Use of High Frequency Oscillatory Ventilation (HFOV) in Neurocritical Care Patients

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Abstract

Introduction Adult respiratory distress syndrome (ARDS) can be a common problem associated with the treatment of acute brain injury. High frequency oscillatory ventilation (HFOV) is a developing therapy for the treatment of ARDS in adult patients that can be life saving. However, often patients with acute, severe brain injury demonstrate intracranial hypertension (hICP) due to a variety of injuries (e.g., traumatic brain injury, mass lesion, acute hydrocephalus). There is concern over the use of HFOV due to its effects on intracranial pressure in patients with hICP.

Methods Retrospective case series study.

Results We describe the effects of HFOV on hemodynamics, respiratory function, and intracranial pressure in five patients with acute brain injury being treated for ARDS.

Conclusions HFOV did not cause unmanageable or sustained increases in ICP in our series of patients. It appears HFOV may be a relatively safe and effective means of oxygenating patients with severe ARDS and concomitant hICP secondary to acute brain injury.

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Introduction

Patients with acute brain injury are often at risk for the development of adult respiratory distress syndrome (ARDS). Treating ARDS has become an increasingly common problem for healthcare providers managing critically ill patients in neurocritical care units. Etiologies such as ventilator associated pneumonia, pulmonary trauma, and interventions whose complications include pulmonary edema and loss of cilliary function often predispose these patients to the development of ARDS [1, 5, 9]. While ARDSNet data and other resources have helped better define, identify, and prevent ARDS, there is still much debate on appropriate treatment strategies especially in patients with complicated neurologic damage.

High frequency oscillatory ventilation (HFOV) is one form of ventilation aimed at treating poor oxygenation associated with ARDS. This ventilation treatment strategy is used to recruit alveoli while reducing sheer forces within the lung, which can exacerbate ARDS [1, 5, 9]. While frequently used in pediatric populations its use among adults has been limited to salvage therapy techniques [13]. Initial data in other adult population subgroups shows favorable outcomes with the use of HFOV on ARDS patients. Though significant strides over the last decade have been made in the development of new strategies to manage respiratory failure in the neurologically ill, newer ventilation methods have not been evaluated [2, 15]. Little is known about how HFOV affects intracranial pressures (ICP) in those with acute brain injury, and there are

warranted concerns over the effects of passive hypercapnea, sustained high mean airway pressures, and sedation required for non-conventional ventilation. At this time to our knowledge, there is no published evidence to support or dismiss the use of HFOV in patients with neurologic injury. With the exception of one article regarding the effects of high frequency percussive ventilation (HFPV) [13], there is almost no data to suggest the utility or safety of high frequency ventilation (HFV) in the adult neurocritical care population. To date some providers may have avoided utilizing HFV, specifically HFOV, to treat patients with ARDS simply from a lack of knowledge about the effects of HFV on the brain. Here we report five cases of HFOV used in patients with acute brain injury and its effect on ICP.

Methods and Results

Patients who received HFOV were identified through the Duke University Medical Center Respiratory Database. In total seven patients received HFOV in the NeuroCritical Care Unit (NCCU) over the course of 18 months. It was determined five of these patients had acute brain injury as their primary diagnosis and ARDS as a secondary diagnosis.

Case 1

A 16-year-old female was admitted to the hospital for treatment of a traumatic brain injury she sustained from a rollover motor vehicle accident in which she was ejected from the car. A CT of the brain revealed multiple small focal hemorrhages in the bilateral frontal lobes and left cerebellar hemisphere consistent with diffuse axonal injury (DAI). Additional injuries included a grade IV splenic laceration, left femur fracture, bilateral pulmonary contusions, and facial lacerations. The patient was intubated in the field with a GCS of 4 (E1, M2, V1) for airway protection. She was initially admitted to the surgical intensive care unit (SICU) but was transferred to NCCU on day four of her hospitalization for management of worsening intracranial hypertension. The patient's condition was further complicated by an aspiration pneumonia (S. marcescens) acquired prior to admission, and by day four she met criteria for diagnosis of ARDS.

