Use of High-Frequency Percussive Ventilation in Inhalation Injuries

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Inhalation injury causes significant morbidity and mortality, accounting for nearly 80% of non-fire-related deaths and affecting nearly 25% of all patients hospitalized with thermal injury. High-frequency percussive ventilation (HFPV) has been reported to decrease both the incidence of pulmonary barotrauma and pneumonia in inhalation injury. It has evolved into a ventilatory modality promoted to rapidly remove airway secretions and improve survival of patients with smoke inhalation injury. From 1997 to 2005, a total of 92 patients with inhalation injury were treated with HFPV. This group was compared with 130 patients treated with conventional mechanical ventilation between 1997 and 2005. The diagnosis of inhalation injury was made on admission, based on the following clinical criteria: injury in a closed space, carbonaceous sputum, and/or positive bronchoscopy (presence of carbonaceous deposits, erythema or ulceration). Both modes of ventilation were begun within 24 hours of injury. Both groups were similar with respect to demographics and injury severity. The mean number of ventilator days, days in the intensive care unit, length of stay, and incidence of pneumonia did not differ significantly between groups. Twenty-six of 92 (28%) patients treated with HFPV, and 56 of 130 with conventional mechanical ventilation (43%) died. There was a significant decrease in both overall morbidity and mortality in the subset of patients with ≤40% TBSA treated with HFPV. Future randomized, controlled trials are needed to determine the precise role of HFPV in the treatment of inhalation injuries. (J Burn Care Res 2007;28:396–400)

Inhalation injury frequently occurs with cutaneous burns and is one of the leading causes of death in patients with burn injuries. The mortality of smoke inhalation ranges from 20% to 80%.[1,2] Thermal injury of the tracheobronchial tree causes mucosal sloughing, impairment of mucociliary clearance, and deposition of fibrin casts in small airways. The resultant mechanical obstruction causes carbon dioxide retention, impaired oxygenation, and progressive ventilation-perfusion mismatch. Free radicals further damage the lungs and are thought to be caused by polymorphonuclear leukocyte migration into the pulmonary microcirculation.[3] The end result is an increase in microcirculatory permeability and progressive pulmonary edema. Inhalation injury is associated with increased fluid requirements during burn resuscitation. Decreased pulmonary compliance associated with edema and release of inflammatory mediators results in high airway pressures which, in the past, has necessitated high positive end-expiratory pressures to maintain adequate oxygenation. This has also been shown to increase mortality.[4] Pneumonia is relatively common in burn patients, with mortality rates ranging from 40 to 60%.[5] Plugging of airways and subsequent atelectasis often leads to the development of pneumonia, which occurs in nearly 70% of patients within the first week after burn.[3] Spontaneous pneumothorax, a common sequela of pulmonary barotrauma, often is related to the high peak inspiratory pressures needed to maintain adequate oxygenation.

Conventional ventilator modes, using either pressure or volume control settings, do nothing to promote the removal of carbon or sloughed organic material. Routine tracheal suctioning often is ineffective, because much of the airway obstruction

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is in the distal bronchial tree, well beyond the reach of suction catheters.

In 1980, Dr. Forrest Bird developed the concept of intrapulmonary percussion, enabling diffusion of oxygen with subtidal volume breaths along with convective washout of carbon dioxide. This was the basis for the development of high-frequency percussive ventilation (HFPV). The percussive nature of this mode of pulmonary support also serves to enhance clearance of secretions from the bronchial tree. The first clinical trial was conducted 9 years later, when HFPV was applied to a small group of patients with inhalation injuries. Oxygen saturation and clearance of carbon dioxide were improved when compared to patients supported with conventional ventilation.[6] Since that time, there have been numerous reports using HFPV in patients with inhalation injury.[4,6–9] Unfortunately, the relative merits of HFPV are not clearly defined. This report comprises the largest series of patients with inhalation injuries treated with HFPV to date.

