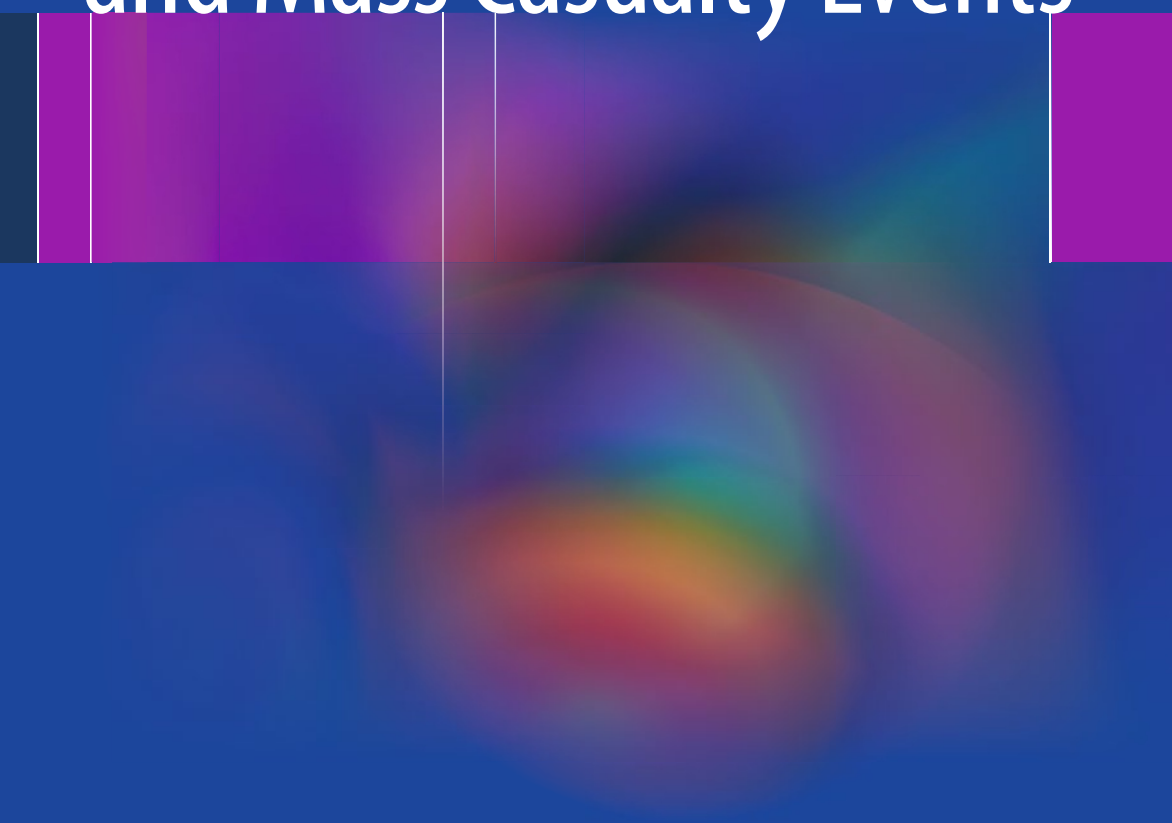
Antonio M. Esquinas *Editor*

Noninvasive Ventilation in High-Risk Infections and Mass Casualty Events



Springer

Noninvasive Ventilation in High-Risk Infections and Mass Casualty Events

Antonio M. Esquinas
Editor

Noninvasive Ventilation in High-Risk Infections and Mass Casualty Events

Springer

Editor
Antonio M. Esquinas, MD, PhD
Internacional Fellow AARC
Intensive Care and Non Invasive Ventilatory Unit
Hospital Morales Meseguer
Murcia
Spain

ISBN 978-3-7091-1495-7 ISBN 978-3-7091-1496-4 (eBook)
DOI 10.1007/978-3-7091-1496-4
Springer Wien Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013953862

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To my wife Rosario and daughters Rosana and Alba…
my source of inspiration

Preface

Pulmonary infections represent one of the main causes of development of severe acute respiratory insufficiency that requires hospital admission in pneumology wards and intensive care units. In this scenario, mechanical ventilation is cornerstone in severe forms.

However, some types of pulmonary infections are characterized by severity and high risk of contamination, especially for health personnel and debilitated critically ill patients. These high-risk pulmonary infections are characterized by their great capacity for rapid spread and mortality, as determined in the current and past pandemics as SARS, swine flu and the classical outbreak infections of pulmonary tuberculosis or legionella pneumophila. Lastly, some forms of bioterrorism and biochemical agents have been added as new potential source of acute respiratory failure affecting a great number of patients.

This is a continuum and permanent challenge to resolve to Emergency Medicine, Pneumology and Critical Care Medicine community.

In this last decade selection of more appropriate non-invasive therapeutic options may avoid complications associated with invasive mechanical ventilation as ventilator associated pneumonia and prolonged mechanical ventilation. In this scenario, non-invasive mechanical ventilation has been shown as growing practical and safe alternative.

However, there are no practical books that define appropriate criterias for selection, contraindications and rational preventive programs for pre and hospital health organization. In this book entitled *Noninvasive Ventilation in High-Risk Infections and Mass Causalities*, we discuss from a practical point of view, what is the role of non-invasive mechanical ventilation, best hospital organizational recommendations, protection mechanisms and patient care during non-invasive mechanical ventilation in patients suffering high-risk pulmonary infections and mass causalities.

Murcia, Spain — Antonio M. Esquinas

Acknowledgement

Thanks to all authors who have believed in this project and have made a huge effort to develop the content of these chapters, masterfully by combining science and practice. Without them we would never have been possible to develop this work.

To all patients we treat every day; they are part of this effort to encourage us to think that this book was necessary.

