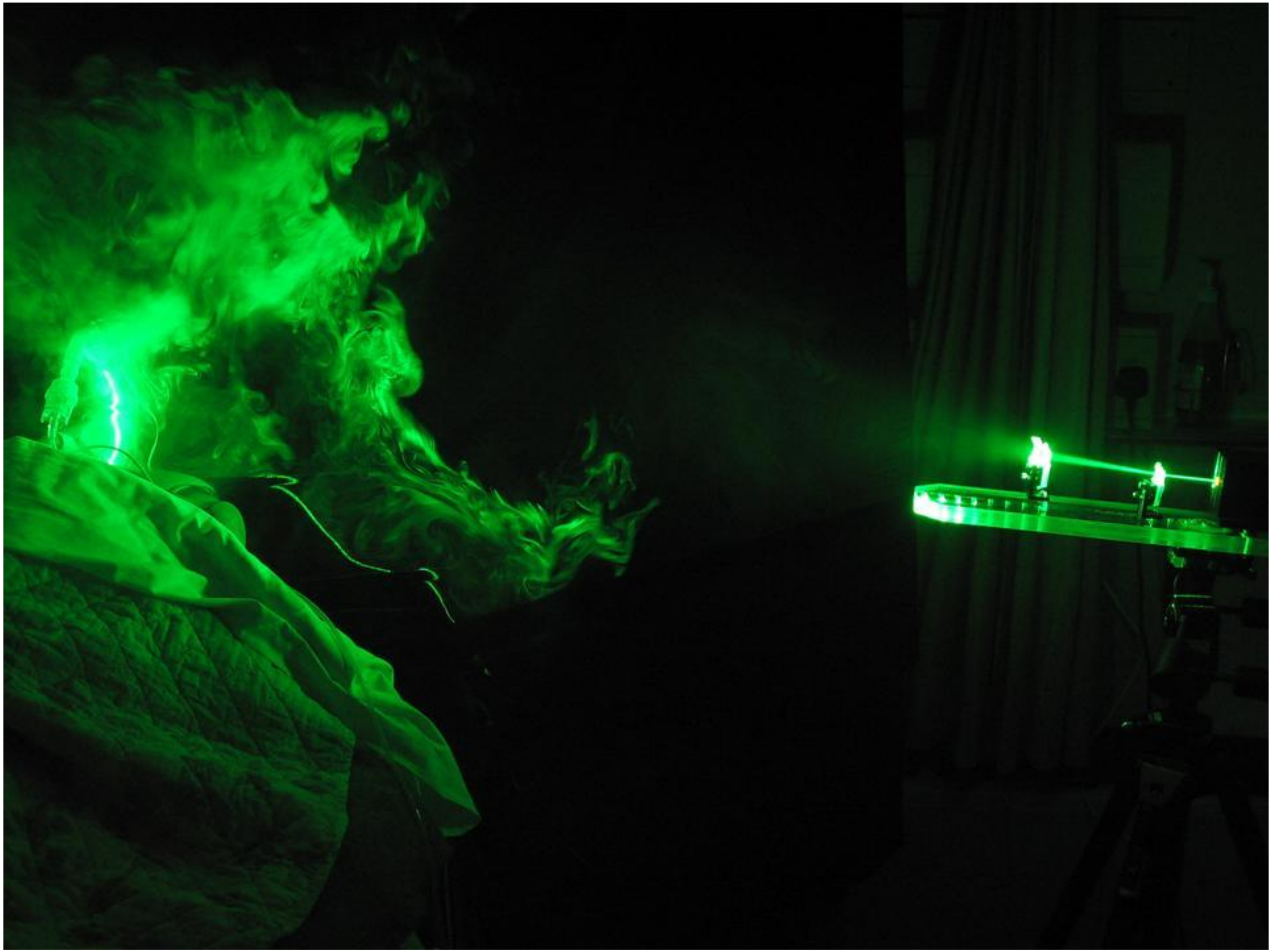


Figure: Photograph showing aerosol dispersion and patient exhaled air plume of jet nebulizer.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Image Capture and Frame Extraction

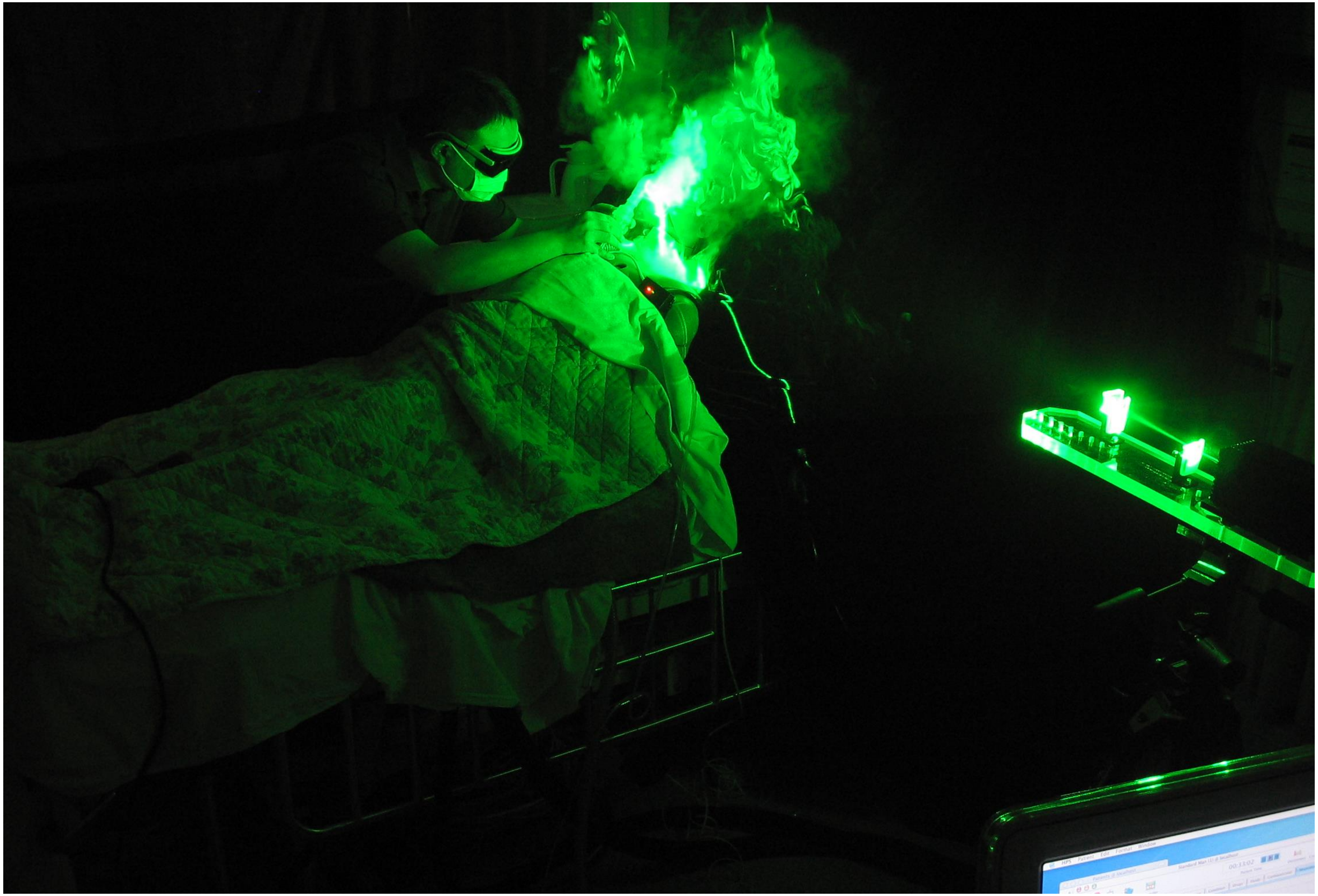


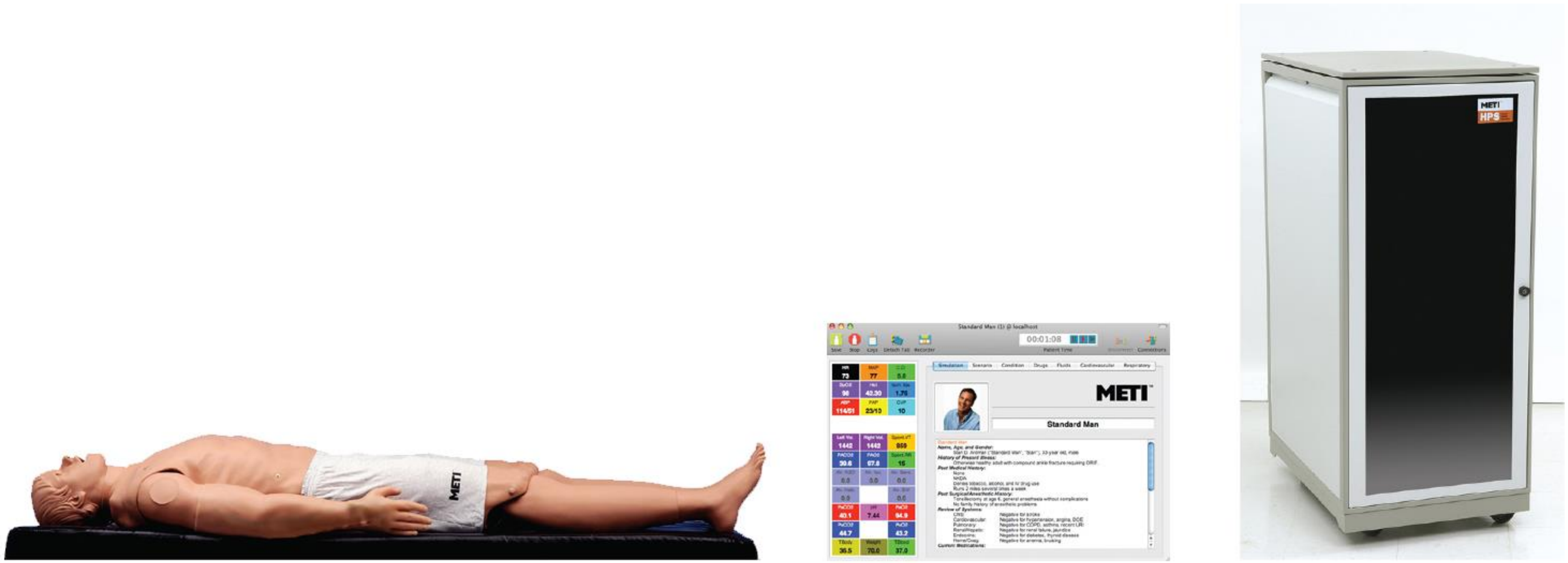
Figure: Mask fitting to seal the air leakage and aliging the laser light sheet to the centerline of the mask side vents.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Deliberated Air Leakage of ResMed Ultra Mirage Full Face Mask

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Human Patient Simulator – Support Physiological Functions



HPS Mannequin + HPS Console + HPS Lab Rack

Figure: HPS system includes a mannequin, a control console and a lab rack (METI 2009).

