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High-frequency Percussive Ventilation for Airway Clearance in Cystic Fibrosis: A Brief Report

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Abstract Exacerbations of cystic fibrosis (CF) lung disease are characterized by increased inspissation of abnormally viscid pulmonary secretions with resultant plugging of small airways, worsened ventilation/perfusion mismatch, and increased physiological deadspace. In this circumstance, hypoxic respiratory failure necessitating mechanical ventilation can be life-threatening. We present such a case of CF lung disease poorly responsive to conventional mechanical ventilatory strategies, in which high-frequency percussive ventilation (HFPV) using volumetric diffusive respiration mobilized copious amounts of inspissated pulmonary secretions and improved refractory hypoxia. Subsequent transient hypercarbia necessitated titrating ventilator parameters to return the $PaCO_2$ to baseline; the voluminous clearance of secretions and improvement in oxygenation were sustained. HFPV appears unique in its ability to function as a methodological continuum from noninvasive percussion to invasive percussive ventilation for airway clearance, a fundamental tenet of the CF treatment paradigm.

Keywords Cystic fibrosis · Respiratory failure · High-frequency positive pressure ventilation · High-frequency percussive ventilation · Volumetric diffusive respiration

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Introduction

Cystic fibrosis (CF) lung disease results in inspissation of abnormally viscid pulmonary secretions with resultant airway obstruction, inflammation, and infection causing lung damage [1]. Airway clearance strategies are the mainstay of pulmonary therapy for chronic inspissated secretions; a detailed descriptive review is available elsewhere [1, 2]. Worsening of this underlying dysregulated airway homeostasis during acute respiratory failure in CF is not only clinically challenging, but potentially life-threatening, especially when mechanical ventilation is necessary. In this context, the use of high-frequency percussive ventilation (HFPV) to bridge the continuum of noninvasive airway clearance methodologies typified by intrapulmonary percussive ventilation (IPV) [2, 3] would intuitively appear beneficial, given its potential to assist with clearance of tenacious pulmonary secretions. HFPV using the volumetric diffusive respirator (VDR-4®, Percussionaire; Bird Space Technologies; Sandpoint, ID) for clearance of secretions in patients with inhalational burn injuries has been well reported [4, 5]. Interestingly, the use of HFPV during mechanical ventilation of CF lung disease has not been reported.

Case Summary

A 28-year-old Caucasian male with CF and severe obstructive lung physiology ($FEV_1 = 18\%$ predicted) presented with acute bilateral pneumonia characterized by worsening dyspnea and increased purulent sputum. He was treated with intravenous broad-spectrum antibiotics and aggressive airway clearance therapy using IPV and nebulized bronchodilators, but inexorably progressed to respiratory failure