Contents

Abbreviations

ACPO	Acute cardiogenic pulmonary oedema
AGP	Aerosol generating procedures
AHRF	Acute hypoxemic respiratory failure
AIDS	Acquired immunodeficiency syndrome
ALI	Acute lung injury
APACHE II	Acute Physiology and Chronic Health Evaluation II
APRV	Release airway pressure ventilation
ARDS	Acute respiratory distress syndrome
ARF	Acute respiratory failure
ARF	Acute hypoxemic respiratory failure
ASB	Assisted spontaneous breathing
ATS	American Thoracic Society
AVAPS	Average volume assured pressure support
BAL	Bronchoalveolar lavage
BAS	Broncoaspiration
BiPAP	Bilevel nasal positive system
BiPAP (S/T)	Bilevel positive airway pressure (spontaneous/timed)
BTS	British Thoracic Society
CAP	Community Acquired Pneumonia
CDC	Center for Disease Control
CMV	Cytomegalovirus
CMV	Conventional mechanical ventilation
COPD	Chronic Obstructive Pulmonary Disease
CPAP	Continuous positive airway pressure
C_{rs}	Low respiratory system compliance
CT	Computed tomography
DAMPs	Danger associated molecular patterns
DPI	Days post inoculation
ECMO	Extracorporeal membrane oxygenation
EPAP	Expiratory positive airway pressure
ERS	European Respiratory Society
ESICM	European Society of intensive medicine
ETI	Endotracheal intubation

ETT	Endotracheal tube
EU FFP2	European Union Filtering Face-piece class 2
EVT	Exhaled tidal volume
FB	Fiberoptic bronchoscopy
FC	Flail chest
FiO_2	Inspired fraction of oxygen
FRC	Functional residual capacity
GRADE	Grading of Recommendations Assessment, Development and Evaluation
H1N1pdm09	Pandemic 2009 influenza A (H1N1) virus
HAART	Highly Active Antiretroviral Therapy
HCWs	Health care workers
HFC	High flux cannula
HFNC	High-flow nasal cannula
HH	Heated humidifier
HIV/AIDS	human immunodeficiency virus/acquired immunodeficiency syndrome
HME	Heat and moisture exchanger
HPS	Human simulator patient
ICU	Intensive Care Unit
IDSA	Infectious Diseases Society of America
ILV	Independent lung ventilation
IMV	Invasive mechanical ventilation
IPAP	Inspiratory positive airway pressure
ISB	Isothermic saturation boundary
ISO	International organization for standardization
ISS	Injury Severity Score
IV	Invasive ventilation
LFNC	Low-flow nasal cannulas
LM	Laryngeal mask
LRTI	Low respiratory tract infection
Ml/kg	Milliliters per kilogram
MOF	Multiorgan failure
MV	Mechanical ventilation
mWCAS	Modified Wilson clinical asthma score
NAVA	Neurally adjusted ventilatory assist
NIMV	Noninvasive mechanical ventilation
NIPPV	Non-Invasive Positive Pressure Ventilation
NIV	Non-invasive ventilation
NP	Nosocomial infection
PaO_2	Partial pressure of oxygen in arterial blood
PaO_2/FIO_2 ratio	Blood oxygen partial pressure/inspired oxygen fraction ratio
PBS	Protected brush specimen
PC	Pulmonary contusion

PCO_2	Carbon dioxide partial pressure
Pdi	Transdiaphragmatic pressure
PED	Pediatric emergency department
PEEP	Positive end expiratory pressure
P_{es}	Esophageal pressure
PICU	Pediatric intensive care unit
PIP	Peak inspiratory pressure
PMNs	Polymorphonuclear leukocytes
PPE	Personal Protective Equipment
PSV	Pressure Support Ventilation
PTP	Pressure time product
PTP di	Diaphragm pressure time product
RCTs	Randomized controlled trials
RH	Relative humidity
RHDCU	Respiratory high-dependency units
RR	Respiratory rate
RSV	Respiratory syncytial virus
SaO_2	Oxygen hemoglobin saturation
SAPS II	Simplified Acute Physiology Score
SARS	Severe acute respiratory syndrome
SARS-CoV	Severe acute respiratory syndrome-Coronavirus
SEMICYUC	Sociedad Española de Medicina Intensiva y Unidades Coronarias
TB	Tuberculosis
TBLB	Transbronchial lung biopsy
TLC	Total lung capacity
TNF α	Tumor Necrosis Factor α
UK	United Kingdom
US NIOSH	United States National Institute for Occupational Safety and Health
VA	Ventilatory assistance
VAP	Ventilator-Associated Pneumonia
VEGF	Vascular Endothelial Growth Factor
Vt	Tidal Volume
VZV	Varicella Zoster virus
WHO	World Health Organization
WOB	Work of breathing

Part I

Rationale and Equipment

High-Risk Infections: Influence of Down-Regulation and Up-Regulation of Cough Using Airway Reflexes and Breathing Maneuvers

1

Zoltan Tomori and Viliam Donic

Keywords

Acute respiratory failure • Aspiration pneumonia • Aspiration reflex • Expiration reflex • Coughing • Flu A (H1N1) • Breathing maneuvers

Coughing is a watchdog of the lungs. It represents the most important airway defensive reflex and one of the main symptoms of respiratory disease. During coughing and sneezing, particles of mucus can be expelled for a distance of up to 9 m [1]. Various pathogens, if present, may therefore infect nearby people and animals, contributing to massive dissemination of airborne infections. In addition to using various protective measures, down-regulation of coughing plays a substantial role in preventing dissemination of respiratory infections. For example, about 80 % of passengers on a 3-h airplane trip may be infected by the cough of an individual carrying the flu virus. These newly infected passengers then disseminate the viral infection at their destinations worldwide.

Protective and therapeutic actions are particularly urgent during a pandemic of influenza A (H1N1 virus), which mainly affects the most marginal and immunocompromised members of a population, including children. There are several pathophysiological forms of cough down-regulation [2] that can be applied during a flu pandemic.

The *D222G* mutation of the 2009 pandemic virus A (H1N1) caused destruction of the tracheobronchial ciliated cells as well as the bronchiolar and alveolar cells. This, in turn, disabled the clearing mechanisms of the lungs, which in Spain caused a 3.5-fold increase in the fatal outcome of the 2009 flu pandemic [3, 4].