MATERIALS AND METHODS

A retrospective review of all patients admitted to the Parkland Memorial Hospital Burn Intensive Care Unit with a diagnosis of inhalation injury was undertaken. Bronchoscopy was performed when the diagnosis of inhalation injury was not readily apparent by combination of history and endotracheal tube suctioning. Inhalation injury was defined by a history of being trapped in a closed, smoke-filled space (eg, home, vehicle) with the need for endotracheal intubation, recovery of large amounts of carbonaceous material from the endotracheal tube, a requirement of more than 96 hours of mechanical ventilation, bilateral infiltrates on chest radiograph, no evidence of fluid overload, and a PaO_2:FiO_2 ratio of less than 200. Patients meeting these criteria underwent bronchoscopy based on clinical status and bronchoscope availability. For patients who underwent bronchoscopy (n = 62 for HFPV, n = 49 for CMV), inhalation injury was diagnosed if carbonaceous sputum, mucosal ulcerations, edema, or erythema were present. Initiation of treatment began within 24 hours of injury in all cases in both treatment groups.

High-Frequency Percussive Ventilation

The high-frequency percussive ventilator (Bird Space Technologies, Percussionaire Corporation, Sandpoint, ID) delivers a high-frequency series of stacked subtidal volume breaths followed by passive exhalation to a baseline, preset continuous positive airway pressure. Respiration is time-cycled and pressure-limited, with frequency, amplitude, inspiratory-expiratory ratios, and waveforms programmed to provide maximal ventilation and perfusion (Figure 1). Changing the inspiratory to expiratory (I:E) ratio of the subtidal volume breaths varies the dynamics of the high frequency waveform, creating either a diffusive (lower I:E ratio) or percussive (higher I:E ratio) flow wave. The pulse frequency of subtidal volume breaths can be varied from 0 to 600 to assist in providing maximal oxygenation. The amplitude of these subtidal volume breaths also can be varied, which correlates with the patient's peak inspiratory pressure. Interruption of the percussive phase of respiration permits passive CO_2 elimination. A mandatory respiratory rate is created by the variable inspiratory-expiratory times. Initially, a rate of approximately one half to two thirds of a conventional respiratory rate is used. Ventilator variables are subsequently adjusted based on arterial blood gas analyses to optimize gas exchange. Most patients in this series were weaned from the VDR to conventional ventilators prior to extubation when there was no further evidence of carbonaceous material present during routine suctioning. In this study, initial settings on the VDR were as follows: respiratory rate of 8 breaths per minute, I:E ratio of 1:1, pulse frequency of 450 os-

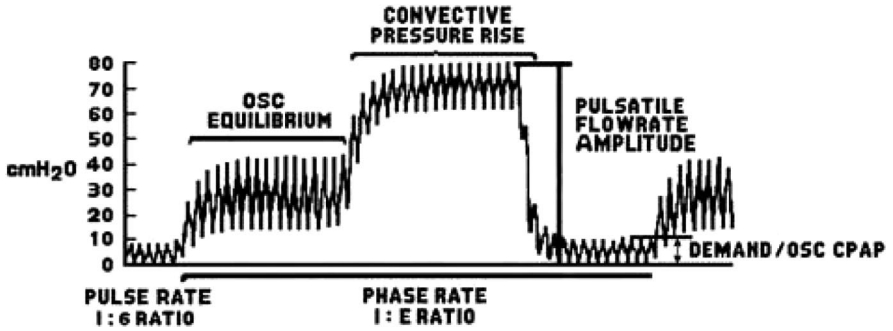

Figure 1. High-frequency percussive ventilator waveform modified.[10]

cillations per minute, and peak inspiratory pressure set at less than 35 cm of water. Settings were then adjusted based on patient response. All patients treated with the VDR after mid-1998 had an aerosolized solution containing 5000 units of heparin, 0.5 ml of 0.5% albuterol, and 3 ml of 20% acetylcysteine administered every 4 hours until there was no further carbonaceous material suctioned from the endotracheal tube.[11]