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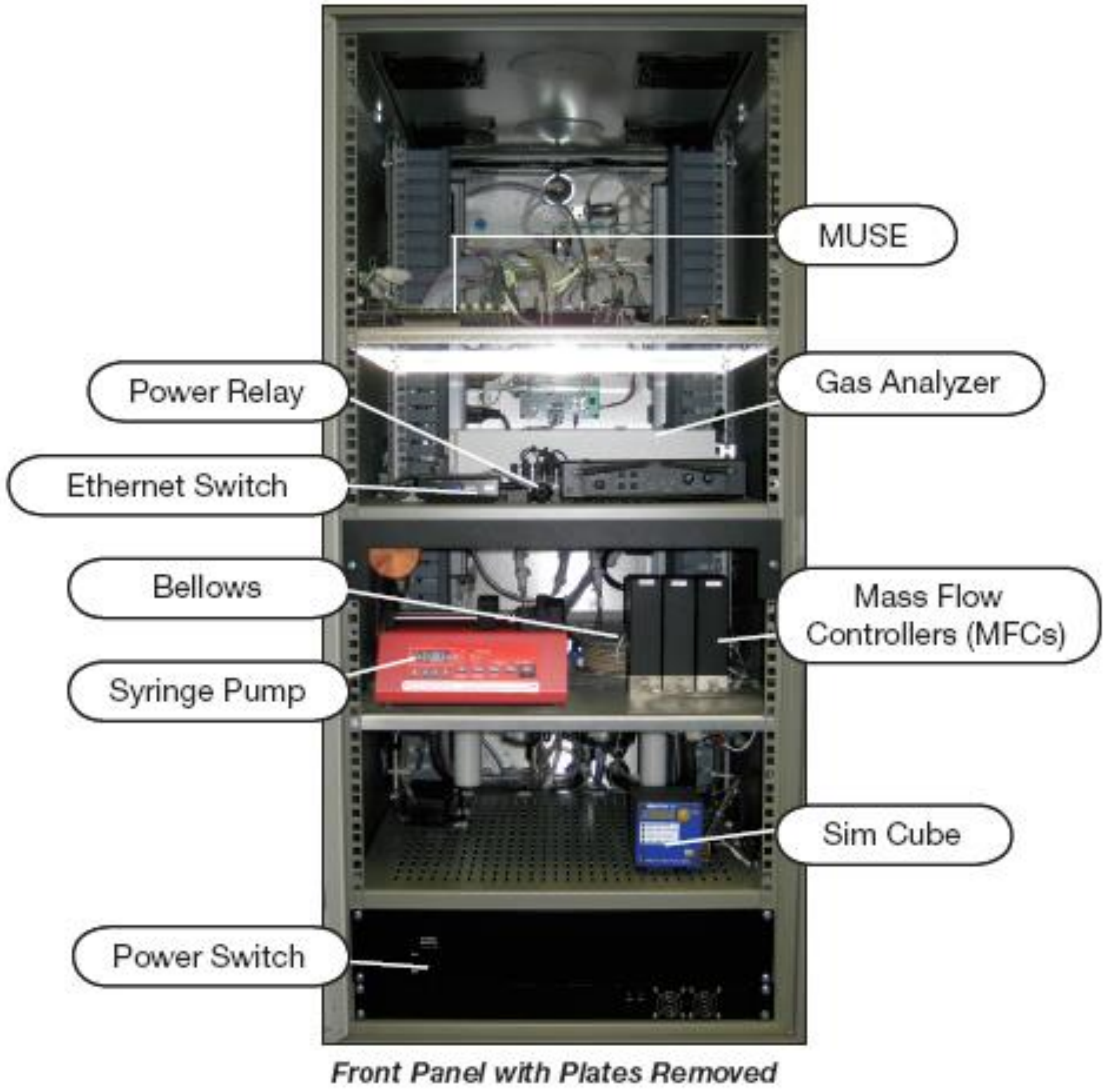
Human Patient Simulator – Support Physiological Functions



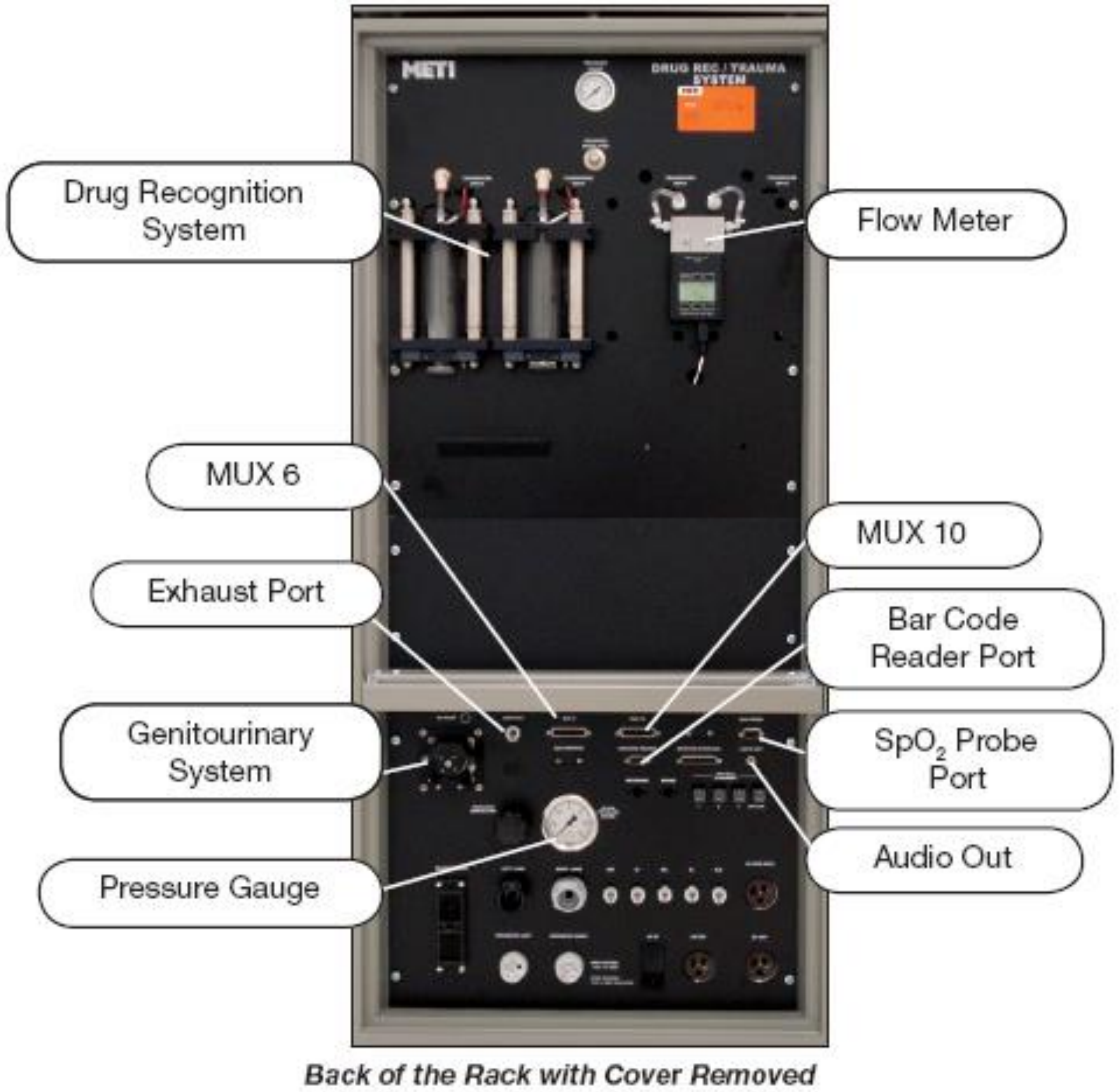


Figure: The HPS lab rack is equipped with sophisticated mechanical lung bellows and precise mass flow controllers to simulate the human airway and oxygen compliance physiology (METI 2009).

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Human Patient Simulator – Support Physiological Functions

Figure: HPS mannequin with realistic airway including oropharynx, nasopharynx and larynx for simulating human respiratory physiology.

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Human Patient Simulator – Support Physiological Functions

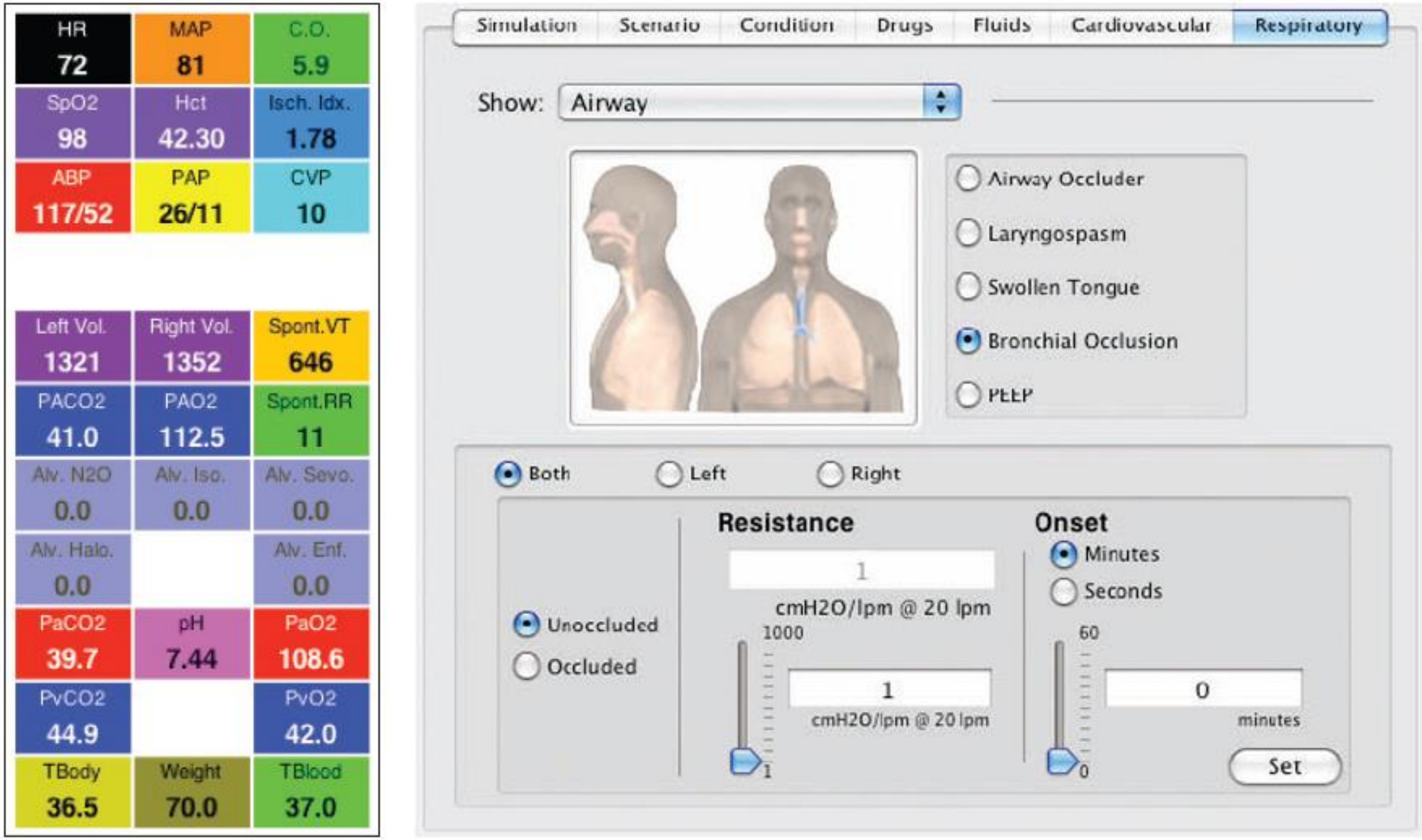

Figure: HPS system console can dynamically control the airway parameters, including variation of tidal volume, respiratory rate and oxygen consumption (METI 2009).

Dr. Benny CHOW
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Human Patient Simulator – Support Physiological Functions

Control Parameters	Normal Lung Condition	Mild Lung Injury	Severe Lung Injury
Oxygen consumption (ml/min)	200	300	500
Lung compliance (ml/cmH_2O)	70	35	10
Respiratory rate (breaths/min)*	12	25	40
Tidal volume (ml)*	700	300	150

* The respiratory rate and tidal volume were adjusted by the HPS program to achieve the target oxygen consumption and lung compliance.

Figure: Three different lung settings of the HPS applied in this study.

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Human Patient Simulator – Support Physiological Functions

Figure: On-site equipment setup of the HPS, including HPS lab rack and HPS control console with supporting accessories.

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Human Patient Simulator – Support Physiological Functions

Figure: A mini device developed for the study to synchronize the mechanical movement of the HPS bellows with the laser imaging system (LIS).