Z. Tomori (✉) • V. Donic
Department of Physiology and Sleep Laboratory, Faculty of Medicine,
University of P.J. Safarik, Kosice, Slovakia
e-mail: zoltan.tomori@gmail.com

A.M. Esquinas (ed.), *Noninvasive Ventilation in High-Risk Infections and Mass Casualty Events*,
DOI 10.1007/978-3-7091-1496-4_1,

During the breathing cycle, the lung volume at the moment determines the actions of two alternating tendencies—inspiration and expiration—mediated by two distinct ventilatory reflexes. The reflexes are induced by stimulation of the airway and lung receptors, again depending on the lung volume and local pressure at the moment. At the early phase of inspiration, the lung volume is very low, just starting to increase gradually from its functional residual capacity (FRC). There is a strong general tendency to inspire at this point [5].

Inspiratory efforts can be provoked by various methods for stimulating airway rapidly adapting receptors (RARs). In cats, rapid inspiratory efforts can be evoked by nasopharyngeal stimulation, manifesting as the sniff- and gasp-like aspiration reflex (AspR) [1, 6–8] and by rapid lung inflation [5], which decreases the frequency and intensity of the subsequent expiratory efforts of cough and postpones them [9]. During gastroesophageal reflux or inhalation of irritant substances to the larynx, there is a strong "urge to cough" that can be voluntarily suppressed. To prevent aspiration of irritant substances into the lower airways, the necessary effort of coughing may be postponed by a previous, very slow voluntary inspiration followed by breath-holding and swallowing of the bolus to the esophagus. Only then can the effort to cough be initiated for expulsion of irritants from the airways [10–12]. Similar voluntary cough suppression commonly decreases the disturbing effect of coughing during a concert. It can similarly strongly inhibit dissemination of airborne infections due to coughing. Such ventilatory maneuvers might be usefully applied to the fight against flu pandemics and other widespread respiratory infection outbreaks.

On the other hand, the increasing lung volume at and above the tidal volume (V_T) stimulates the slowly adapting receptors (SARs). Also, because of the Hering Breuer inspiration inhibiting reflex (HBIIR), after inspiratory "switch-off" the V_T induces the expiratory phase. The tendency to expire is strong at the end of tidal inspiration [5]. Therefore, stimulation of laryngeal RARs interrupts the inspiration and evokes laryngoconstriction and the expiration reflex (ExpR) [1, 7, 8]. Additionally, an inspired or inflated volume above the normal V_T or blockade of lung deflation at the beginning of expiration by positive pressure can adequately speed up and increase the intensity of the subsequent expiratory effort. It is caused by stimulation of airway receptors and manifests as the Hering Breuer expiration facilitating reflex (HBEFR) [5].

Hyperinflation or occlusion of airways and hindering lung deflation by a ventilator or a pressure pulse provokes the ExpR and the cough reflex (CR). Such rapid expiratory efforts might promote expulsion of infected mucus, preventing its protrusion from the larynx to the lungs and preclude, or at least postpone, the development of dangerous aspiration pneumonia [13]. A proposed voluntary breathing maneuver consists of several rapid sniffs with a closed mouth of 0.5 s duration, each followed by forced expiration lasting about 3 s. Such a maneuver might save many lives and improve the quality of life of millions of people worldwide during imminent flu pandemics or other widespread respiratory infections. The early inspiratory sniffs and other spasmodic inspirations, including provocation of the AspR, result in down-regulation of coughing and may substantially retard a flu or other respiratory infection pandemic.

Rapid reflex or voluntary hyperinflation or occluded lung deflation—started at the early expiratory phase by pressure pulses—may result in reflex up-regulation of cough due to stimulation of airway receptors and mediated by HBEFR [5]. Such up-regulation may prevent, or at least postpone, the development of mostly fatal aspiration pneumonia. The sniff- and gasp-like AspR provoked by nasopharyngeal stimulation in anesthetized cats decreased the number and intensity of cough efforts provoked in the tracheobronchial region [9]. Similarly, the urge to cough may be suppressed, and even the motor act of coughing might be inhibited or at least postponed by voluntary action, helping to decrease the dissemination of airborne infections [11, 12]. Rapid, deep breaths through the nose, but not through the mouth, have bronchoprotective and bronchospasmolytic effects in probands and patients with mild bronchial asthma. This bronchoprotective effect in humans requires rapid inspiratory airflow [14, 15]. The sniff-like voluntary inspiration decreases the bronchoconstriction detected by one-second forced expiratory volume (FEV_1), induced by metacholine inhalation in adult asthmatics [16] and decreased the number of coughs provoked by capsaicin inhalation in young asthmatics [17]. These results indicate a reflex origin of the bronchodilator effect of nasopharyngeal stimulation, which decreases in parallel with bronchodilation and bronchoconstrictor-triggered coughing [18]. Taking advantage of voluntary airway reflexes and ventilatory maneuvers have many important practical applications [19]. They include detection of preparatory movement activity in the premotor area in persons in a vegetative state [20, 21]. The control of wheelchairs by trained paraplegics [22] can be reproduced by voluntary performance of aspiration and expiration reflexes, representing binary signals [19]. Gasping respiration developing in animals can provide autoresuscitation for few minutes even during cardiac arrest [23]. Therefore, provocation of the gasp-like AspR persisting even in agonal state or voluntary sniffs, might provide autoresuscitation in emergency situations [7, 19].

References

1. Korpáš J, Tomori Z. Cough and other respiratory reflexes. Basel/Munchen/New York/Sydney: J Karger; 1979. p. 356.
2. Widdicombe J, Singh V. Physiological and patho-physiological down-regulation of cough. Respir Physiol Neurobiol. 2006;150:105–17.
3. Rello J, Rodríguez A, Ibañez P, et al. Intensive care adults patients with severe respiratory failure caused by influenza A (H1N1)v in Spain. Crit Care. 2009;13:R148.
4. Ñamendys-Silva SA, Hernández-Garay M, Rivero-Sigarroa E. Non-invasive ventilation for critically ill patients with pandemic H1N1 2009 influenza A virus infection. Crit Care. 2010;14:407–8.
5. Marek W, Muckenhoff K, Prabhakar NR. Significance of pulmonary vagal afferents for respiratory muscle activity in the cat. J Physiol Pharmacol. 2008;59 Suppl 6:407–20.
6. Tomori Z, Widdicombe JG. Muscular, bronchomotor and cardiovascular reflexes elicited by mechanical stimulation of the respiratory tract. J Physiol. 1969;200:25–49.
7. Tomori Z, Poliaček I, Jakuš J, Widdicombe J, Donič V, Beňačka R, Grešová S. Distinct generators for aspiration and expiration reflexes: localization, mechanisms and effects. J Physiol Pharmacol. 2010;61:5–12.