On admission to the NCCU the patient did not open her eyes, flexed minimally to pain, and remained intubated with a GCS of 6. Her ICP ranged from 19 mm to 31 mm Hg and her CPP ranged from 59 mm to 82 mm Hg. In addition to draining cerebral spinal fluid, mannitol and hypertonic saline were used to maintain ICP < 25 mm Hg. Propofol and fentanyl infusions were used for sedation. A

Camino bolt had been placed on day two of her hospitalization to measure ICP. On day four the bolt was replaced with a ventriculostomy and a LICOX® monitor was inserted to help monitor perfusion of oxygen to the injured brain ($PbtO_2$). The ICP readings correlated to those obtained with the bolt and initial $PbtO_2$ measurements ranged from 22 mm to 25 mm Hg. However, over 48 h ICP rose and $PbtO_2$ measurements dropped below the desired level of 20 mm Hg; head CTs confirmed worsening cerebral edema but no change in the size of contusions or new focal findings. The positive-end expiratory pressure (PEEP) and the percentage of oxygen (FiO_2) delivered via mechanical ventilation were increased with subsequent improvement in $PbtO_2$ values. Over the course of a week similar ventilator adjustments were made to maintain $PbtO_2$ greater than 20 mm Hg. However, by day nine of her hospitalization the patient's oxygen saturation, arterial oxygenation values, and $PbtO_2$ declined despite full CMV support. The decision was made to switch to HFOV, and sedation changed from propofol to midazolam and cisatracurium. Table 1 outlines the criteria for the implementation of HFOV used at Duke University Medical Center. Table 2 illustrates the patient's vital statistics immediately before and after the switch to HFOV. After HFOV initiation the patient's ICP, PaO_2, $PaCO_2$, and $PbtO_2$ all improved. The patient remained on HFOV for 2 weeks and was eventually successfully transitioned back to CMV once oxygenation with 50% FiO_2 and a mean airway pressure of less than 24 was achieved. Her neurologic exam improved to a GCS of 15 and she was weaned off the ventilator over the course of a week. About 3 weeks later she was discharged from the hospital. She spent several weeks in intense rehabilitation, and on repeat clinic visits has demonstrated a significant recovery to independent living and has returned to school.

Case 2

A 55-year-old female who complained of a severe headache, became acutely unresponsive, and collapsed at work. The patient had regained consciousness and was following

Table 1 Indications for HFOV

A patient may be a candidate for HFOV if their oxygenation status is inadequate and not amenable to conventional mechanical ventilation as evidenced by 3 or more of the following:

A. Plateau Pressure ≥ 30 cm H2O

B. FiO2 ≥ 50%

C. Presence of bilateral infiltrates consistent with ARDS

D. Presence of gross airleak with inability to adequately expand alveoli

Table 2 Vital statistics: this table represents values measured 12 h before and 16 h after switch from CMV to HFOV. 0 h is the time switch

	12-9hrs	8-5hrs	4-0hrs	0-4hrs	5-8hrs	9-12hrs	13-16hrs
Patient 1 ICP	13	12	21	15	10	15	6
Patient 2 ICP	22	58	20	17	15	12	13
Patient 3 ICP	13	20	14	17	14	14	7
Patient 4 ICP	18	21	26	20	16	13	15
Patient 5 ICP	14	8	18	3	8	14	16
Patient 1 CPP	74	71	58	60	66	64	76
Patient 2 CPP	92	90	89	99	101	101	97
Patient 3 CPP	80	71	66	63	58	83	90
Patient 4 CPP	69	79	63	65	92	88	87
Patient 5 CPP	78	73	83	76	72	76	71
Patient 1 PaO2	64	62	38	51	45	70	81
Patient 2 PaO2	66	66	53	63	91	78	83
Patient 3 PaO2	82	63	53	124	84	113	123
Patient 4 PaO2	82	69	46	56	83	90	122
Patient 5 PaO2	75	65	54	96	82	76	121
Patient 1 PaCO2	64	62	45	44	63	54	57
Patient 2 PaCO2	64	69	65	73	40	39	36
Patient 3 PaCO2	37	38	39	54	47	45	46
Patient 4 PaCO2	38	43	41	54	48	39	36
Patient 5 PaCO2	51	54	56	51	54	59	55
Patient 1 PbTO2	15	12	4	16	9	16	17
Patient 2 PbTO2	6	2	9	10	9	12	24
Patient 3 PbTO2	7	5	7	25	20	18	21
Average ICP	16	24	20	14	13	14	11
Average CPP	79	77	72	73	78	82	84
Average PaO2	74	65	49	78	77	85	106
Average PaCO2	51	53	52	55	50	47	46