Dr. Benny CHOW
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Quantitative Flow Visualization Analysis

Figure: Background intensity image with ambient lighting switched off for stray background light subtraction.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Quantitative Flow Visualization Analysis

Figure: Grey scale camera frames captured for light intensity analysis routine to generate normalized particle concentration contours.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Quantitative Flow Visualization Analysis

Mean of intensity $c := 1.3$ background reducer $\min(AG) = 7$ $\max(AG) = 255$

$$AM_{i,j} := \frac{A_{i,j}}{N} - \frac{AG_{i,j}}{c}$$ subtract background later

$\min(AM) = -56.185$ $\max(AM) = 205.058$

Checkmean concentration contours

$P := 2$ squarepixel summing region $\text{rows}(AM) = 720$ $\text{cols}(AM) = 1280$

Counters

$Imax := \text{rows}(AM)$
$Jmax := \text{cols}(AM)$

$\frac{Imax}{P} = 360$ $\text{floor}\left(\frac{Imax}{P}\right) = 360$ $\text{rows}(AM) - \text{floor}\left(\frac{Imax}{P}\right)\cdot P = 0$ pixelsat bottom edge ignored

$\frac{Jmax}{P} = 640$ $\text{floor}\left(\frac{Jmax}{P}\right) = 640$ $\text{cols}(AM) - \text{floor}\left(\frac{Jmax}{P}\right)\cdot P = 0$ pixelsat right edge ignored

$i := 1..\text{floor}\left(\frac{Imax}{P}\right)$ $j := 1..\text{floor}\left(\frac{Jmax}{P}\right)$

Meancalculation

$BX_j := \frac{P}{2} + (j-1)\cdot P + 0.5$ x ypixel values at center of square region

$BY_i := \frac{P}{2} + (i-1)\cdot P + 0.5$

$$IM_{i,j} := \frac{\sum_{b=1}^{P}\sum_{a=1}^{P} AM_{a+(i-1)\cdot P,\, b+(j-1)\cdot P}}{P\cdot P}$$

$\min(IM) = -19.832$ $\max(IM) = 197.068$

Proportionalise $IMave := 130$

$$IM_{i,j} := \frac{IM_{i,j}}{IMave}$$

x y scaling correction

Centre point in pixels $Cx := 990$ $Cy := 506$

Magnification factor - pixels over 200 mm length on grid

Horizontal $PHleft := 282$ $PHright := 932$

$MH := \frac{800}{PHright - PHleft}$ $MH = 1.23076923$

Vertical $PVbott := 465$ $PVtop := 144$

$MV := \frac{400}{PVbott - PVtop}$ $MV = 1.24610592$

Magnification Factor

$MF := \frac{MH + MV}{2}$ $MF = 1.23843757$

Scaling $\min(BX) = 1.5$ $\max(BX) = 1279.5$ $\min(BY) = 1.5$ $\max(BY) = 719.5$
$\text{rows}(BX) = 640$ $\text{cols}(BX) = 1$ $\text{rows}(BY) = 360$ $\text{cols}(BY) = 1$

$BX_j := (BX_j - Cx)\cdot MF$

$BY_i := (BY_i - Cy)\cdot -MF$

$Z := 0$ Z plane

Convert to columns

$DX_{i,j} := BX_j$
$DY_{i,j} := BY_i$
$DZ_{i,j} := Z$
$DM_{i,j} := IM_{i,j}$

Combine mean in matrix C

$D := \text{stack}(DX, DY, DZ, DM)$

WRITEPRN("cmean.prn") := D Nolines in C $\text{rows}(BY)\cdot\text{rows}(BX) = 230400$

VARIABLES= "X""Y""Z""Cmean"
ZONE T="01" I=no.lines F=BLOCK

Figure: MathCAD routines developed for the calculation of ensemble-averaged intensity and normalized particle concentration contours.

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Quantitative Flow Visualization Analysis

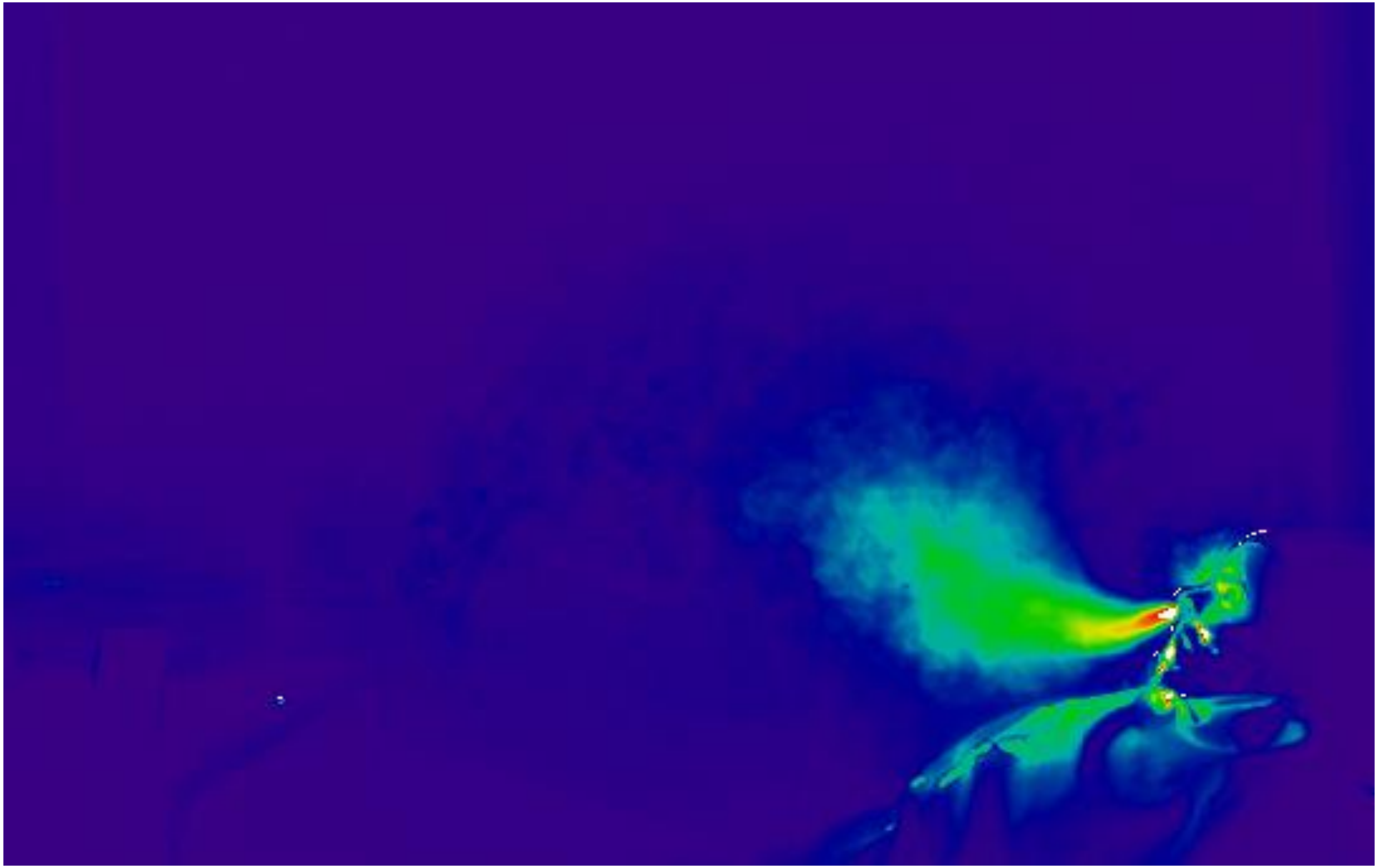

Figure: Normalized concentration contour after the background light subtration and intensity averaging routine.

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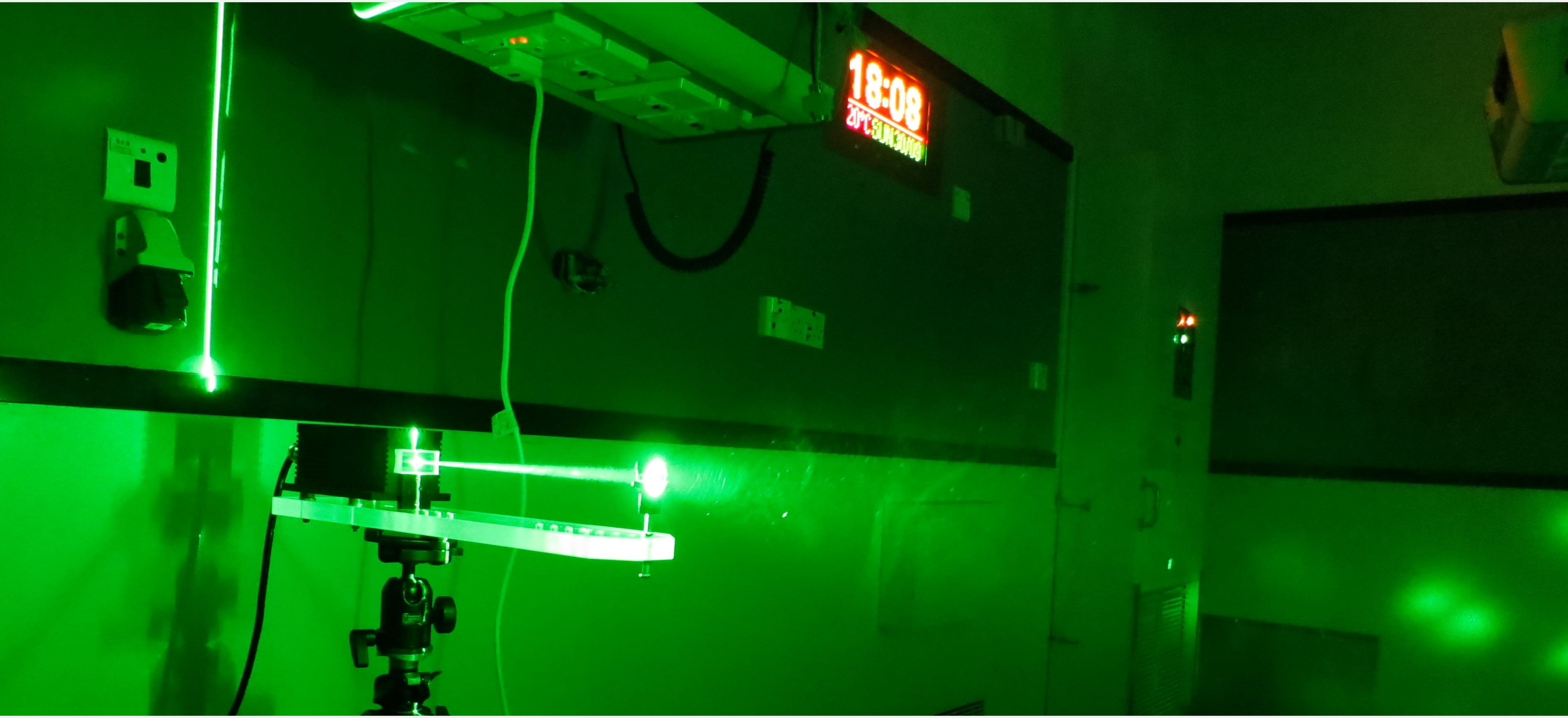
EXPERIMENTS ON DIFFERENT ISOLATION WARD DESIGNS



Negative Pressure Isolation Ward

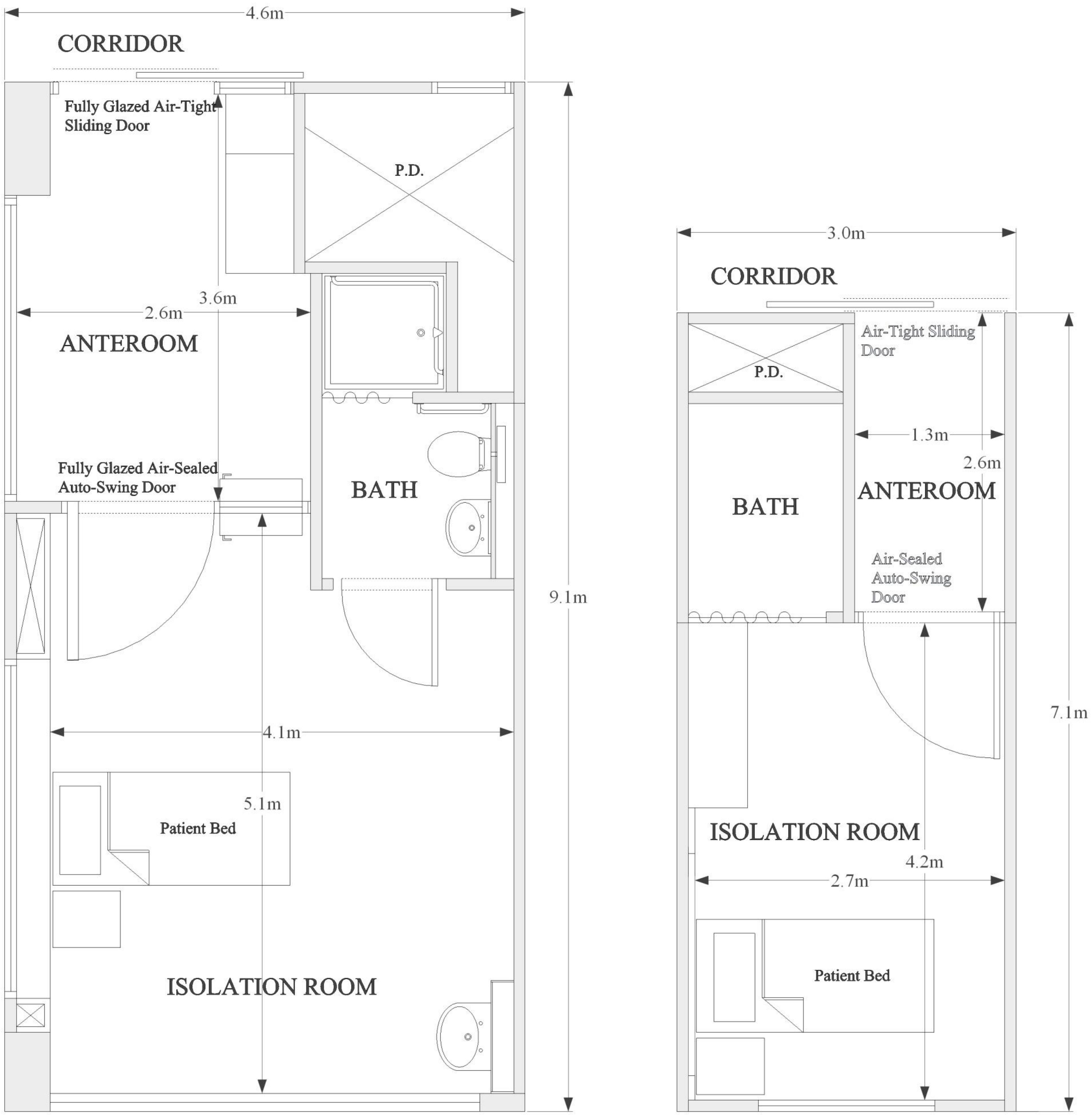


Figure: Isolation room A at PMH (left) and isolation room B of PWH (right) used in experiments.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Summary of the Configurations of the Isolation Rooms

Settings	Room A	Room B
Dimension (W x L x H)	4.1 x 5.1 x 2.6m	2.7 x 4.2 x 2.4 m
Pressure	-7 Pa	-5 Pa
Air changes per hour	16	12
Number of beds	1	1
Ambient temperature (C)	21.4 degree	23.4 degree
Relative humidity	62%	65%
Double exhaust fans	No	No

Figure: Summary of the patient ward configurations, geometries and physical settings for the experiments.