8. Jakus J, Tomori Z, Stransky A. Neuronal determinants of breathing, coughing and other motor behaviours. Wist: Martin; 2004. p. 333.
9. Poliacek I, Jakus J, Simera M, Barani H, Visnovcova N, Halasova E, Tomori Z. Excitability and rhythmicity of tracheobronchial cough is altered by aspiration reflex in cats. J Physiol Pharmacol. 2009;60 Suppl 5:105–10.
10. Davenport P. Urge to cough: what can it teach us about cough. Lung. 2008;186(S1):107–11.
11. Vertigan AE, Gibson PD. Urge to cough and its application to the behavioral treatment of cough. Bratisl Lek Listy. 2011;112(3):102–8.
12. Hegland KW, Pitts T, Bolser DC, Davenport PW. Urge to cough with voluntary suppression following mechanical pharyngeal stimulation. Bratisl Lek Listy. 2011;112(3):109–14.
13. Addington WR, Stephens RE, Widdicombe JG, Anderson JW, Rekab K. Effect of tartaric acid-induced cough on pulmonary function in normal and asthmatic humans. Am J Phys Med Rehabil. 2003;82:374–8.
14. Scichilone N, Marchese R, Soresi S, Interante A, Togias A, Bellia V. Deep inspirations-induced changes in lung volume decrease with severity of asthma. Respir Med. 2007;101(5):951–6.
15. Scichilone N, Togias A. Deep inspiration-induced bronchoprotection is stronger than bronchodilation. Am J Respir Crit Care Med. 2000;162(3 Pt 1):910–6.
16. Legath L, Perecinsky S, Varga M, Orolin M, Tomori Z, Legath J. Latent airway hyperresponsiveness: a phenomenon bordering bronchial asthma definition. In: Pokorski M, editor. Respiration regulation – clinical advances, Advances in experimental medicine and biology, vol. 755. New York: Springer; 2013. p. 97–101.
17. Pecova R, Michnova T, Fabry J, Zatko T, Neuschlova Klco P, Hanacek J, Tatar M, Tomori Z. Deep nasal inspirations increase the cough threshold in children in mild asthma. In: Pokorski M, editor. Respiration regulation – clinical advances, Advances in experimental medicine and biology, vol. 755. New York: Springer; 2013. p. 65–9.
18. Ohkura N, Fujimura M, Tokuda A, Hara J, Hori A, Nishitsuji M, Abo M, Katayamam N. Bronchodilator effect of deep inspiration and bronchoconstriction-triggered cough. Cough. 2009;5:9. doi:10.1186/1745-9974-5-9.
19. Tomori Z, Donic V, Benacka R, Gresova S, Peregrim I, Kundrik M, Pallayova M, Jakus J. Reversal of functional disorders by aspiration, expiration, and cough reflexes and their voluntary counterparts. Front Physiol. 2012;3:467. doi:10.3389/fphys.2012.00467.
20. Simonyan K, Saad ZS, Loucks TM, Poletto CJ, Ludlow CL. Functional neuroanatomy of human voluntary cough and sniff production. Neuroimage. 2007;37:401–9.
21. Bekinschtein TA, Manes FF, Villarreal M, Owen AM, Della-Maggiore V. Functional imaging reveals movement preparatory activity in the vegetative state. Front Hum Neurosci. 2011. doi:10.3389/fnhum.2011.00005.
22. Plotkin A, Sela L, Weissbrod A, Kahana R, Haviv L, Yeshurun Y, Soroker N, Sobel N. Sniffing enables communication and environmental control for the severely disabled. PNAS. 2007;107:14413–8.
23. Xie J, Weil MH, Sun S, Yu T, Tang W. Spontaneous gasping generates cardiac output during cardiac arrest. Crit Care Med. 2004;32:238–40.

Noninvasive Mechanical Ventilation: Models to Assess Air and Particle Dispersion

2

David S.C. Hui

Keywords
Exhaled air • Dispersion • NIV • Influenza • SARS

2.1 Introduction

Respiratory failure is a major complication of viral infections such as severe acute respiratory syndrome (SARS) [1], avian influenza H5N1 infection [2], and the 2009 pandemic influenza (H1N1) infection [3]. The course may progress rapidly to acute respiratory distress syndrome (ARDS) and multi-organ failure, requiring intensive care. Noninvasive ventilation (NIV) may play a supportive role in patients with severe viral pneumonia and early ARDS/acute lung injury. It can act as a bridge to invasive mechanical ventilation, although it is contraindicated in critically ill patients with hemodynamic instability and multi-organ dysfunction syndrome [4]. Transmission of some of these viral infections can convert from droplets to airborne during respiratory therapy.

During the major outbreak of SARS, endotracheal intubation [5], oxygen therapy, and NIV were found to be risk factors for major nosocomial outbreaks affecting health care workers [6]. Possible aerosol transmission during a nosocomial outbreak of seasonal influenza was temporally related to the application of NIV in an index patient with hypercapnic respiratory failure due to acute exacerbation of chronic obstructive pulmonary disease (COPD). The patient was on a medical ward with an imbalanced indoor airflow [7]. As influenza virus may be contained in fine

D.S.C. Hui, MD
Department of Medicine and Therapeutics, The Chinese University of Hong Kong, Prince of Wales Hospital, 30-32 Ngan Shing St., Shatin, N.T., Hong Kong

Stanley Ho Center for Emerging Infectious Diseases, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong
e-mail: dschui@cuhk.edu.hk

A.M. Esquinas (ed.), *Noninvasive Ventilation in High-Risk Infections and Mass Casualty Events*,
DOI 10.1007/978-3-7091-1496-4_2,

particles generated during tidal breathing [8], NIV may disperse potentially infected aerosols, especially when patients cough and sneeze frequently, contributing to nosocomial transmission of influenza. Pulmonary tuberculosis (TB) is well known to spread by the airborne route. A recent study showed that a small number of patients with pulmonary TB (28 %) produced culturable cough aerosols [9].