simple commands when EMS arrived. She was noted to be hypertensive, had left sided weakness, and was transported to the emergency department. On admission her GCS was 14 (E4, M6, V4), but after an acute episode of vomiting, she deteriorated to a score of 7 (E2, M4, V1) at which time she was intubated for airway protection. A head CT revealed a $5 \times 5 \times 5$ cm right basal ganglia hemorrhage with intraventricular extension, 6 mm of right to left midline shift, effacement of the cisterns, and right uncal herniation. She was given recombinant factor VII to prevent extension of the bleed. A ventriculostomy and LICOX® monitor were placed to monitor ICP and PbtO$_2$, initially ranging from 14–44 mm Hg to 16–17 mm Hg, respectively. Intracranial hypertension remained problematic over the course of her stay, despite aggressive management with ventricular drainage, mannitol, hypertonic saline, intravascular cooling, and sedation with both propofol and fentanyl.

This patient developed an aspiration-associated pneumonia (K. oxytoca), and by day seven of her hospitalization she clearly met criteria for ARDS. Over the course of the week the patient's neurologic condition did not improve, and she required increasing CMV support due to poor oxygenation. Moreover, due to sepsis-related hypotension, a norepinephrine infusion was started to maintain a CPP > 60 mm Hg. On day eight of her hospitalization she was transitioned to HFOV (See Table 2 for vital statistics at the time of transition). Oxygen saturation, PaO$_2$, and PbtO$_2$ measurements initially improved with the use of HFOV, and intracranial hypertension did not worsen. Over her 8 days on HFOV, multiple attempts were made to wean ventilator support, but none were successful. Her antibiotic regimen was broadened, and aggressive ICP and hemodynamic management were continued. On day 17 of her ICU stay, she had an acute decrease in her PaO$_2$ while on 100% FiO$_2$ and suffered a complete hemodynamic collapse resulting in pulseless electrical activity (PEA) arrest. Attempts were made at cardiopulmonary resuscitation without success.

Case 3

A 41-year-old male with cerebral palsy and ventricular septal defect fell at home and sustained bi-frontal hemorrhagic contusions, traumatic subarachnoid hemorrhage

(SAH), and a fractured right hip. The patient was transferred to our institution and was admitted to the NCCU with a GCS of 6 (E1, M4, V1). He was intubated for airway protection, and a follow-up head CT was performed which revealed obstructive hydrocephalus. A ventriculostomy was placed for CSF drainage, and initial ICP readings were 17–34 mm Hg. With drainage to an ICP of 10 mm Hg, the patient's neurologic exam initially improved to a GCS of 10 (E4, M5, V1). However, intracranial hypertension became less responsive to drainage, and his GCS again declined to 7 (E2, M4, V1). Hyperosmotic therapy was instituted with mannitol and hypertonic saline. Propofol and fentanyl infusions were also instituted. By day six of his hospitalization the patient developed a ventilator-associated pneumonia (methicillin sensitive S. areus). Appropriate antibiotic therapy was instituted but the patient went on to develop ARDS on day eight. At the same time his ICP became more difficult to control with ventricular drainage and maximal medical therapy including induction of hypothermia via intravascular cooling, and at that point, his neurological exam consisted of only a minimally reactive dilated left pupil. Concurrently the patient's respiratory status slowly declined, and he was subsequently transitioned from CMV to HFOV on day 12 of his hospitalization for management of hypoxia (See Table 2 for values on transition). A therapeutic bronchoscopy was performed for lobar collapse prior to the switch and broad spectrum antibiotics were continued.

With HFOV the patient's oxygenation and his neurologic exam improved slightly with bilateral pupils becoming equal and reactive at 3 mm. His PbtO$_2$ increased from 7 mm Hg to 25 mm Hg within 4 h of transitioning to HFOV. He was transitioned back to CMV on day 14, but at the family's request due to poor overall prognosis, life-support was withdrawn and the patient died.

Case 4

A 56-year-old male who was involved in a single motor vehicle rollover accident. The driver was restrained and extraction time was prolonged. On admission he was hypertensive to a systemic pressure of 240/180 mm Hg, and his GSC was 13 (E3, M6 V4); however, over a 45-min period the patient's level of consciousness deteriorated to a GCS of 7 (E1, M5, V1), and though his brainstem reflexes remained intact, he was intubated for airway protection. A head CT was performed which showed a 2.5 × 3.2 cm right basal ganglia hemorrhage with intraventricular extension into the third and fourth ventricles, midline shift, and hydrocephalus. After placement of a ventriculostomy, initial ICP was ≥25 mm Hg. Hyperosmotic therapy with mannitol and hypertonic saline was instituted, and although

his initial course was complicated by seizures and hypertension, his ICP was manageable by drainage and medical therapy. On ICU day four the patient's exam declined and a repeat head CT showed new right pontine and left posterior cerebral artery infarcts with no interval change in hemorrhage size. In addition, he developed ventilator associated pneumonia (MSSA) on day five of his hospitalization and was started on appropriate antibiotic therapy. Likewise, sedation, analgesia, and paralytics were used to promote ventilator synchrony and control ICP.