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Ventilation Performance of Isolation Room A

Figure: Room interior of the single patient bed isolation room for on-site measurement.

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(ASHRAE-HKC/Med.CUHK)

Ventilation Performance of Isolation Room A

Figure: Unoccupied isolation floor at PMH for the smoke particle experiment.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Ventilation Performance – Air Changes per Hour

Figure: The whole 7th floor of Infectious Disease Center at PMH holds large scale mechanical plants for supporting the air change and negative pressure requirements of AII rooms.

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Ventilation Performance – Air Changes per Hour

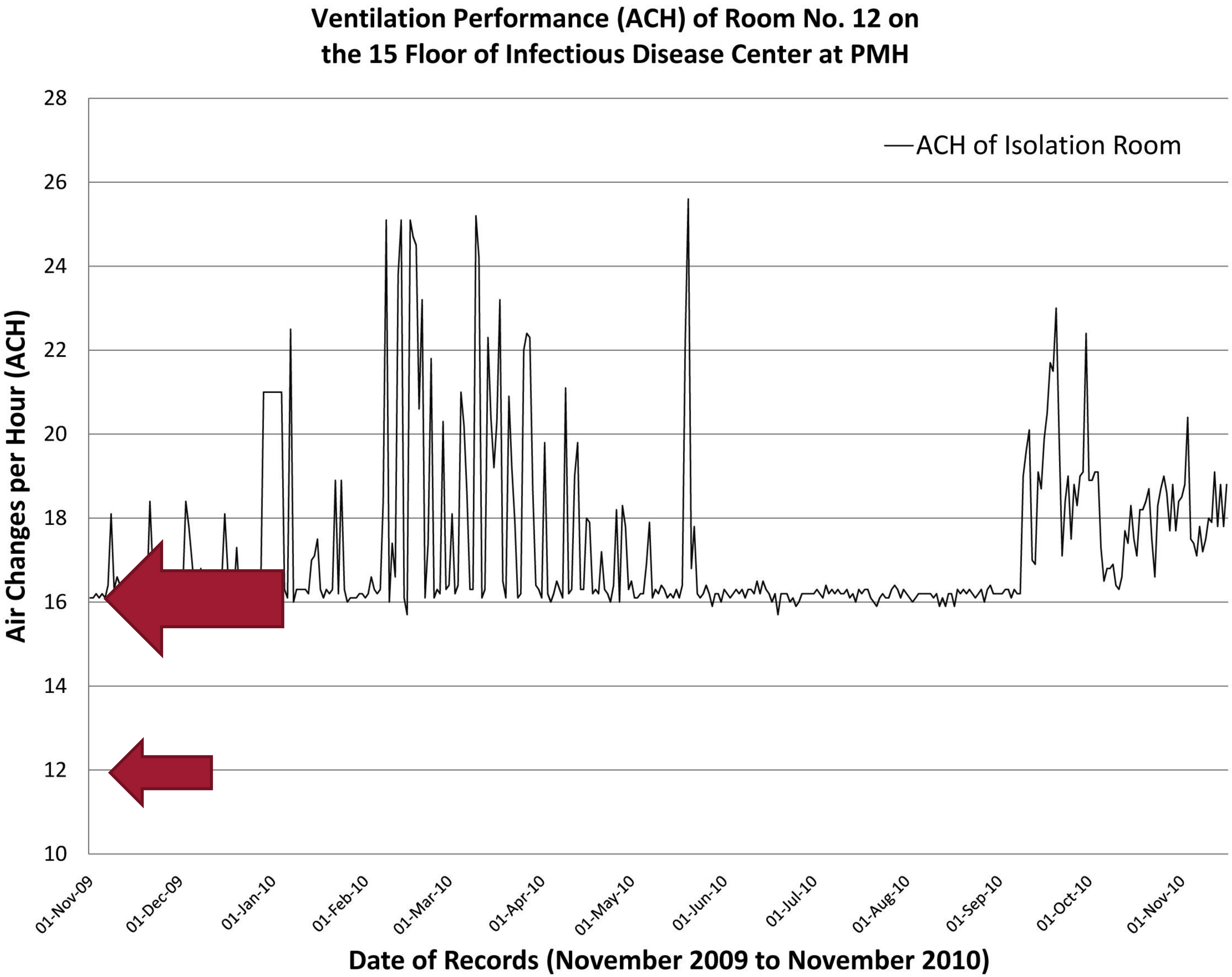

Figure: Ventilation performance of the isolation room A at PMH in daily averaged ACH.

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Ventilation Performance – Negative Pressure Control

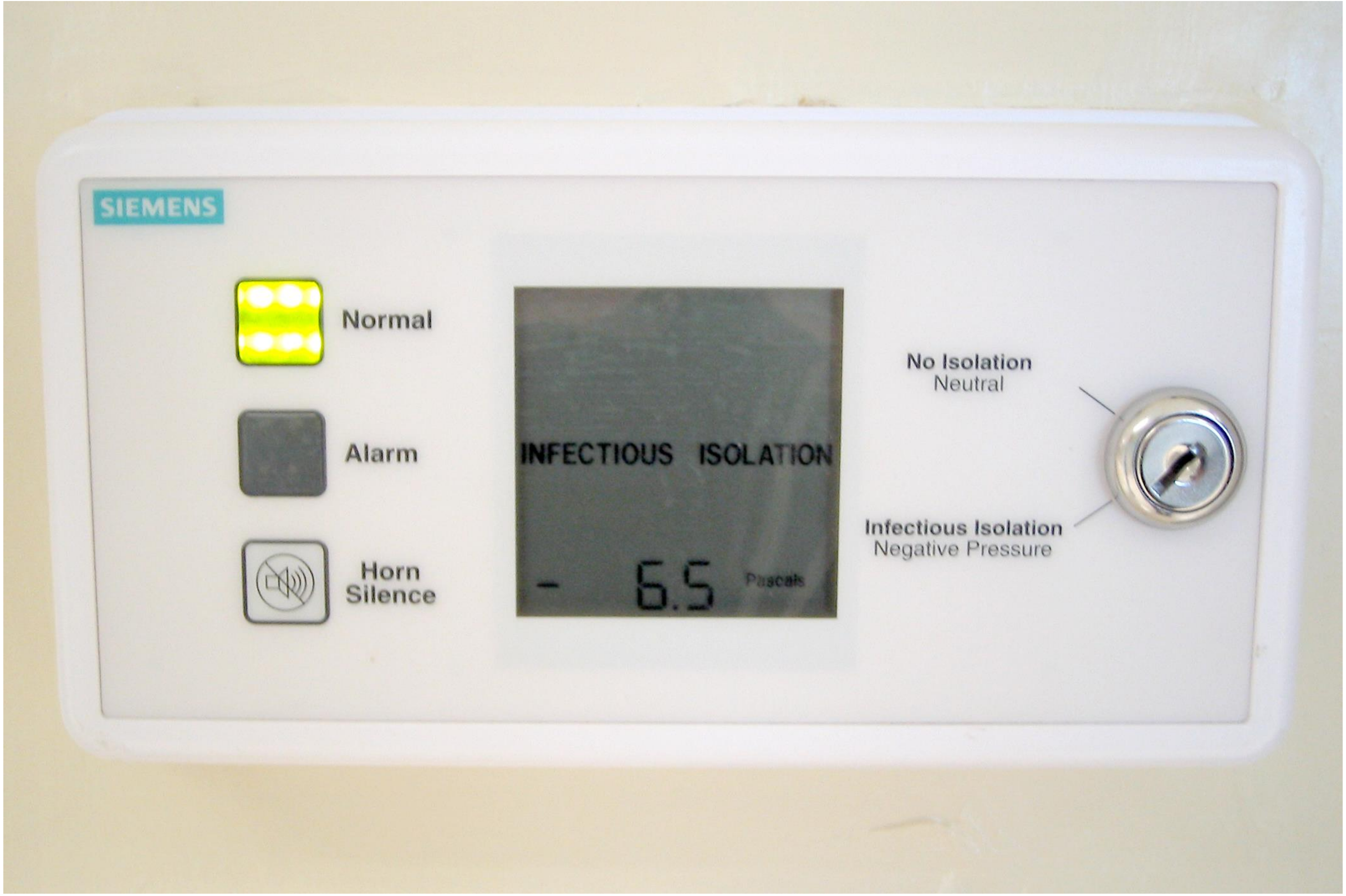

Figure: Front door panel for monitoring the negative pressure in the room.

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Ventilation Performance – Auto-Swing Door Closed

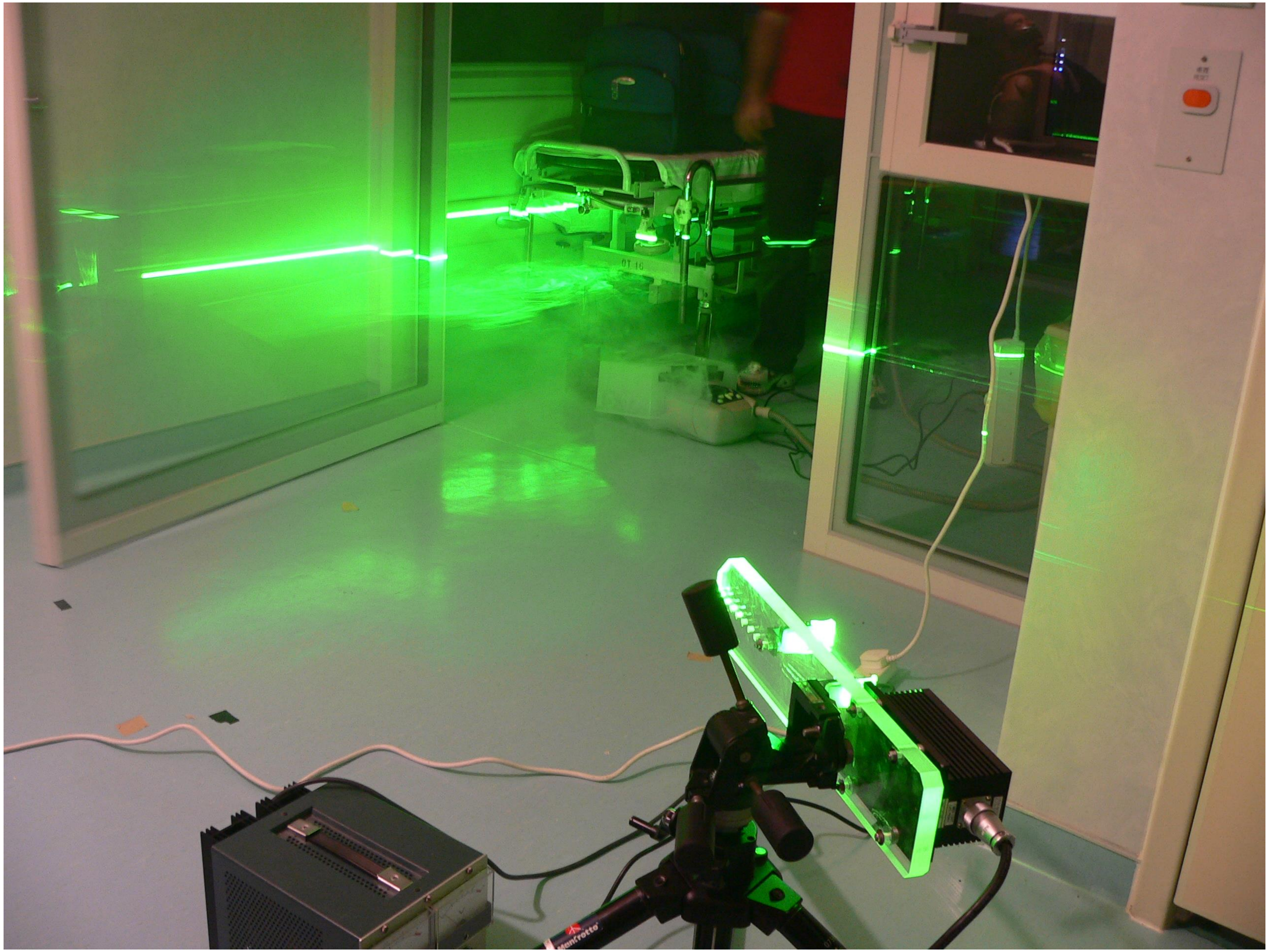

Figure: Laser light sheet parallel to the floor revealed the smoke particle movement between the anteroom and the patient room (viewing from patient room towards anteroom).