Thus, it is important to examine the exhaled air directions and dispersion distances during application of NIV to patients with respiratory failure via commonly used face masks. The data can improve our understanding of and knowledge about infection control. Such knowledge can facilitate the development of preventive measures to reduce the risk of nosocomial transmission during application of NIV to high-risk patients with respiratory infections.

2.2 Methods

As there is no reliable, safe marker that can be introduced into human lungs for experimental purposes, the laser smoke visualization method and the human patient simulator (HPS) model have been adopted as the method for studying exhaled air dispersion during application of various types of respiratory therapy in hospital medical wards, including the negative-pressure isolation room [10–13].

2.2.1 NIV and Lung Model

The HPS represents a 70-kg adult man sitting on a 45°-inclined hospital bed (Fig. 2.1). The HPS contains a realistic airway and is programmed to remove oxygen and inject carbon dioxide into the system according to a preset respiratory exchange ratio and oxygen consumption. The lung compliance can also be changed to simulate different degrees of lung injury during chest infection. By varying the oxygen consumption (200, 300, and 500 ml/min) and lung compliance (70, 35, and 10 ml/cmH_2O), these sets of values produce a range of tidal volumes, respiratory rates, and peak inspiratory flow similar to those of patients with minimal (essentially normal lung function), moderate, or severe lung injury, respectively. For example, lung compliance is set at 35 ml/cm H_2O and oxygen consumption at 300 ml/min to mimic mild lung injury. Tidal volume and respiratory rate are regulated so a respiratory exchange ratio of 0.8 is maintained during measurements. Typically, this is achieved with a tidal volume of 300 ml and a respiratory rate of 25 breaths/min [10–13]. Lung compliance and airway resistance also responds in a realistic manner to relevant respiratory challenges. The HPS produces an airflow pattern that is close to the in vivo situation. It has been applied in previous studies to simulate human respiration [14–17].

Deliberate leakage from the exhalation ports of the Mirage mask (ResMed, Bella Vista, NSW, Australia) [10], ComfortFull 2, and Image 3 masks (Respironics, Murrysville, PA, USA) [11] firmly attached to a high-fidelity HPS (HPS 6.1; Medical Education Technologies, Sarasota, FL, USA) has been evaluated. NIV was

Fig. 2.1 Human patient simulator (HPS) lying at 45° on a bed undergoing noninvasive ventilation via the ResMed Mirage face mask. A laser beam located on the right side of the bed lateral to the human patient simulator illuminates the exhaled air particles leaking from the exhalation ports of the face mask in the coronal plane. A camera was positioned along the sagittal plane at the end of the bed to capture lateral dispersion of exhaled air illuminated by the laser device. Positions of the camera and the laser device would be exchanged when the exhaled air dispersion from the face mask is examined along the sagittal plane

applied using a bilevel positive airway pressure device (VPAP III ST; ResMed) via each mask. The inspiratory positive airway pressure (IPAP) was initially set at 10 cmH_2O and gradually increased to 18 cmH_2O. The expiratory positive airway pressure (EPAP) was maintained at 4 cmH_2O throughout the study [10, 11].

2.2.2 Flow Visualization

Visualization of airflow around each NIV face mask was facilitated by marking the air with smoke particles produced by a M-6000 smoke generator (N19; DS Electronics, Sydney, Australia), as in our previous studies [10–13]. The oil-based smoke particles, measuring less than 1 μm in diameter, are known to follow the airflow pattern precisely with negligible slip [18]. The smoke was introduced continuously to the right main bronchus of the HPS. It mixed with alveolar gas and then was exhaled through the airway. Sections through the leakage jet plume were then revealed by a thin, green laser light sheet (532 nm wavelength, continuous-wave

mode) created by a diode-pumped solid-state laser (OEM UGH-800 mW; Lambda Pro Technologies, Shanghai, China) with custom cylindrical optics to generate a two-dimensional laser light sheet [10–13].

The light sheet was initially positioned in the median sagittal plane of the HPS and subsequently shifted to paramedian sagittal planes. This allowed us to investigate the regions directly above and lateral to the mask and the patient [10–13].

All leakage jet plume images revealed by the laser light sheet were captured by a high-definition video camera—Sony high-definition digital video camcorder (HDR-SR8E; Sony, Tokyo, Japan); ClearVid complementary metal oxide semiconductor sensor (Sony) with a Carl Zeiss Vario-Sonnar T* Lens (Carl Zeiss, Jena, Germany)—with optical resolution of 1,440 × 1,080 pixels per video frame. The normalized smoke concentration in the plume was estimated from the light intensity scattered by the smoke particles [10–13].

2.2.3 Image Analysis

The normalized smoke concentration in the mask leakage air was estimated from the light scattered by the particles. The analysis was based on scattered light intensity being proportional to the particle concentration under the special conditions of constant-intensity laser light sheet illumination and monodispersion of small (submicron) particles [18]. In short, the thin laser light sheet of near-constant intensity illuminated the smoke particle markers in the mask airflow leakage. Smoke particles scattered laser light perpendicular to the light sheet. The pictures were then collected and integrated by the video camera element and lens [10–13].

2.2.4 Image Capture and Frame Extraction

A motion video of at least 20 breathing cycles for each NIV setting was captured and individual frames extracted as gray-scale bitmaps for intensity analysis. Frames were extracted at time points starting from the beginning of each inspiration to generate an ensemble average for the corresponding instant of the respiratory cycle [10–13]. The time at which the normalized concentration contours spread over the widest region from the NIV mask was chosen for the ensemble average to estimate the greatest dispersion distance. This was found to be approximately at the mid-respiratory cycle [10, 11].