Control Population

The control population was all patients with inhalation injury treated with CMV during the study period (1997–2005). A total of 130 patients were identified. Before 2001, volume control ventilation was initially used with tidal volumes of 10 ml/kg. Peak airway pressures were adjusted to maintain oxygenation and keep tidal volumes within the target range. After publication of the ARDSNET data, pressure control ventilation was used, peak airway pressures were kept to less than 35 cm H_2O, and tidal volumes limited to 6 ml/kg in most patients.[4]

Statistical Analysis

The primary outcome studied was patient mortality. Mortality rates were calculated based on total body surface area burned broken down into 0–40%, 41–59%, and ≥60%. Secondary endpoints were total length of hospital stay, length of stay (LOS) in the intensive care unit (ICU), total ventilator days, incidence of ventilator associated pneumonias, and pneumothoraces. Pneumonia was defined as the development of a new unilateral pulmonary infiltrate on chest radiograph, leukocytosis (white blood cell count >11,500), hyperthermia (body temperature >39°C), and the presence of a dominant organism on culture after more than 48 hours of continuous mechanical ventilation. Age, TBSA burn, and percent of full-thickness burn were averaged among groups for comparison. Chi-square analysis was used to determine differences between mean values in each category. Multivariate linear regression analysis was then performed for all patients in the dataset. Data are expressed as mean ± SEM.

RESULTS

Ninety-two patients with inhalation injury were treated with HFPV. Patient characteristics are shown in Table 1. Mechanisms of injury were similar in both groups and are as follows: house fires, flame burns, gasoline fires, motor vehicle crashes, and steam burns, with the vast majority being house fires. There were no significant differences between groups with regards to age, %TBSA, and % full-thickness TBSA.

Table 1. Patient characteristics

	HFPV (n = 92)	CMV (n = 130)	P Value
Sex			
Male	66	79	.098
Female	26	51	.098
Age (years)	37 ± 2.1	37 ± 2.1	.95
TBSA (%)	31 ± 2.7	36 ± 2.4	.16
Full-thickness burn (TBSA%)	21 ± 2.7	27 ± 2.5	.13

Table 2 illustrates outcome differences between study and control groups. Length of ICU stay for the HFPV group was 23 ± 2.2 days, not significantly different from that of the control group (22 ± 2.7 days, p = 0.90). Overall LOS also was not significantly different between groups (30 ± 2.9 vs 27 ± 3.1 days, p = 0.46). Mean HFPV ventilator days did not reach statistical significance when compared with control patients (17 ± 1.8 vs 18 ± 2.4 days, respectively, $P = .92$). The incidence of pneumonia was 30% in both groups ($P = .73$). Spontaneous pneumothoraces were infrequent in both groups, occurring in 2.4% of patients on HFPV and in 7% of controls ($P = .13$).

Mortality in patients receiving HFPV was 28%, a statistically significant benefit from that seen in patients treated with conventional modes of ventilation (43%, $P = .02$). When subgroup analysis was performed, there was also a significant mortality benefit among patients with minor burns (≤40%; 15 vs. 32%, $P = .02$). However, this did not hold true for patients

Table 2. Results and complications

	HFPV (n = 92)	CMV (n = 130)	P Value
Length of stay, days	30 ± 2.9	27 ± 3.1	.46
Intensive care unit stay, days	23 ± 2.2	22 ± 2.7	.90
Ventilator days	17 ± 1.8	17.8 ± 2.4	.92
Mortality (%)	26 (28)	56 (43)	.02
0–40% TBSA	9/61 (15)	25/79 (32)	.02
41–59% TBSA	8/17 (47)	10/23 (44)	.82
>60% TBSA	9/14 (64)	21/28 (75)	.47
Ventilator-associated pneumonia (%)	28 (30)	40 (30)	.73
Pneumothorax (%)	2 (2)	9 (7)	.13

Table 3. Patients who survived to discharge

	HFPV (n = 59)	CMV (n = 74)	P Value
Ventilator days	19.0 ± 3.6	24.4 ± 3.5	.12
Intensive care unit stay, days	25.7 ± 2.7	31.7 ± 2.9	.15
Length of stay, days	35.1 ± 2.2	39.6 ± 2.6	.37

with burns of 40% TBSA or greater. Use of HFPV did not result in being a significant predictor of mortality when multivariate regression analysis of the entire population was performed. Among patients who survived to discharge, there was no significant difference in length of stay, ventilator days, or number of ICU days (Table 3).