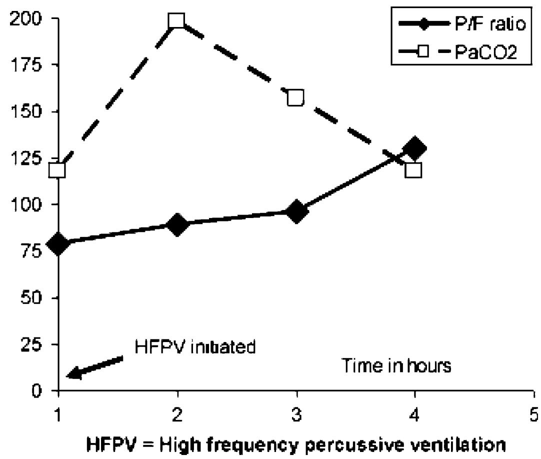

Fig. 1 Plot of PaO_2/FiO_2 (P/F) ratio and $PaCO_2$ (mmHg) after initiating HFPV

necessitating mechanical ventilation. A diagnosis of gram-negative septic shock was established based on sputum culture positivity for *Pseudomonas aeruginosa* coupled with worsening fevers, leukocytosis, and hypotension necessitating vasopressor use; early goal-directed therapy was initiated as per existing guidelines. A low tidal volume (V_T) strategy using volume-controlled ventilation at 6 ml/kg predicted body weight was adopted in view of acutely evolving bilateral infiltrates indicative of ARDS secondary to sepsis. Because of persistent hypoxemia, treatment with high levels (18–20 cmH_2O) of positive end-expiratory pressure (PEEP) on an $FIO_2 = 1.0$ resulted in plateau pressures well above 30 cmH_2O. Thick and tenacious pulmonary secretions precluded effective endotracheal suctioning in spite of nebulized dornase alpha (2.5 mg) twice daily, as well as albuterol (2.5 mg) and ipratropium (0.5 mg) delivered as metered doses into the ventilator circuit every 4 h. In light of worsening hypoxia and hypercarbia, the decision was made to switch to HFPV using the VDR-4® ventilator. Initial set parameters were peak inspiratory pressure (PIP) of 30 cmH_2O, oscillatory PEEP of 10 cmH_2O, inspiratory and expiratory time of 2 s, ventilator rate of 12/min, and pulse frequency of 500 Hz. The resultant mean airway pressure (Paw_{mean}) on these settings was 24 cmH_2O. The endotracheal cuff was partially deflated to maintain a minimal audible cuff leak; this was maintained throughout the course of HFPV as per institutional protocol. Within 4–5 h of initiating HFPV, the PaO_2/FiO_2 ratio improved (Fig. 1) in conjunction with the issuance of copious secretions totaling over 1000 ml from the endotracheal tube (ETT) as well as from around the partially deflated ETT cuff. There was simultaneous radiographic improvement within a few hours as visualized by decreased bilateral pulmonary infiltrates and improved lung aeration (Fig. 2). Notably, transient hypercarbia within an hour of initiating HFPV was corrected (Fig. 1) by increasing the PIP to 40 cmH_2O, decreasing the pulse frequency to 450 cmH_2O, and decreasing the oscillatory PEEP to 10 cmH_2O. The improved oxygenation was sustained over the next 12 h along with continued clearance of copious airway secretions. The patient eventually expired from worsening septic shock.

Discussion

HFPV is a form of high-frequency ventilation that improves gas exchange by delivering low V_T percussive breaths at high frequencies to enhance alveolar gas mixing by multiple mechanisms, including convective flow, asymmetric velocity profiles, Taylor dispersion, molecular diffusion, cardiogenic mixing, and pendelluft [6]. In severe exacerbations of CF, augmented inspissation of secretions causes widespread plugging of smaller airways which greatly contributes to ventilation/perfusion mismatch and progressive hypoxemia. Conventional ventilatory strategies do not address the need for aggressive airway clearance in intubated CF patients and are thus limited to endotracheal suctioning and the use of bronchodilators. In contrast, the laminar flow of gas through collateral pathways distal to secretions in obstructed airways during HFPV results in expulsion of inspissated secretions by improving their

Fig. 2 Chest X-ray before (**a**) and 5 h after (**b**) initiating high-frequency percussive ventilation showing improved lung infiltrates and aeration bilaterally

physical and transport properties [7, 8]. The subtidal volumes delivered by pulsed percussive breaths during HFPV additionally facilitate mobilization of secretions and clearance of lung infiltrates [9]. Although recently debated [10], the partially deflated ETT cuff used with HFPV lessens the risk for generating potentially damaging intra-alveolar pressures. The resultant decreased PIP with a concomitantly increased Paw_{mean} possibly reduces ventilator-induced lung injury, as originally reported by Cioffi and colleagues in 1989 [11]. This is potentially advantageous in CF lung disease given the proclivity to develop pneumothoraces.

In our case, HFPV stabilized and improved hypoxemia, principally by aggressively inducing airway clearance. We theorize that as for IPV [3], HFPV indirectly reduces dynamic hyperinflation by improving mucus clearance, thereby improving lung mechanics and gas exchange. Even so, we acknowledge the limitations of this report. Rapid fluctuations of $PaCO_2$, as in our case, warrant assiduous monitoring of gas exchange upon initiation of HFPV. Even though the short-term effect on airway clearance and oxygenation was favorable in this report, it did not alter the eventual clinical outcome. In addition, the relative contribution of HFPV to adverse hemodynamics with resultant worsening of shock in such cases has not been well studied. Lastly, invasive mechanical ventilation in advanced-stage CF lung disease is generally not recommended, although existing guidelines [12] predate the current armamentarium of newer therapeutic strategies. On the other hand, stabilization of refractory hypoxemia in select cases, especially in CF lung disease of lesser severity, may well provide a bridge to clinical recovery or even lung transplantation [13].

To summarize, we report the conceptual use of HFPV in invasively ventilated CF lung disease, given suboptimal airway clearance on conventional mechanical ventilation. HFPV appears to be an acceptable alternative to conventional ventilatory strategies in this setting. Furthermore, HFPV is unique in its similarity to noninvasive IPV, thus establishing a continuum for aggressive airway clearance, a fundamental tenet of the CF treatment paradigm [14]. To our knowledge, this is the first reported case of using HFPV delivered via volumetric diffusive respiration to promote airway clearance and address refractory hypoxemia during mechanical ventilation of CF lung disease. Additional experience is needed to better define the role of HFPV in mechanically ventilated CF patients.

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