2.2.5 Intensity Averaging and Concentration Normalization

All gray-scale frames were read into a program specifically developed for these studies [10–13] (MathCad 8.0; MathSoft, Cambridge, MA, USA) [19] along with the background intensity images obtained with the laser switched off. The background intensity image was subtracted from each frame, pixel by pixel, to remove any stray background light. The pixel intensity values were averaged over all frames

to determine the average intensity. The resulting image was the total intensity of light scattered perpendicular to the light sheet by the smoke particles. It was directly proportional to the smoke concentration under the conditions mentioned above. The image was normalized against the highest intensity found within the leakage jet plume to generate normalized particle concentration contours [10–13].

As the smoke particles marked air that originated from the HPS's airways before leaking from the mask, the concentration contours effectively represent the probability of encountering air around the patient that has come from within the mask and the patient's respiratory system. The normalized concentration contours are made up of data collected from at least 20 breaths. A contour value of 1 indicates a region that consists entirely of air exhaled by the patient, where there is a high chance of exposure to the exhaled air, such as at the mask exhaust vents. A value near 0 indicates no measurable air leakage in the region and a small chance of exposure to the exhaled air [10–13].

2.3 Results

The results are presented with reference to the median sagittal plane.

2.3.1 Noninvasive Positive-Pressure Ventilation Applied via the ResMed Mirage Mask

With the ResMed Mirage mask, a jet plume of air escaped through the exhaust holes to a distance of approximately 0.25 m radially during application of IPAP 10 cmH_2O, with some leakage from the nasal bridge. The leakage jet probability was highest about 60–80 mm lateral to the sagittal plane of the HPS. Without nasal bridge leakage, the plume jet from the exhaust holes increased to a 0.40 m radius circle, and exposure probability was highest about 0.28 m above the patient. When IPAP was increased to 18 cmH_2O, the vertical plume extended to about 0.5 m above the patient and the mask, with some horizontal spread along the ward roof [10].

2.3.2 Noninvasive Positive-Pressure Ventilation Applied via the ComfortFull 2 Mask

With the ComfortFull 2 mask, a vertical, cone-shaped plume leaked out from the mask exhalation diffuser and propagated well above and almost perpendicular to the patient at an IPAP and an EPAP of 10 and 4 cmH_2O, respectively. The maximum dispersion distance of smoke particles—defined as the boundary with a region encountering <5 % normalized concentration of exhaled air (light blue contour smoke concentration scale)—was 0.65 m, whereas that of a high concentration (containing >75 % normalized concentration of exhaled air, red zone, and above) was 0.36 m. There was no significant room contamination by exhaled air (as reflected by the blue background in the isolation room) other than the exhalation jet plume [11].

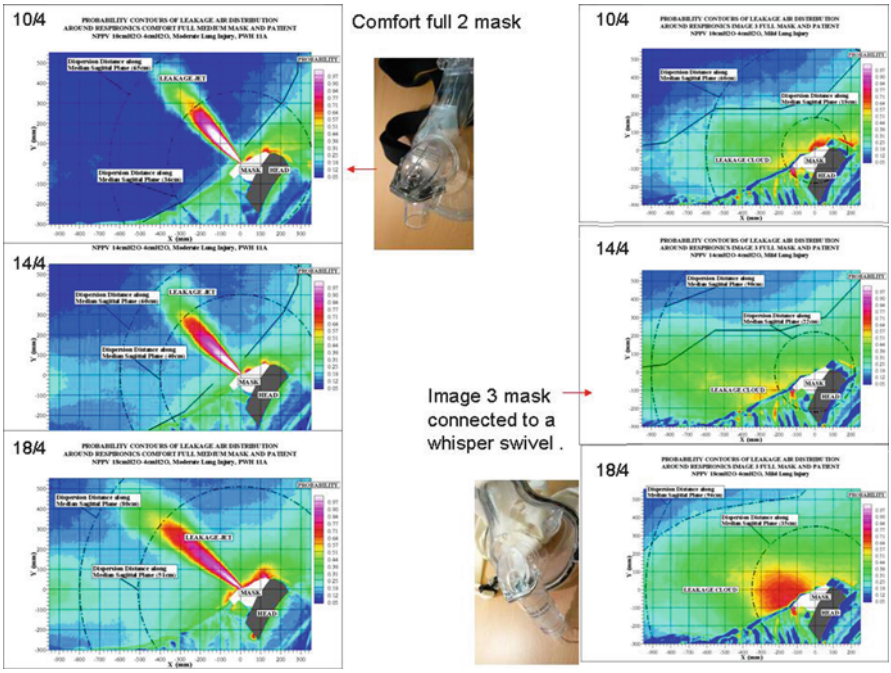


Fig. 2.2 Exhaled air dispersion along the median sagittal plane when the recumbent HPS was wearing the Comfortfull 2 mask (images on the *left*) or the Image 3 mask connected to the whisper swivel (images on the *right*) when the inspiratory positive airway pressure was increased from 10 to 14 and then 18 cmH_2O while the expiratory positive airway pressure was fixed at 4 cmH_2O [11]

When the IPAP was increased from 10 to 14 cmH_2O, the maximum exhaled dispersion distance of low-concentration exhaled air was similar at 0.65 m, but that of high-concentration exhaled air increased to 0.40 m, with contamination of the isolation room. Also, there was some exhaled air concentration outside the exhalation jet plume. When IPAP was increased to 18 cmH_2O, the dispersion distance of low-concentration exhaled air was 0.85 m, whereas that of high-concentration exhaled air increased to 0.51 m along the median sagittal plane. More background contamination of the isolation room by smoke particles was noted at higher IPAPs owing to interaction between the downstream ceiling-mounted ventilation vent and the upstream exhaled air from the HPS (images at left in Fig. 2.2) [11].

2.3.3 Noninvasive Positive-Pressure Ventilation Applied via the Image 3 Mask Connected to the Whisper Swivel

The Image 3 mask required an additional exhalation device (whisper swivel) to prevent carbon dioxide rebreathing. The exhaled air leakage was much more diffuse than that with the ComfortFull 2 mask because of the downstream leakage of

exhaled air through the whisper swivel exhalation port. At an IPAP of 10 cmH_2O, the maximum dispersion distance of a low concentration in exhaled air (light blue zone on the smoke concentration scale) was 0.95 m toward the end of the bed, whereas that of a medium concentration (containing >50 % of the normalized concentration of exhaled air, green zone, and above) was about 0.6 m along the median sagittal plane. As the IPAP was increased from 10 to 14 cmH_2O, the exhaled air with a medium concentration increased to 0.95 m toward the end of the bed along the median sagittal plane of the HPS [11].