By ICU day seven, the patient went on to develop ARDS and was transitioned to HFOV. The patient remained on the oscillator for 7 days, during which he had marked improvement in his oxygenation, overall pulmonary function, and ICP control. He was transitioned back to CMV on ICU day 13 and subsequently weaned off the ventilator completely a few days later. Over the course of 6 weeks the patient's exam gradually improved to the point he was again following simple commands and would engage activities of care. He was close to decannulation of his tracheostomy upon transfer to a long-term acute care facility for rehabilitation 8 weeks after his accident.

Case 5

A restrained 56-year-old male involved in a MVC, motorcycle versus tree. The patient was reportedly confused and combative at the scene; however, on admission his exam had deteriorated to a GCS of 7 (E1, M4, V2), and he was intubated for airway protection. The patient's neurological injuries included multiple small hemorrhagic contusions associated with intraventricular hemorrhage, subdural hemorrhage, and diffuse axonal injury (DAI). Additional injuries included a C-5 fracture, a left clavicular fracture, and bilateral severe elbow lacerations. By day two of his hospitalization his neurologic exam had deteriorated to a GCS of 4 (E1, M2, V1), and repeat head CT showed increased cerebral edema. A ventriculostomy was placed with initial ICP ranging from 18 mm Hg to 39 mm Hg. Drainage of CSF and hyperosmotic therapy were initiated with successful control of his ICP to <20 mm Hg. The patient was diagnosed with an aspiration pneumonia (H. flu) and started on appropriate antibiotics; however, by day three he met criteria for a diagnosis of ARDS. His ability to maintain adequate oxygenation continued to deteriorate on maximum CMV support, and on day four the patient was transitioned from CMV to HFOV. Sedation, analgesia, and paralytics were used to control ICP on both CMV and HFOV. While on HFOV his ICP remained controlled, oxygenation improved significantly, and the patient required smaller amounts of mean airway pressure to maintain adequate ventilation. He remained on the

oscillator for 7 days and was transitioned back to CMV on ICU day 12. After successfully weaning off of mechanical ventilation, he was discharged to a rehabilitation program after a 6-week hospital course. At his follow-up clinic visit his wife reports difficulty with short-term memory as his only lasting neurological problems.

Each of the five charts was retrospectively reviewed to evaluate changes in ICP, cerebral perfusion pressure (CPP), blood pressure (BP), carbon dioxide ($PaCO_2$) and oxygenation (PaO_2) specifically around the transition to and from HFOV. In some cases $PbtO_2$ values, end-tidal CO_2 measurements, and BIS scores were also present for comparison. The values obtained while on conventional ventilation were compared with values recorded on HFOV.

All five patients survived their acute brain injury and were able to be transitioned from CMV to HFOV and then back to CMV. None of the patients exhibited clinically significant changes in ICP, CPP, or BP during transition or while receiving HVOF as compared to conventional ventilation. Some patients did experience an increase in $PaCO_2$ levels. The majority of these changes were transient and did not cause unmanageable increases in ICP. All patients experienced an improvement in PaO_2. Likewise, in the patients with LICOX® monitoring, $PbtO_2$ increased with the improvement in oxygenation from HFOV.

Discussion

In recent years there has been an increased interest in the use of high frequency ventilation (HFV) for the management of ARDS in adult populations and has thus far been most extensively published regarding the use of HFOV [1]. However, whether HFOV presents the best lung protective ventilation strategy for the treatment of ARDS remains to be determined. Its implementation has been largely as a rescue therapy or salvage treatment when CMV fails. However, there is research to suggest that implementing HFOV earlier may benefit patients and decrease mortality. David and colleagues found mortality was significantly increased, 64% vs. 20%, in patients ventilated for 3 days or more prior to initiation of HFOV in comparison to those receiving the therapy sooner [1]. At our institution there has been increased interest in earlier utilization of HFOV, and we have developed a protocol to assist in determining when this mode of ventilation may be of benefit. Developed in the medical ICU, the protocol suggests that patients should transition from CMV to HFOV when three or more of the following criteria are met: plateau pressure is ≥ 30 cm H_2O, FiO_2 is ≥ 50%, presence of bilateral infiltrates consistent with ARDS, or presence of gross air leak with inability to adequately expand alveoli [11].