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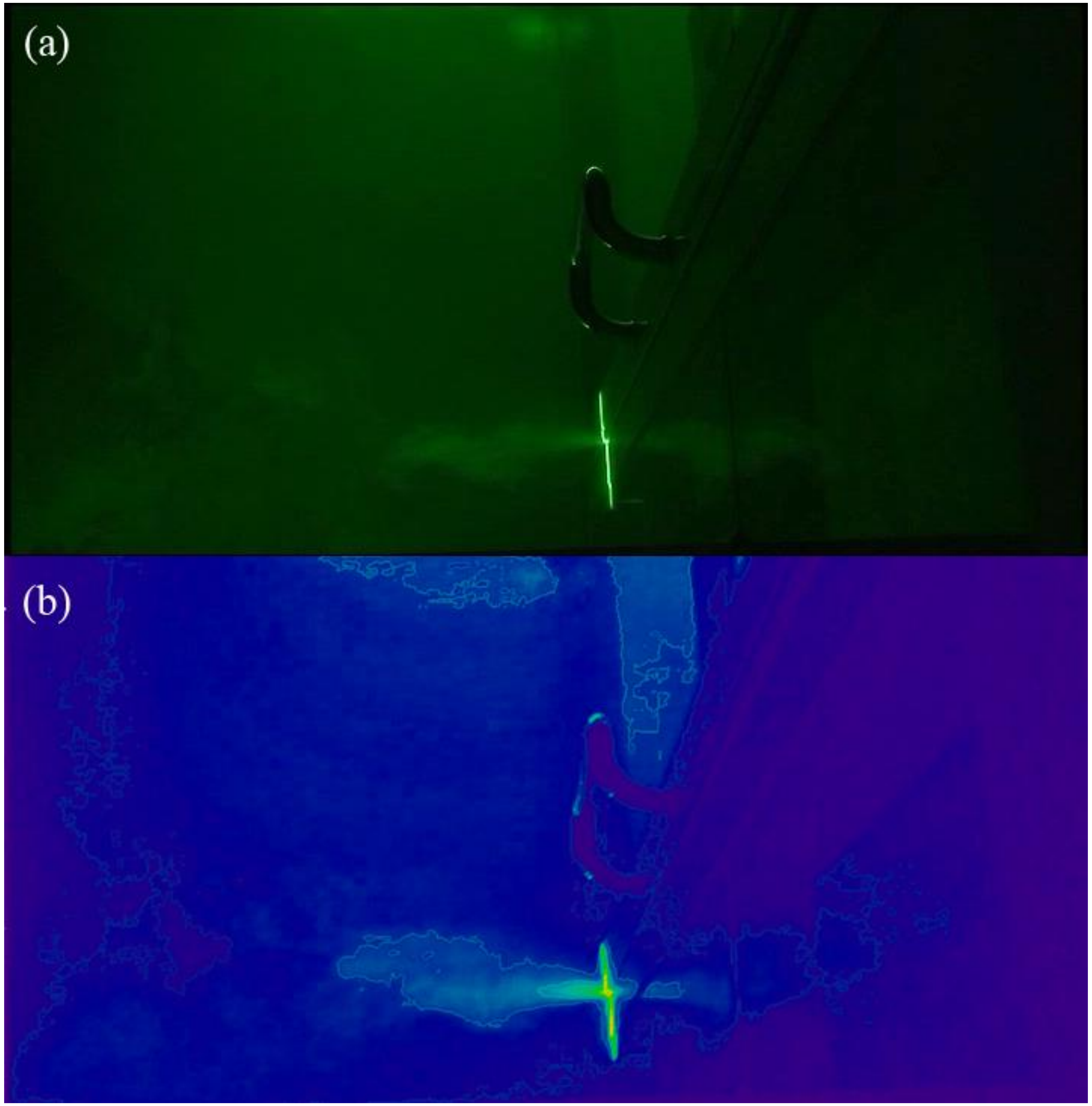
Ventilation Performance – Auto-Swing Door Closed



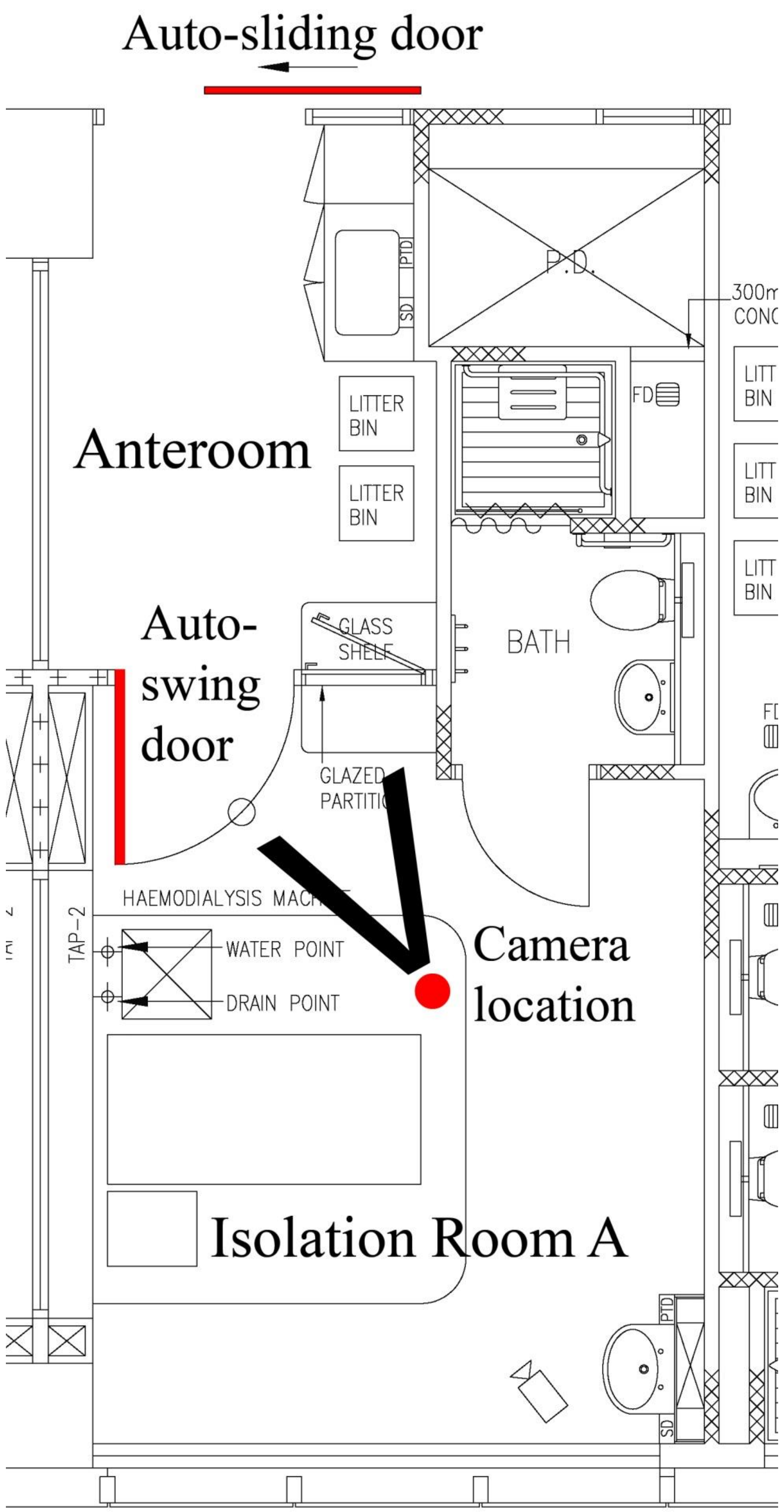


Figure: Laser flow visualization showing air enters in from the anteroom (right) to the patient room (left) from the door gap at the auto-swing door, (above) visual image (below) false color map of normalized smoke particle concentration.

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)

Experimental study on specialized ventilation system of airborne infection isolation room

Airflow Direction Control (view from patient ward to anteroom)

(Isolation Ward) **(Anteroom)**

(-ve Pressure) ← **(designated airflow direction)**

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Ventilation Performance – Auto-Swing Door is being Opened

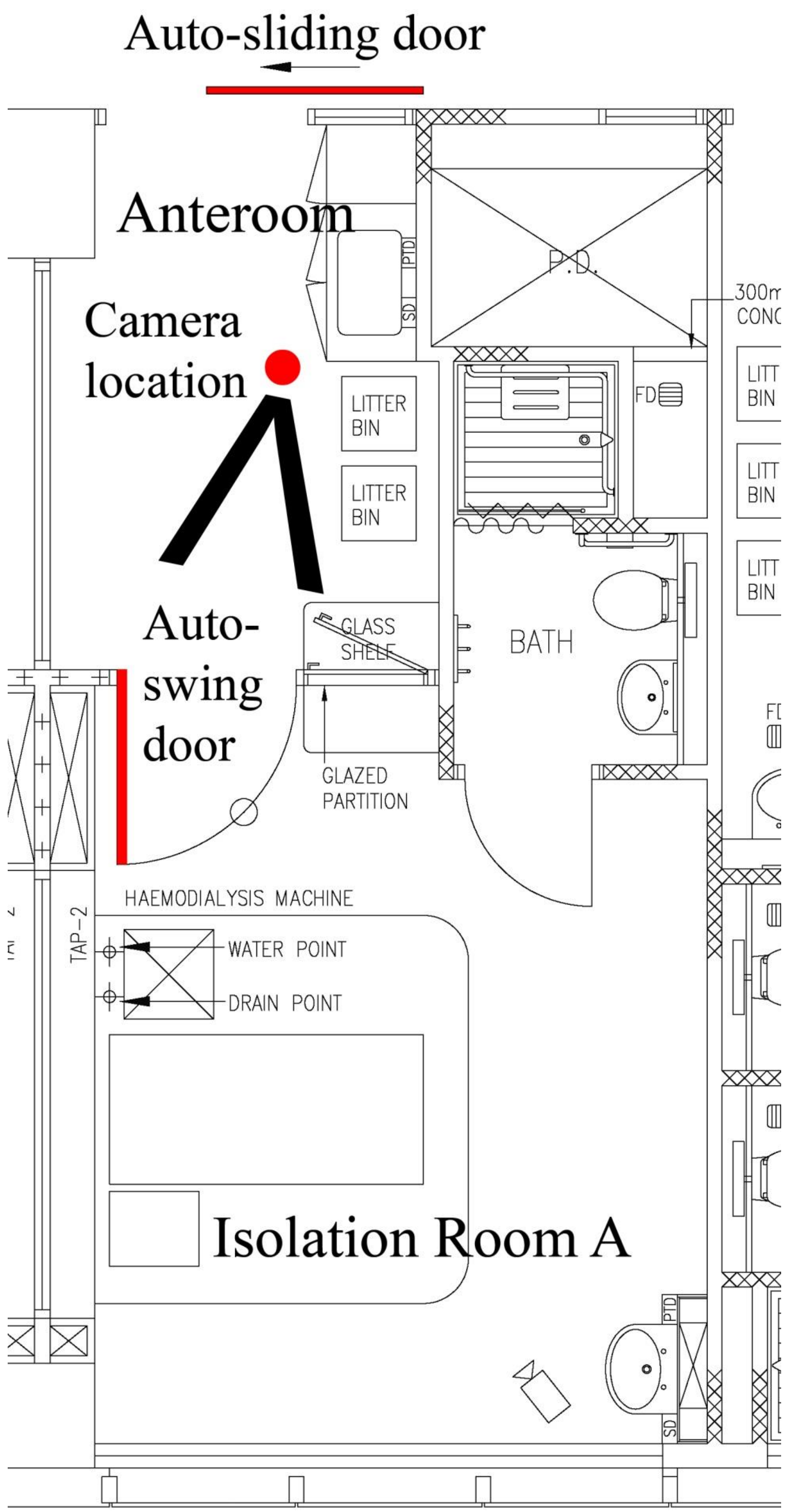

Figure: Laser flow visualization showing air enters in from the anteroom (right) to the patient room (left) from the door gap at the auto-swing door, (above) visual image (below) false color map of normalized smoke particle concentration.