When the IPAP was increased to 18 cmH_2O, the exhaled air with a low concentration dispersed diffusely to fill up most of the isolation room (i.e., beyond 0.95 m, as captured by the camera), whereas that with a medium concentration, occupying wider air space, was noted to spread 0.8 m toward the end of the bed, with accumulation of a high concentration of exhaled air (red zone on scale) within 0.34 m from the center of the mask, along the median sagittal plane of the HPS (images on the right in Fig. 2.2) [11].

2.4 Discussion

There is no reliable, safe marker that can be introduced into human lungs for experimental purposes. Hence, the maximum distribution of exhaled air, marked by very fine smoke particles, from the HPS during application of NIV using three face masks was examined by the laser smoke visualization method on a high-fidelity HPS model. The studies showed that the maximum distances of exhaled air particle dispersion from patients undergoing NIV with the ResMed Ultra Mirage mask was 0.5 m along the exhalation port [10]. In contrast, the dispersion distances of a low, normalized concentration of exhaled air through the ComfortFull 2 mask exhalation diffuser increased from 0.65 to 0.85 m at a direction perpendicular to the head of the HPS along the sagittal plane when IPAP was increased from 10 to 18 cmH_2O. There was also more background contamination of the isolation room at the higher IPAP [11]. Even when a low IPAP of 10 cmH_2O was applied to the HPS via the Image 3 mask connected to the whisper swivel exhalation port, the exhaled air leaked far more diffusely than from the ComfortFull 2 mask, dispersing a low normalized concentration of 0.95 m along the median sagittal plane of the HPS. The higher IPAP resulted in wider spread of a higher normalized concentration of smoke around the HPS in the isolation room with negative pressure [11].

Simonds et al. [20] applied the laser visualization method to assess droplet dispersion during application of NIV in humans with an optical particle sizer (Aerotrak 8220; TSI Instruments, High Wycombe, UK) and showed NIV as a droplet- (not aerosol-) generating procedure, producing droplets measuring >10 μm. Most of them fell onto local surfaces within 1 m of the patient.

Noninvasive ventilation is an effective treatment for patients with respiratory failure due to COPD, acute cardiogenic pulmonary edema, or pneumonia in immunocompromised patients. However, evidence supporting its use in patients with pneumonia is limited. NIV was applied to patients with severe pneumonia caused by

a 2009 pandemic influenza (H1N1) infection with a success rate of about 41 %. Although there were no reported nosocomial infections [21], there is a potential risk of applying NIV to patients hospitalized with viral pneumonia on a crowded medical ward with inadequate air changes [7]. In this regard, deliberate leakage via the exhalation ports may generate droplet nuclei and disperse infective aerosols through evaporation of water content of respiratory droplets, resulting in a superspreading event. Nonetheless, NIV was applied using a single circuit to treat patients effectively with respiratory failure due to SARS in hospitals with good infection control measures (including installation of powerful exhaust fans to improve the room air change rate and good protective personal equipment at a level against airborne infection). There were no nosocomial infections among the health care workers involved [22, 23]. In contrast, a case–control study involving patients in 124 medical wards of 26 hospitals in Guangzhou and Hong Kong identified the need for oxygen therapy and use of NIV as independent risk factors for superspread of nosocomial SARS outbreaks [6]. Similarly, a systematic review has shown a strong association between ventilation, air movement in buildings, and airborne transmission of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox, and SARS [24].

These studies of infection with the HPS model [10, 11] and in humans [20] have important clinical implications for preventing future nosocomial outbreaks of SARS and other highly infectious conditions such as pandemic influenza when NIV is provided. NIV should be applied in patients with severe community acquired pneumonia only if there is adequate protection for health care workers because of the potential risk of transmission via deliberate or accidental mask interface leakage and flow compensation causing dispersion of a contaminated aerosol [10, 11]. Pressure necrosis may develop in the skin around the nasal bridge if the NIV mask is applied tightly for a prolonged period of time. Many patients loosen the mask strap to relieve discomfort. Air leakage from the nasal bridge is definitely a potential means of transmitting viral infections. Fitting a mask carefully is important for successful, safe application of NIV. Addition of a viral/bacterial filter to the breathing system of NIV, between the mask and the exhalation port, or using a dual-circuit NIV via full face mask or helmet without heated humidification may reduce the risk of nosocomial transmission of a viral infection [11, 25].

In view of the observation that higher ventilator pressures result in wider dispersion of exhaled air and more air leakage [10, 11], it is advisable to start NIV with a low IPAP (8–10 cmH_2O) and increase it gradually as necessary. The whisper swivel is an efficient exhalation device to prevent carbon dioxide rebreathing, but it would not be advisable to use such an exhalation port in patients with febrile respiratory illness of unknown etiology. This is especially true in the setting of an influenza pandemic with the high potential of human-to-human transmission for fear of causing a major outbreak of nosocomial infections. It is also important to avoid the use of high IPAP, which could lead to wider distribution of exhaled air and substantial room contamination [11].

There are some limitations regarding the use of smoke particles as markers for exhaled air. The inertia and weight of large droplets in an air-droplet two-phase flow would certainly cause them to have less horizontal dispersion than occurs with the continuous air carrier phase during which the particles travel with increased inertia and drag. However, evaporation of the water content of some respiratory droplets

during coughing or sneezing when exposed to NIV may produce droplet nuclei suspended in air, whereas the large droplets fall to the ground in a trajectory pathway [10–13]. As smoke particles mark the continuous air phase, the data contours described refer to exhaled air. The results would therefore represent the "upper bound" estimates for dispersion of the droplets—which would be expected to follow a shorter trajectory than an air jet due to gravitational effects—but not fully reflect the risk of large-droplet transmission [10–13].

