

Mucus On the Move: Embed It or Expel It—The Patient, the Clinician, and Now the Ventilator

Intubation and mechanical ventilation may impair mucociliary clearance and lead to sputum retention, airway occlusion, atelectasis, and ventilator-associated pneumonia.^{1,2} Early work demonstrated that airway clearance can be augmented by an expiratory flow bias generated through the 2-phase gas-liquid transport mechanism.^{3,4} Higher expiratory flow than inspiratory flow combined with dynamic airway compression contributes to the clearance of airway secretions in intubated patients,^{3,4} and can be achieved by physical methods, including manual lung hyperinflation.⁵

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Clinicians may find it challenging when repositioning a heavily sedated, intubated, ventilated patient who has poor or absent cough and secretion retention, because repositioning may result in substantial arterial hypoxemia, hypercarbia, and increased patient work of breathing. The prevalence, sequelae, and optimal methods to manage or prevent these episodes are yet to be adequately described in the literature. The patient's respiratory-muscle strength, position, volume, viscosity, and location of airway secretions, depth of sedation, and "cough strength" (expiratory flow generated spontaneously or in response to suction) are some of the variables that may determine the impact of secretion retention on ventilation, gas exchange, and patient outcome. The minimum standard of airway care currently advocates adequate humidification and suctioning.^{6,7}

Below I will discuss various definitions and means to monitor secretion-retention in an intubated and ventilated patient, and methods to maintain a patent artificial airway, enhance secretion clearance, and prevent secretion retention.

Diagnosis and Monitoring

Lung auscultation and chest palpation may be useful to identify the presence of airway secretions, but may be unreliable.⁸ Airway secretions may also be suspected with changes in pulmonary mechanics at the bedside. However, measurements of airway pressure and flow are often taken at the proximal end of the endotracheal tube, and hence are mainly affected by the mechanical properties of the tube.⁹

A "saw tooth" pattern on the expiratory flow waveform and coarse expiratory sounds over the trachea are good indicators of retained secretions in the major airways.¹⁰ Endotracheal tube and bronchial obstruction can be detected by a characteristic increase in the early expiratory time constant⁹ and by acoustic reflectometry.¹⁰⁻¹² We have yet to accurately diagnose secretion retention, but flow waveform analysis and good clinical examination may be useful.

Patent Airway

Adequate humidification and airway suctioning are required to maintain airway patency.^{6,7} Closed suctioning can minimize potential adverse physiologic effects of airway suctioning but may not be as effective for secretion clearance.¹³⁻¹⁶ Ventilator breaths triggered by closed suctioning may migrate secretions away from the suction catheter tip (due to inspiratory flow bias).^{13,17} Open suctioning, higher suction pressure, a wider-bore suction catheter, or the removal of positive end-expiratory pressure (PEEP)/pressure support can improve secretion clearance and may be required under certain conditions, such as major airway occlusion, but may compromise gas exchange in the short term.^{13,16} The "pipe cleaner" effect of the suction catheter may additionally assist to ensure airway patency and needs to be further investigated.¹⁶

Using a shorter suction catheter (to prevent contact with the carina) can minimize adverse physiologic effects and may be as effective as suctioning with a standard-length catheter, in terms of duration of intubation, intensive-care-unit stay, intensive-care-unit mortality, and incidence of pulmonary infections.¹⁸ The act of disconnecting the ventilator circuit for open suctioning may explain the equivalent outcomes between shorter and conventional-length catheters (simulated cough due to elastic recoil), and requires further investigation.^{16,18}

Enhanced Secretion Clearance

The expiratory flow bias required to generate annular 2-phase gas-liquid flow can be created with manual lung hyperinflation.^{5,19} Ventilator hyperinflation can also enhance secretion clearance,²⁰ and hyperinflation may be

effective up to the 10th generation of airways.⁴ Manual and ventilator hyperinflation can transiently improve airway resistance and dynamic lung/thorax compliance.^{20,21} Gravity-assisted drainage (head-down tilt) combined with manual lung hyperinflation may further enhance secretion clearance.²²

Chest-wall vibration, with or without manual lung hyperinflation and suctioning, can improve expiratory flow, airway resistance, and dynamic lung/thorax compliance, but has not been demonstrated to improve secretion clearance.^{23,24} Manual lung hyperinflation with PEEP > 10 cm H₂O may retard the expiratory flow to below that required for 2-phase gas-liquid flow.²⁵

In a rabbit model with pressure-controlled ventilation, no PEEP, and artificial mucus instilled to create atelectasis, chest-wall vibration was associated with significant deterioration in dynamic lung/thorax compliance and gas exchange. Unfortunately, those authors did not measure airway resistance.²⁶ The resultant deterioration in lung mechanics and gas exchange in that animal model may support the hypothesis that chest-wall vibration can mobilize peripheral secretions to the proximal airways.²⁶ These adverse changes in ventilation probably occur during routine patient care (eg, patient repositioning) but have yet to be studied. Adding manual lung hyperinflation, head-down positioning, and airway suctioning to chest-wall vibration may be a more effective strategy to manage or prevent these secretion-related adverse events.