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(ASHRAE-HKC/Med.CUHK)

Airflow Direction Control (view from anteroom to patient ward)

lOW
(ASHRAE-HKC/Med.CUHK)

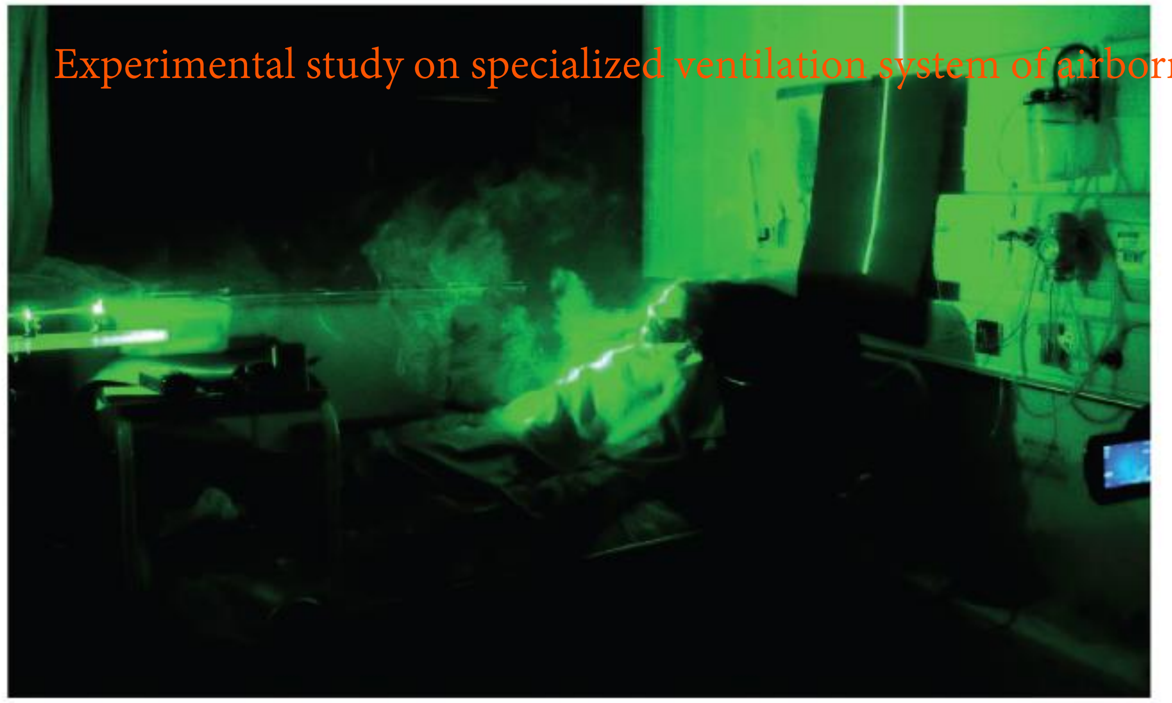


Figure 2 Room ventilation design and experimental set-up. The room (only room B is shown) is fitted with the downward ventilation systems. The design is to supply conditioned and clean air from the ceiling diffuser to sweep away contaminants, which would then be removed via the outlets at the floor level. Nasal cannulae were fitted to the human-patient simulator. The exhaled air plume was marked with intrapulmonary smoke, and was revealed by the laser light-sheet. The images were captured by a high-definition camera positioned to the left side of the simulator. Smoke concentration in the plume was estimated from the light scattered by smoke particles.

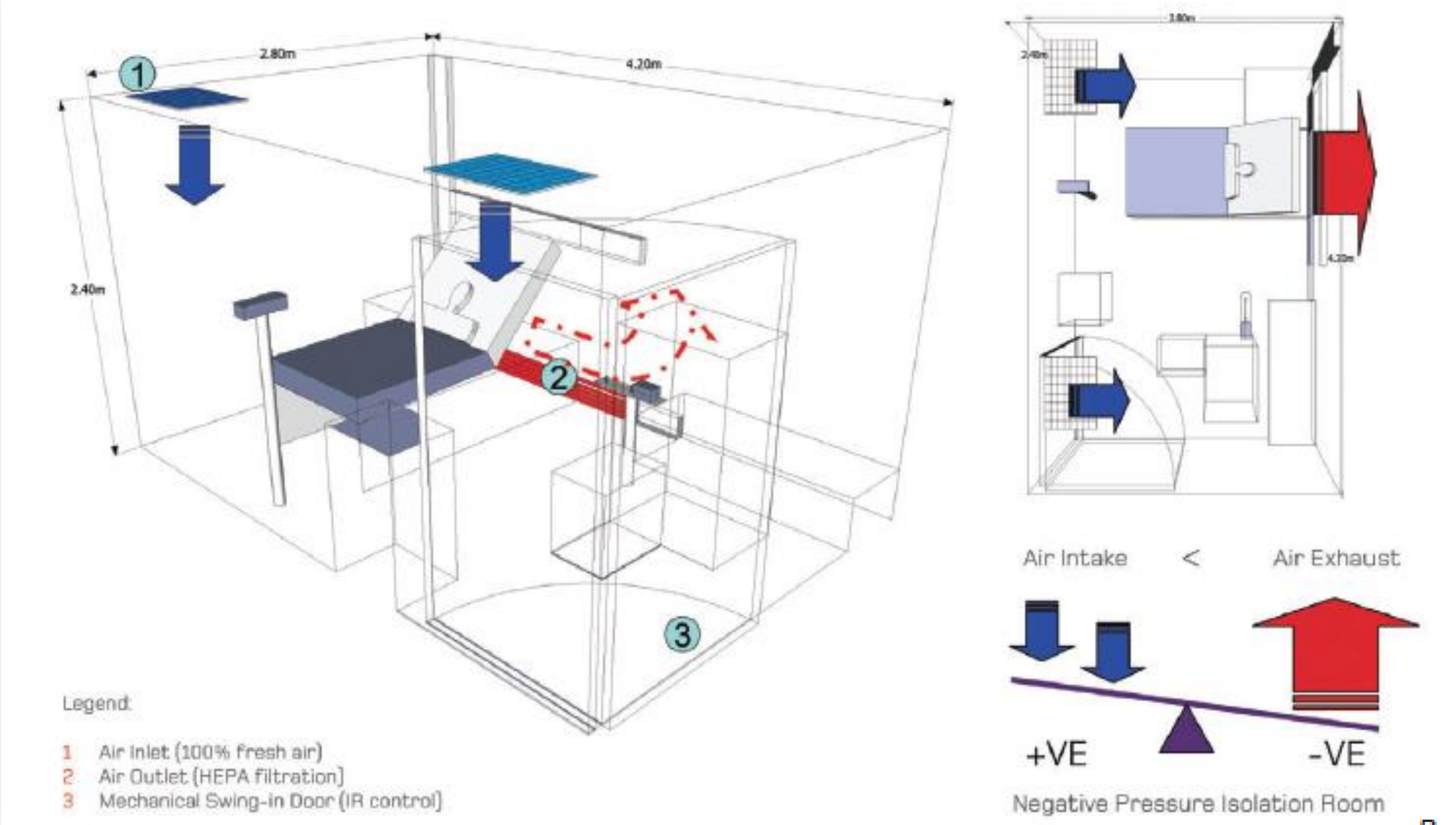
Respirology

ORIGINAL ARTICLE

Exhaled air dispersion and removal is influenced by isolation room size and ventilation settings during oxygen delivery via nasal cannula

David S. Hui,[1,2] Benny K. Chow,[3] Leo Chu,[4] Susanna S. Ng,[2] Sik-To Lai,[5] Tony Gin[4] and Matthew T.V. Chan[4]

[1]Stanley Ho Center for Emerging Infectious Diseases, Departments of [2]Medicine and Therapeutics, [3]Architecture and [4]Anaesthesia and Intensive Care, The Chinese University of Hong Kong, and [5]Department of Medicine and Geriatrics, Princess Margaret Hospital, Hong Kong, China



d the exhaled
delivery via
ator (HPS) in
rapulmonary
as gradually
sitting at 45°.
er light-sheet
video. Smoke
ted from the
experiments
tive pressure
× 5.1 × 2.6 m,
ges/h (ACH)
experiments
a dimension
and 12 ACH
read almost
f the HPS to
when oxygen
respectively.
he downward
d air from the
oke towards
As oxygen flow was increased gra

SUMMARY AT A GLANCE

This study demonstrates that larger isolation rooms with 16 air exchanges/h (ACH) are relatively better than the smaller isolation room with 12 ACH in air mixing and dilution ventilation for removing exhaled air from the patient and preventing room contamination during administration of oxygen therapy.

Key words: exhaled air dispersion, infection control, influenza, nasal cannula, severe acute respiratory syndrome.

INTRODUCTION

Respiratory failure is a major complication of emerging respiratory infections such as severe acute respiratory syndrome (SARS),[1,2] avian influenza H5N1[3] and pandemic influenza (H1N1) 2009 infection.[4] Rapid and effective oxygen delivery is an essential component in the clinical management of critically ill patients with respiratory failure. While mechanical ventilation via non-invasive positive pressure ventilation ... racheal intubation is required in the ...s, oxygen delivery via nasal cannula

Respirology (2011) 16, 1005–1013

Experimental study on specialized ventilation system of airborne infection isolation room

Experimental Setup – Effects of Different Room Settings

Figure: HPS sitting on a 45 degree inclined hospital bed with nasal cannula.

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(ASHRAE-HKC/Med.CUHK)

Experimental Setup – Effects of Different Room Settings

Figure: Experimental set-up, light sheet in sagittal plane at room B.

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(ASHRAE-HKC/Med.CUHK)

Room A:

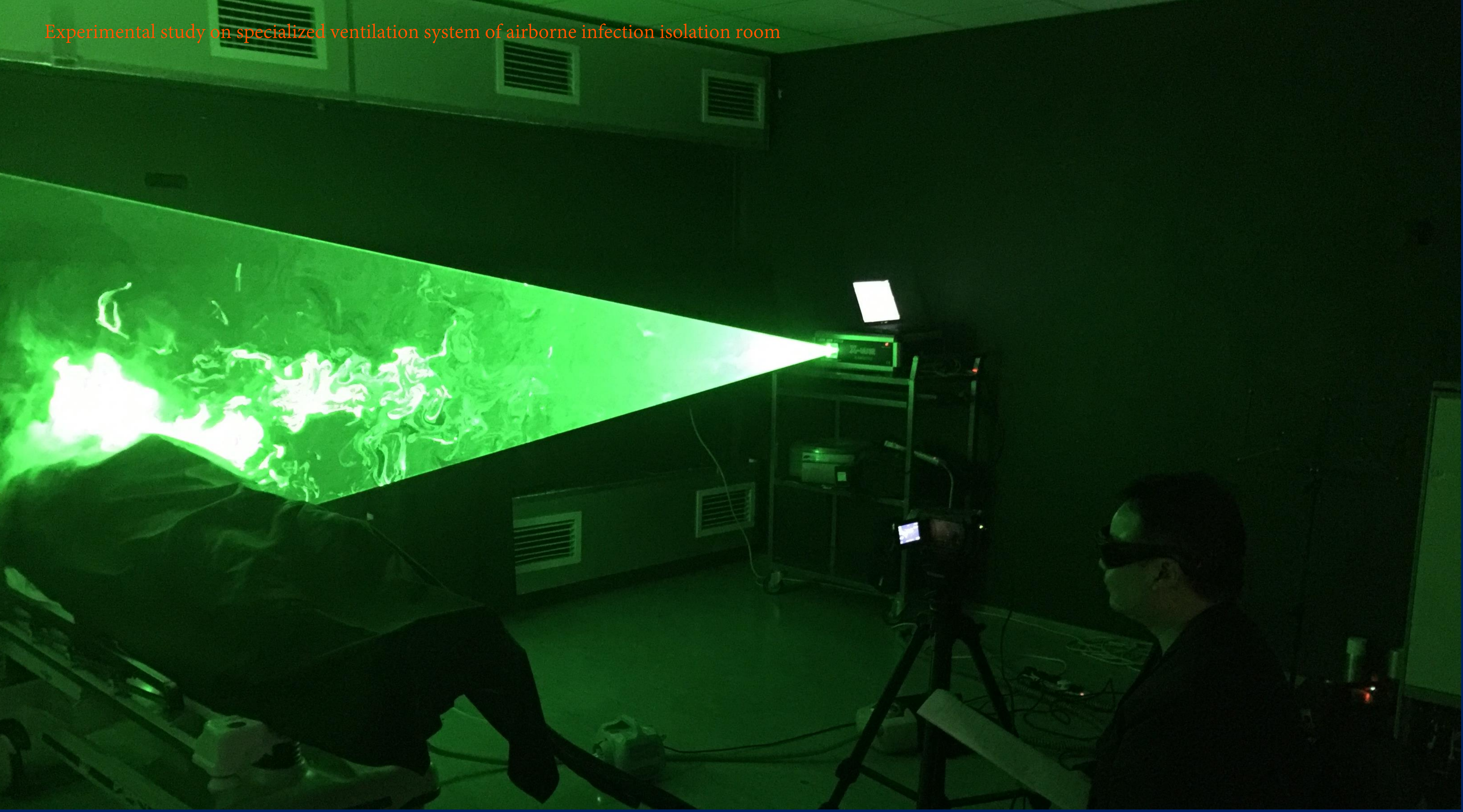
- Smaller room
- 12 ACH
- Turbulent flow ventilation system