DISCUSSION

Inhalation injury is thought to cause pulmonary damage via a number of pathophysiologic mechanisms and is a frequent cause of death among patients sustaining thermal injury.[2,3] Smoke applied to the airways causes endothelial cell damage, leading to cellular edema and occlusion of small airways. Endothelial sloughing also leads to occlusion of smaller airways by cellular casts. Post-obstructive pneumonia rapidly develops in these patients, and is associated with mortality rates of 40% to 60%.[2,4,6,8] HFPV has been shown to reduce development of pneumonia in patients with inhalation injury.[5,12] However, our study failed to show a difference in the development of pneumonia in patients with inhalation injury when treated with HFPV. Anecdotally, HFPV is much more effective in clearing airway debris than CMV, although this benefit is difficult to quantify.

Many studies have shown that both high tidal volumes and airway pressures worsen mortality in patients with acute respiratory distress syndrome.[5,13–15] To maintain gas exchange, conventional modes of mechanical ventilation merely provide supportive care to patients with inhalation injury in the form of higher fractions of inspired oxygen and increased airway pressures. The concept underlying HFPV for the treatment of inhalation injury is that addition of stacked, subtidal volume breaths allows for diffusion of oxygen into the distal airways at lower mean airway pressures while avoiding repetitive cyclical opening and closing of terminal airways. In the pediatric population, HFPV improves gas exchange at lower peak airway pressures when compared to pressure control ventilation.[16] This mode of ventilation mimics the action of the mucociliary system at lower oscillatory frequencies, promoting the clearance of airway debris. Instead of using higher airway pressures to augment gas exchange, HFPV improves alveolar function directly by eliminating the distal obstruction which is the root of the problem.

There were no significant differences between the group treated with conventional mechanical ventilation and the group treated with HFPV with respect to many of the outcome variables. Additionally, there was no difference between the control and HFPV group with regard to pulmonary barotrauma, which was estimated indirectly using rate of pneumothorax development. All patients with pneumothoraces were younger than 56 years of age with one exception, and none had been diagnosed with chronic obstructive pulmonary disease before sustaining their inhalation injury. The incidence of pneumothorax in the conventional mechanical ventilation group was nearly 4.5 times that in the HFPV group, although the lack of a statistical difference might be attributed to a type 2 error. The levels of ventilatory support in this patient population were changed frequently to match corresponding changes in each patient's clinical condition and level of sedation. Details of variables recorded multiple times daily such as mean airway pressures, tidal volumes, and positive end-expiratory pressure applied were not evaluated because of the unavailability of legible, microfiched control group records.

In this study, there was a significant overall survival advantage conferred to the patients treated with HFPV. Subgroup analysis showed that patients with large burns (≥40%) had no significant survival advantage when treated with HFPV. In concordance with the findings of previous animal studies, this result may represent the reduction in mortality that would be expected from ventilator effects alone.[12] There were patients in both HFPV and control groups with inhalation injury who had no associated cutaneous burn. These numbers were relatively equivalent and too small for statistical comparisons.

There are several limitations to this study. First, it is a retrospective chart review, which carries with it inherent weaknesses. Patients in this study were not truly randomized to either control or treatment groups during the study period but were assigned to ventilator modalities based on the preference of the attending burn surgeon. There were no significant differences based on these assignments. During the period patients were accrued for the HFPV group, the concept of low-volume lung protective ventilatory strategies was introduced.[5] Conceptually, this method of ventilation also should improve survival in patients with inhalation injury although, as previously