Mechanical Ventilator Settings

In this issue of *RESPIRATORY CARE*, Volpe et al²⁷ report a study in which they used a test-lung model connected to a mechanical ventilator to investigate the effects of tidal-ventilation airflow, airflow bias, and lung mechanics on the movement of simulated mucus. Ventilator settings that produced an expiratory flow bias moved mucus toward the ventilator, whereas settings that produced an inspiratory flow bias moved mucus deeper into the lung model, away from the ventilator. Thresholds for flow magnitude (minimum of 40 L/min, with a strong association between peak flow rate and mucus movement) and phase differential would shift simulated mucus either closer to or away from the ventilator.²⁷ The absolute difference between the inspiratory flow and expiratory flow better explained the direction of mucus movement than did the ratio of expiratory flow to inspiratory flow. Intrinsic PEEP (from increased minute ventilation) moved mucus toward the ventilator, whereas retarding expiratory flow with an airway resistor (eg, as in asthma or chronic obstructive pulmonary disease) moved secretions deeper into the lung. Interestingly, when 2 connected test lungs were set to different lung-compliance values, there was a rapid transfer of secretions across the “carinal divider” from the less compli-

ant lung to the more compliant lung. These laboratory findings cannot be directly extrapolated to clinical care but should stimulate *in vivo* research.

Overview and Recommendations

The work by Volpe et al²⁷ supports earlier findings that expiratory flow bias can augment secretion clearance^{3,4} and demonstrates how secretions can move between lungs at the carina; it is unclear if this principle extends to the more peripheral airway branchings. Unfortunately, airway suctioning, cough, and gravity were not investigated, but they can play an important role in mucus movement.²⁸ Ventilator settings that have an expiratory flow bias may cause “pooling” of secretions near the central or major airways, which could lead to adverse changes in ventilation and gas exchange, for example in a sedated or paralyzed patient.²⁶ Hence, adjuncts such as manual lung hyperinflation, chest-wall vibration, postural drainage, and airway suctioning could be important tools to prevent secretion retention and ensure major airway patency. Newer artificial airways, such as the “mucus slurper” and “mucus shaver,”⁶ combined with ventilator settings/procedures that cause an expiratory flow bias may reduce the need for conventional suctioning.^{5,16,27}

Even though impaired mucociliary clearance may lead to pulmonary complications such as secretion retention and ventilator-associated pneumonia,^{1,2} studies of chest physiotherapy have had mixed results,²⁹⁻³² but chest physiotherapy warrants further investigation.³¹

The current practice of manual lung hyperinflation,⁵ with inspiratory flow of 90 L/min and expiratory flow of 196 L/min, and an inspiratory-flow-to-expiratory-flow ratio of 0.6, far exceeded the flow-magnitude threshold, expiratory flow bias, and minimum difference between inspiratory and expiratory flow required for mucus movement during tidal ventilation in test lung or animal models.^{3,4,27} It is also conceivable that chest-wall vibration during mechanical ventilation may move airway secretions “to and fro” through the alternating expiratory and inspiratory flow bias (negative pleural pressure on the removal of the chest compression may trigger ventilator breaths and create an inspiratory flow bias), similar to what may occur during closed suctioning.¹³ The work of Volpe et al and others may also explain the “inexplicable” major-airway occlusion and deterioration in gas exchange and ventilation when mechanical ventilator settings favor an expiratory flow bias and the patient has highly viscous secretions, deep sedation, and/or paralysis and absent cough.^{26,33} Because an inspiratory flow bias during mechanical ventilation and closed suctioning may move secretions deeper into the lung, a physiotherapy intervention with 2 clinicians (one applying chest-wall vibration and/or manual lung hyperinflation and the other applying suctioning during the ex-

pulsive maneuvers) may provide more efficacious secretion removal and promote major-airway patency.³⁴

Expiratory flow bias can be achieved with manual lung hyperinflation, chest-wall vibration, and ventilator settings. Whether expiratory flow bias significantly affects secretion retention or major pulmonary complications remains to be determined. Future investigations must first of all adequately define secretion retention and then establish/explore the epidemiology of the condition. Fiberoptic evaluation of the movement of instilled blue dye or particles could be useful to assess mucus movement with various therapies.^{2,35}

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