In summary, the laser visualization technique using smoke particles as a marker in the HPS model is a feasible means of assessing exhaled air dispersion during application of NIV and other modes of respiratory therapy [10–13]. Substantial exposure to exhaled air occurs within 1 m of patients undergoing NIV in an isolation room with negative pressure via the ComfortFull 2 mask and the Image 3 mask connected to the whisper swivel exhalation port. It must be noted that there is far more extensive leakage and room contamination with the Image 3 mask, especially at higher IPAPs [11].

Health care workers should take adequate precautions for infection control. They especially must pay attention to environmental air changes when providing NIV support to patients with severe pneumonia of unknown etiology complicated by respiratory failure.

Key Major Recommendations

- The laser visualization technique using smoke particles as markers in the HPS model is a feasible means of assessing exhaled air dispersion during application of NIV and other modes of respiratory therapy.
- Substantial exposure to exhaled air occurs within 1 m of patients undergoing NIV even in an isolation room with negative pressure.
- During application of NIV, it is advisable to choose face masks with predictable exhaled air directions and distances through the exhalation port without addition of the whisper swivel device.
- It is important to avoid using high inspiratory pressures and any face mask that requires connection to the whisper swivel exhalation port as they would lead to wider distribution of exhaled air and substantial room contamination.

Acknowledgment I thank the Research Fund for the Control of Infectious Diseases #06060202 (Food & Health Bureau, HKSAR) for supporting my studies financially.

References

1. Lee N, Hui DS, Wu A, et al. A major outbreak of severe acute respiratory syndrome in Hong Kong. N Engl J Med. 2003;348:1986–94.
2. Hui DS. Review of clinical symptoms and spectrum in humans with influenza A/H5N1 infection. Respirology. 2008;13 Suppl 1:S10–3.
3. Hui DS, Lee N, Chan PK. Clinical management of pandemic (H1N1) infection. Chest. 2010;137:916–25.

4. Hui DS. Influenza A/H5N1 infection: other treatment options and issues. Respirology. 2008;13 Suppl 1:S22–6.
5. Fowler RA, Guest CB, Lapinsky SE, et al. Transmission of severe acute respiratory syndrome during intubation and mechanical ventilation. Am J Respir Crit Care Med. 2004;169:1198–202.
6. Yu IT, Xie ZH, Tsoi KK, et al. Why did outbreaks of severe acute respiratory syndrome occur in some hospital wards but not in others? Clin Infect Dis. 2007;44:1017–25.
7. Wong BC, Lee N, Li Y, Chan PK, et al. Possible role of aerosol transmission in a hospital outbreak of influenza. Clin Infect Dis. 2010;51:1176–83.
8. Fabian P, McDevitt JJ, DeHaan WH, et al. Influenza virus in human exhaled breath: an observational study. PLoS One. 2008;3(7):e2691.
9. Fennelly KP, Jones-López EC, Ayakaka I, et al. Variability of infectious aerosols produced during coughing by patients with pulmonary tuberculosis. Am J Respir Crit Care Med. 2012;186:450–7.
10. Hui DS, Hall SD, Chan MT, et al. Non-invasive positive pressure ventilation: an experimental model to assess air and particle dispersion. Chest. 2006;130:730–40.
11. Hui DS, Chow BK, Hall SD, et al. Exhaled air dispersion distances during application of non-invasive ventilation via different Respironics face masks. Chest. 2009;136:998–1005.
12. Hui DS, Hall SD, Chan MTV, et al. Exhaled air dispersion during oxygen delivery via a simple oxygen mask. Chest. 2007;132:540–6.
13. Hui DS, Chow BK, Hall SD, et al. Exhaled air and aerosolized droplet dispersion during application of a jet nebulizer. Chest. 2009;135:648–54.
14. Kuhlen R, Max M, Dembinski R, et al. Breathing pattern and workload during automatic tube compensation, pressure support and T-piece trials in weaning patients. Eur J Anaesthesiol. 2003;20:10–6.
15. Good ML. Patient simulation for training basic and advanced clinical skills. Med Educ. 2003;37 suppl 1:14–21.
16. Goodwin JA, van Meurs WL, Sa Couto CD, et al. A model for educational simulation of infant cardiovascular physiology. Anesth Analg. 2004;99:1655–64.
17. Lampotang S, Lizdas DE, Gravenstein N, Robicsek S. An audible indication of exhalation increases delivered tidal volume during bag valve mask ventilation of a patient simulator. Anesth Analg. 2006;102:168–71.
18. Soo SL. Fluid dynamics of multiphase systems. Toronto: Blaisdell Publishing Company; 1967.
19. MathSoft Inc. Mathcad 8.0 for windows, users guide. Cambridge, MA: MathSoft Inc; 2000.
20. Simonds AK, Hanak A, Chatwin M, et al. Evaluation of droplet dispersion during non-invasive ventilation, oxygen therapy, nebuliser treatment and chest physiotherapy in clinical practice: implications for management of pandemic influenza and other airborne infections. Health Technol Assess. 2010;14:131–72.
21. Masclans JR, Pérez M, Almirall J, et al. Early non-invasive ventilation treatment for severe influenza pneumonia. Clin Microbiol Infect. 2013;19(3):249–56. doi:10.1111/j.1469-0691.2012.03797.x.
22. Cheung TM, Yam LY, So LK, et al. Effectiveness of noninvasive positive pressure ventilation in the treatment of acute respiratory failure in severe acute respiratory syndrome. Chest. 2004;126:845–50.
23. Han F, Jiang YY, Zheng JH, et al. Noninvasive positive pressure ventilation treatment for acute respiratory failure in SARS. Sleep Breath. 2004;8:97–106.
24. Li Y, Leung GM, Tang JW, et al. Role of ventilation in airborne transmission of infectious agents in the built environment- a multidisciplinary systematic review. Indoor Air. 2007;17:2–18.
25. Conti G, Larrsson A, Nava S, et al. On the role of non-invasive ventilation (NIV) to treat patients during the H1N1 influenza pandemic. ERS and ESICM guideline Nov 2009. Available at http://www.dev.ersnet.org/uploads/Document/63/WEB_CHEMIN_5410_1258624143.pdf