Room B

- Larger room
- 16 ACH
- Downward laminar flow ventilation

Comparisons of floor vs ceiling vs mixed floor/ceiling level exhaust in a simulated isolation room in removal of exhaled air during aerosol-generating procedures

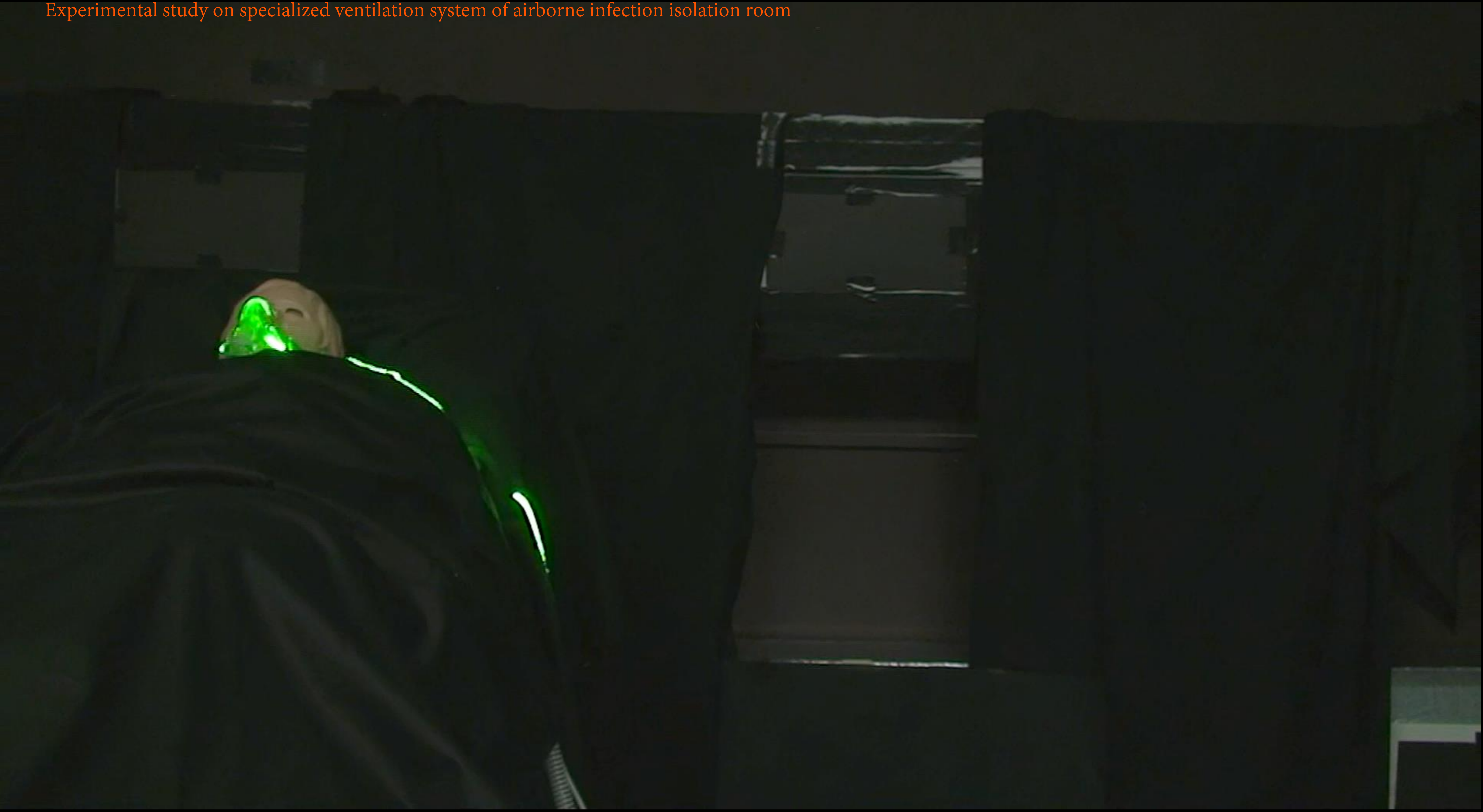
Rationale: Air exhaust is installed at the floor level in conventional negative pressure isolation rooms on the assumption that this would remove respiratory droplets effectively but the idea has not been proven objectively. We compared the exhaled air dispersion distances and directions during application of a jet nebulizer filled with water and driven by 6L/min of air on a high fidelity human patient simulator (HPS) in a simulated isolation room (6.0 x 6.7 x 2.6m (LWH)) with 12 ACH and the air exhaust located at a) ceiling level, b) floor level and c) both ceiling & floor levels.



Methods: The HPS was positioned at 45° and programmed to mimic different severity of lung injury. Airflow was marked with intrapulmonary smoke for visualization. A leakage jet plume was revealed by a laser light-sheet and images captured by high definition video.

Normalized exhaled air concentration in the plume was estimated from the light scattered by the smoke particles.

Significant exposure was arbitrarily defined as where there was ≥ 20% of normalized smoke concentration.

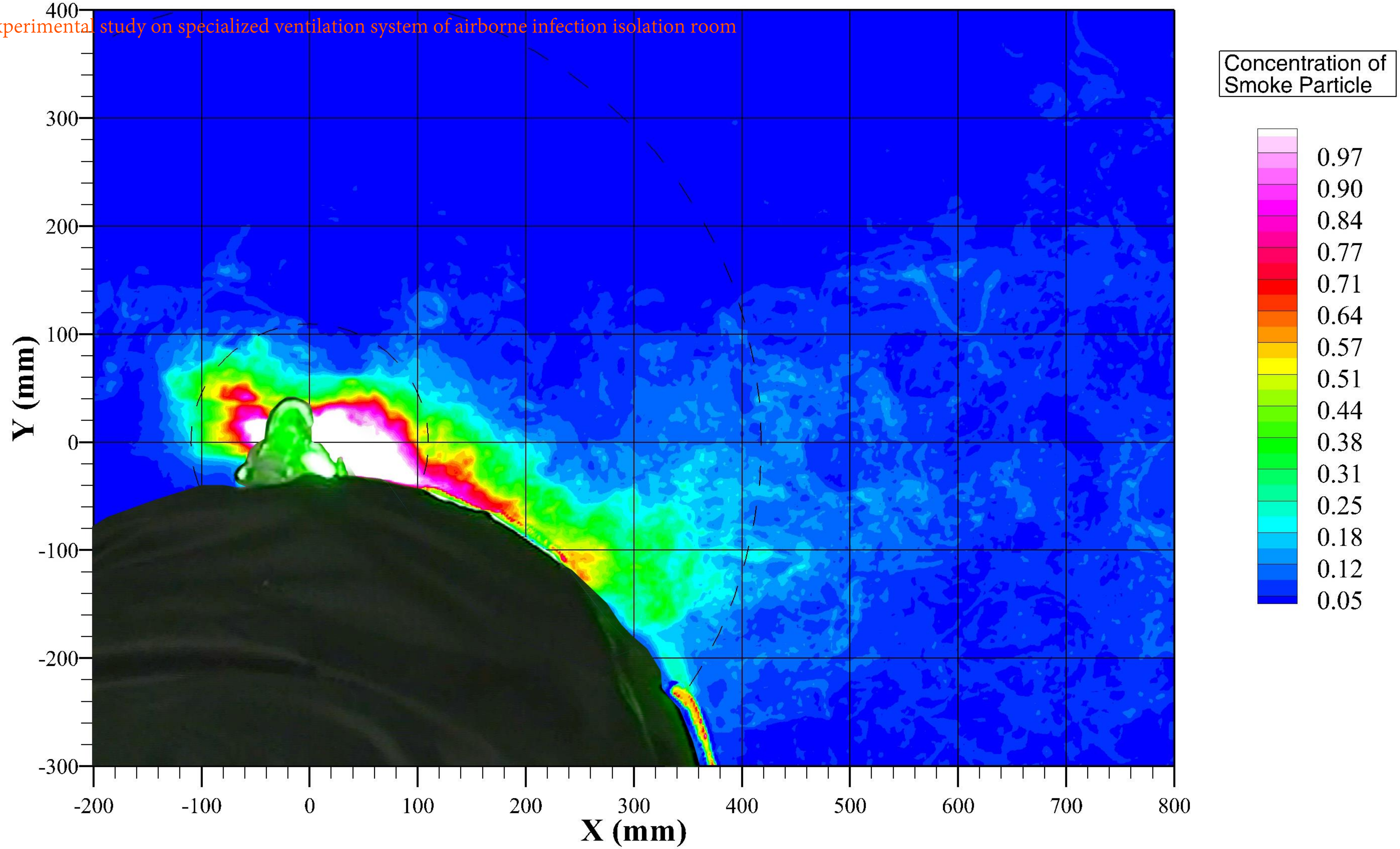


Application of a jet nebulizer to the HPS - Air exhaust located and operated at floor level led to longer exhaled air distance towards the floor but less spatial contamination at the breathing zone than ceiling level exhaust or a combination of ceiling and floor exhausts.
(David Hui et al)

Experimental study on specialized ventilation system of airborne infection isolation room

Application of a jet nebulizer to the HPS - Air exhaust located and operated at floor level led to longer exhaled air distance towards the floor but less spatial contamination at the breathing zone than ceiling level exhaust or a combination of ceiling and floor exhausts. (David Hui et al)

Experimental study on specialized ventilation system of airborne infection isolation room



Application of a jet nebulizer to the HPS - Air exhaust located and operated at floor level led to longer exhaled air distance towards the floor but less spatial contamination at the breathing zone than ceiling level exhaust or a combination of ceiling and floor exhausts.