mentioned, lung-protective ventilatory strategies lack the ability to promote the clearance of airway secretions, a key feature of HFPV. Whether this directly benefits patients has yet to be determined. If this were true, one would expect mortality across all percentages of cutaneous burn to improve. Second, this study, although large, is limited in its scope. Both control and treatment arms are small and from a single institution, increasing the possibility of a type 2 error. A randomized, prospective trial would need to accrue patients in a relatively short time period to avoid confounding results with other newer treatments (such as the advent of low tidal volume ventilation during this trial), a task that would be difficult for a single institution to easily accomplish. There is no well-established grading scale for prospectively determining severity of inhalation injury with respect to the amount of carbonaceous material present in the airways. It would stand to reason that less carbonaceous material might represent a lesser physiologic injury and would be more easily cleared than a more severe one. If this grading failure is not taken into account, it may serve to skew the results of any study involving the treatment of inhalation injury. Statistical discrepancies between chi-square tests and multivariate linear regression models also confound the results. Further study is needed to better determine a solid statistical difference in either direction.

HFPV conferred a mortality benefit to patients with burns less than 40% TBSA. From a resource utilization perspective, patients who are treated with HFPV and survive to discharge do so with fewer overall days in the hospital, and fewer days requiring intensive care unit monitoring and treatment. The results of this study, although not clearly beneficial to all burn sizes, are promising, especially given the results of previous studies in this patient population.[4,6]

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REFERENCES

1. Pruitt BA, Cioffi WG, Schimaze T, et al. Evaluation and management of patients with inhalation injury. J Trauma 1990;30:S63–9.
2. Thompson PB, Herndon DN, Traber DL, et al. Effect on mortality of inhalation injury. J Trauma 1986;26:163–5.
3. Pruitt BA, Cioffi WG. Diagnosis and treatment of smoke inhalation. J Intensive Care Med 1995;10:117–27.
4. ARDS Network. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000;342:1301–8.
5. Cioffi WG, Rue LW, Graves TA, et al. Prophylactic use of high-frequency percussive ventilation in patients with inhalation injury. Ann Surg 1991;213:575–82.
6. Cioffi WG, Graves TA, McManus WF, et al. High-frequency percussive ventilation in patients with inhalation injury. J Trauma 1989;29:350–4.
7. Reper P, Van Bos R, Van Loey K, et al. High frequency percussive ventilation in burn patients: Hemodynamics and gas exchange. Burns 2003;29:603–8.
8. Reper P, Wibaux O, Van Laeke P, et al. High frequency percussive ventilation and conventional ventilation after smoke inhalation: A randomized study. Burns 2002;28: 503–8.
9. Rodeberg D, Maschinot N, Housinger T, et al. Decreased pulmonary barotrauma with the use of volumetric diffusive respiration in pediatric patients with burns: The 1992 Moyer Award. J Burn Care Rehabil 1992;13:506–11.
10. Percussionaire. VDR User's Manual. Sandpoint, IN: Percussionaire; 2002:10.
11. Desai M, Mlcak R, Richardson J, et al. Reduction in mortality in pediatric patients with inhalation injury with aerosolized heparin/acetylcysteine therapy. J Burn Care Rehabil 1998; 19:210–12.
12. Rue L, Cioffi WG, Mason A. Improved survival of burned patients with inhalation injury. Arch Surg 1993;128:772–8.
13. Cioffi WG, deLemos RA, Coalson JJ, et al. Decreased pulmonary damage in primates with inhalation injury treated with high-frequency ventilation. Ann Surg 1993;218: 328–37.
14. Dreyfuss D, Soler P, Basset G, et al. High inflation pressure pulmonary edema: Respective effects of high airway pressure, high tidal volume, and positive end-expiratory pressure. Am Rev Respir Dis 1988;137:1159–64.
15. Muscedere J, Mullen J, Gan K, et al. Tidal ventilation at low airway pressures can cause pulmonary barotrauma. Amer Rev Resp Dis 1992;145:A454.
16. Carman B, Cahill T, Warden G, et al. A prospective, randomized comparison of the volumetric diffusive respirator vs conventional ventilation for ventilation of burned children. J Burn Care Rehabil 2001;23:444–8.