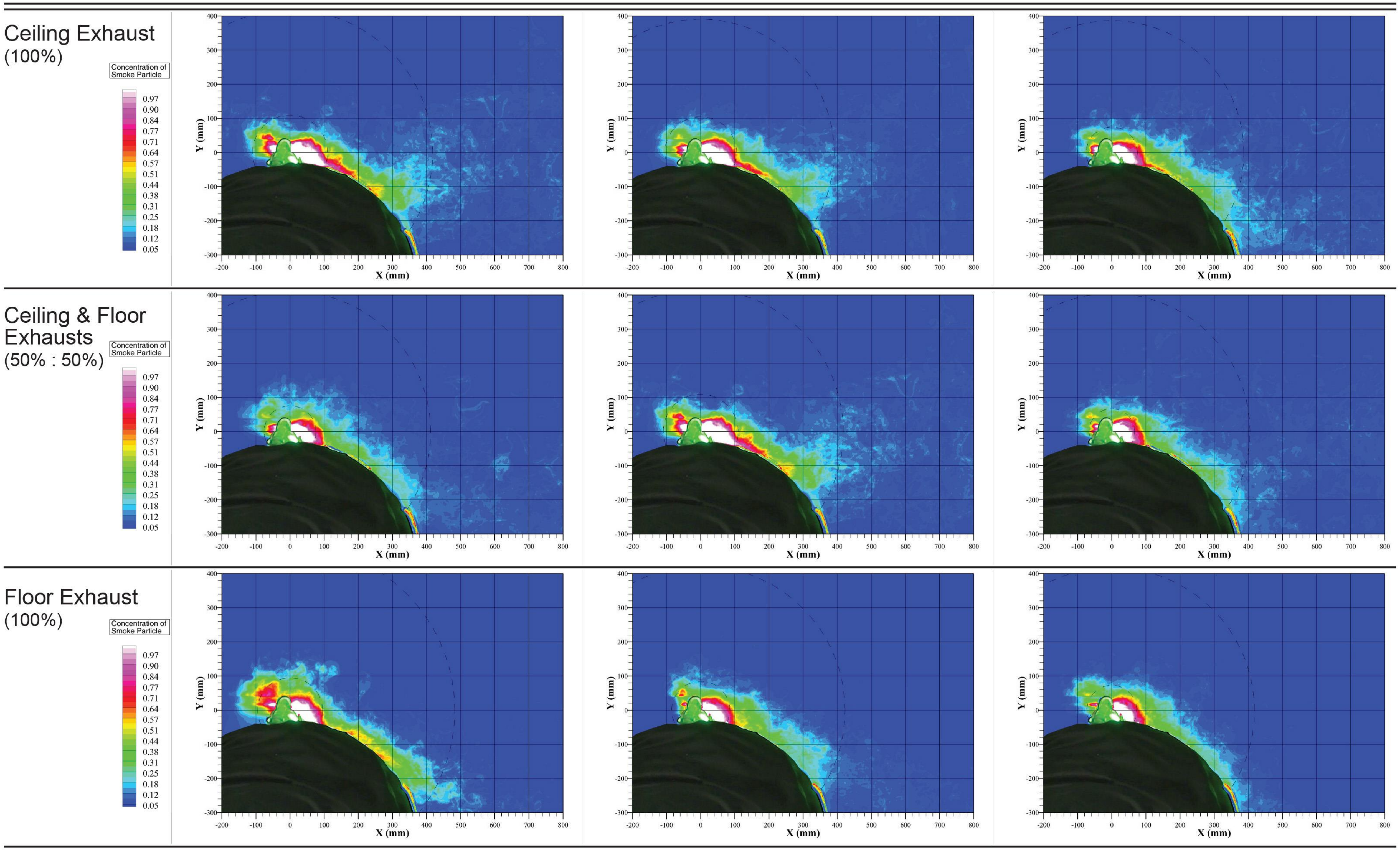
(David Hui et al. Unpublished data)

Experimental study on specialized ventilation system of airborne infection isolation room

12 Air Change per Hour

Jet Nebulizer

(Exhaled leakage jet plume with smoke and droplet particles)



Normal Lung Condition
(700mL / 12 RR)

Mild Lung Injury
(300mL / 25 RR)

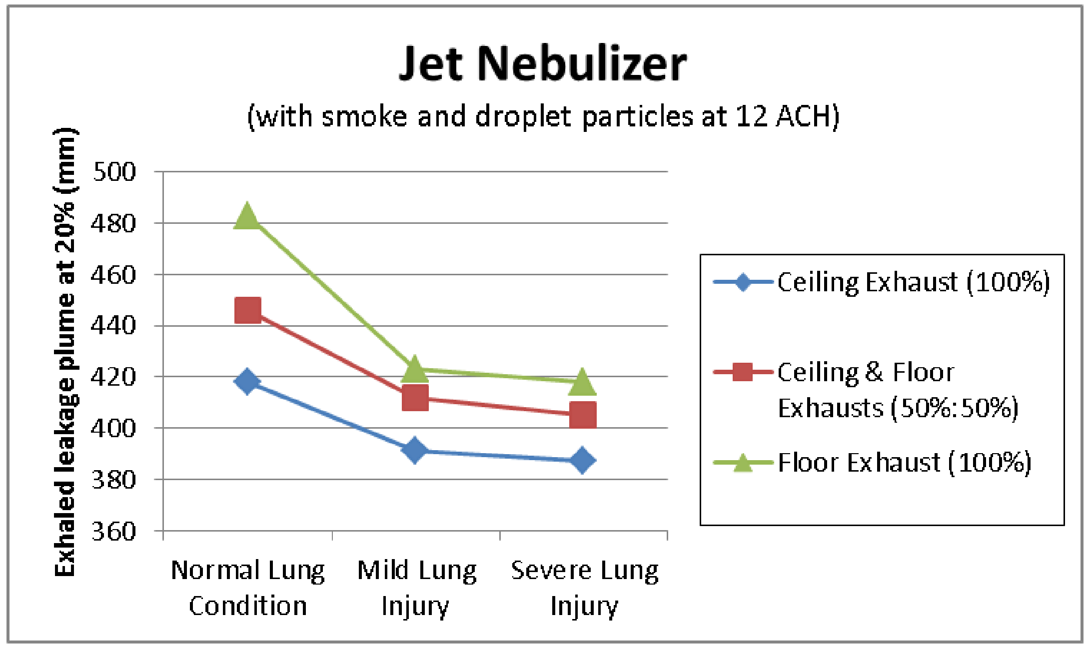
Severe Lung Injury
(150mL / 40 RR)

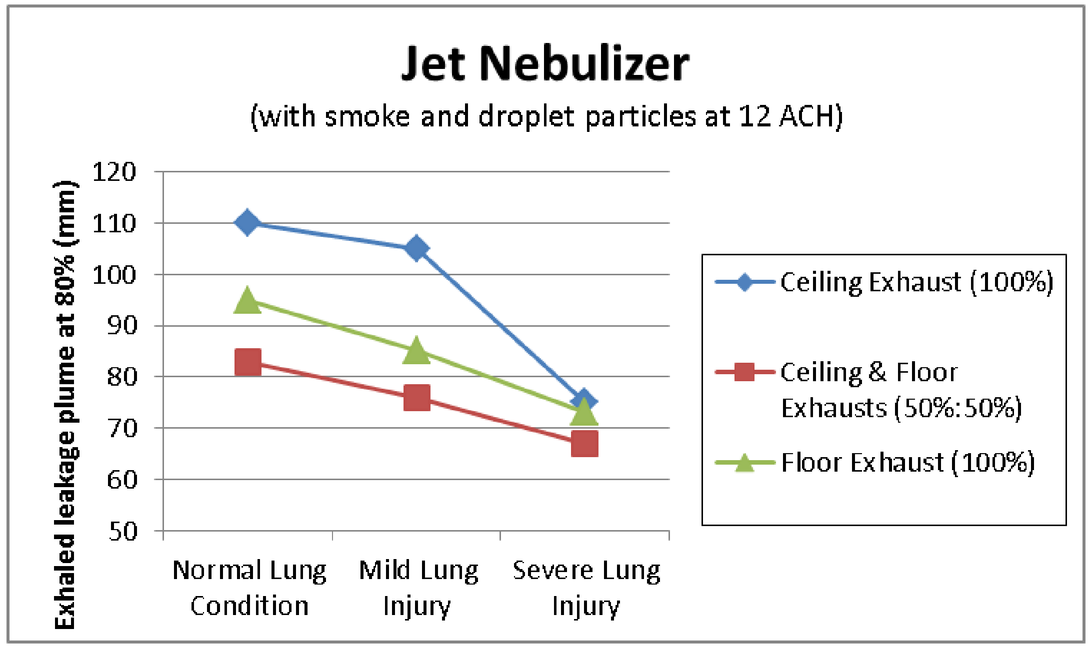
Application of a jet nebulizer to the HPS - Air exhaust located and operated at floor level led to longer exhaled air distance towards the floor but less spatial contamination at the breathing zone than ceiling level exhaust or a combination of ceiling and floor exhausts.

(David Hui et al. Unpublished data)

Jet Nebulizer (with smoke and droplet particles)

Jet Nebulizer (12 ACH)									
Distance at 20% (mm)	Ceiling Exhaust			A 50/50 Split Between Ceiling and Floor Exhausts			Floor Exhaust		
	S1 Normal	S2 Mild	S3 Severe	S4 Normal	S5 Mild	S6 Severe	S7 Normal	S8 Mild	S9 Severe
Mean Average Distance (mm)	418	391	387	446	412	405	483	423	418
SD	98	85	102	96	81	84	65	60	61



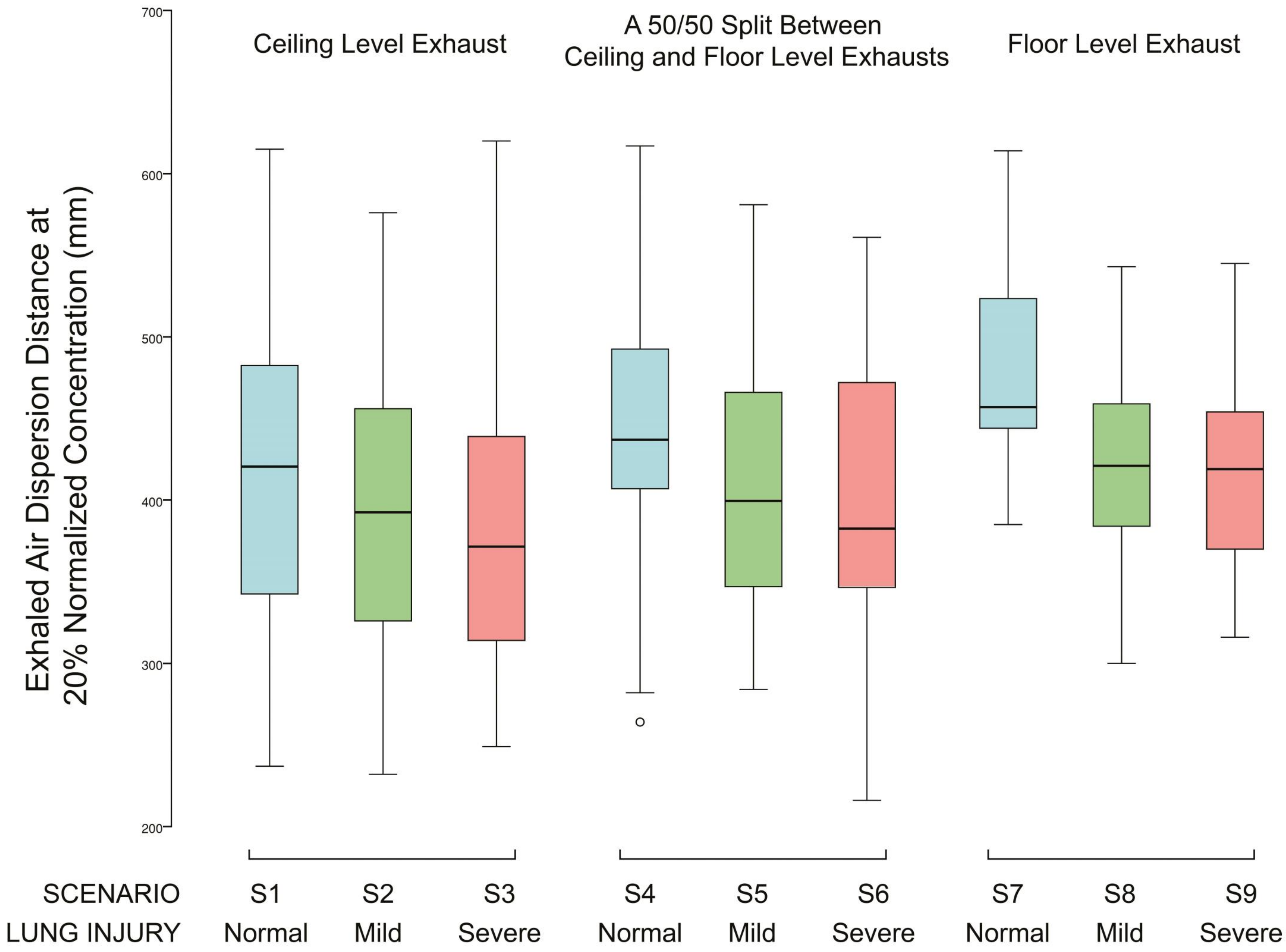


Application of a jet nebulizer to the HPS - Air exhaust located and operated at floor level led to longer exhaled air distance towards the floor but less spatial contamination at the breathing zone than ceiling level exhaust or a combination of ceiling and floor exhausts.

(David Hui et al. Unpublished data)

Experimental study on specialized ventilation system of airborne infection isolation room

Jet Nebulizer (with smoke and droplet particles)



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Self-portrait taken in PWH SARS Ward in 2003
Courtesy: Dr. Benny Chow

Wishing YOU Good Health and Happiness!

Dr. Benny CHOW
(ASHRAE-HKC/Med.CUHK)