There is an ever-growing body of research to support the use of HFV strategies for the effective treatment of ARDS. However, until recently HFOV was not utilized in the neurological ICU due to concerns about its effects on ICP management and the inability to perform neurological examination due to the sedation required for HFOV. It is our supposition that patients with neurological injury and severe ARDS do not appear to be further injured by HFOV, and its early institution may improve patient outcomes and initial ICP management.

Overall there is, to our knowledge, no published research exploring the effects of HFOV on ICP. While the sample size presented here is not adequate to provide statistically significant results, it did yield clinically relevant information. In our patients HFOV appears to have possessed no more risk of increasing ICP than conventional mechanical ventilation. None of the patients in our series showed an unmanageable increase in ICP after starting HFOV, and though $PaCO_2$ did rise this did not translate into uncontrollable or clinically relevant increases in ICP. In fact, after a certain readjustment, or "buffering" period, ICP appeared to fall to previous levels despite hypercapnea, as long as $PaCO_2$ was stable. This reflects work previously showing ICP and $PaCO_2$ relationships in both animals and humans [3, 10, 14].

Another reasonable concern is the possible detrimental relationship between ICP and the sustained high mean airway pressures (mP_{aw}) necessary for HFOV. There are numerous papers on the effect of positive end expiratory pressure (PEEP) on ICP, and it is common practice not to employ high levels of PEEP in patients with intracranial hypertension [4, 7, 10]. The sustained mean airway pressure used during HFOV may be viewed by some clinicians as high PEEP; however, we did not find any significant harmful effect of these pressures in our patients. This may be due to the fact that, though conceptually similar, HFOV does not behave like PEEP in CMV. In HFOV, the large baseline to peak pressure swings are eliminated and instead alveoli remain constantly open, allowing gas exchange to occur. This PEEP-like effect in HFOV results from setting a mP_{aw} and power level, and the traditional tidal volume component in CMV is instead achieved though frequency and inspiratory time settings. All serve to create a steady mP_{aw} with the elimination of baseline to peak pressure swings allowing for the creation of higher mP_{aw} without violating the plateau pressure ceilings of 30 cm H_2O advocated in ARDSNet data [9]. It also creates an environment where shearing forces are eliminated and in turn so is volutrauma.

Our results could be due to the fact that the unfavorable conditions created by increased $PaCO_2$ and high mean airway pressures are offset by the beneficial effects of HFOV, namely improved oxygenation. In our cohort, all

patients saw improved oxygenation after institution of HFOV as evidenced by increased PaO_2; in addition the patients that had brain oxygenation monitoring, all saw improved $PbtO_2$ after initiation of HFOV. The relative hypoxia due to ARDS that patients experience prior to HFOV may be perpetuating difficult ICP management, and, therefore, improved oxygenation may ameliorate the effects of hypercapnea and mP_{aw} by decreasing overall cerebral blood flow. Once this occurs, ICP can begin to normalize. There is some research to suggest that similar HFV strategies may actually improve ICP. Salim and colleagues found the use of high frequency percussive ventilation (HFPV) provided significant improvement in oxygenation with concomitant reduction in ICP within the first 16 h of therapy.[13] Ultimately the same may be true for HFOV with the added advantage of producing less gas trapping than other forms of HFV [12].

Finally, paralysis and heavy sedation are often needed for initiation and continued use of HFOV, and it is reasonable to assume that these factors may also play a role in decreasing ICP. There are data to suggest that paralysis and induction of coma (usually via barbiturates) may be helpful in decreasing intracranial hypertension [6, 8]. A patient is usually paralyzed and heavily sedated in order to tolerate HFOV, and it is reasonable to assume that this may mimic the effects on ICP reported in the literature for barbiturates and/or neuromuscular blockade. Although it is worth noting that while neuromuscular blockers probably have an increased efficacy in ICP control, their use has no correlation with improved outcome. Additionally, this sedation strategy does not allow for neurological examination during the period in which HFOV is utilized. In our patients this did not appear to have detrimental effects, and due to the severity of the relative hypoxia prior to HFOV use, neurological examination may be of secondary importance.

It is clear that a multitude of factors are simultaneously interacting at the time of HFOV initiation and subsequent ventilation. More research is needed to investigate the use of HFOV in the neurocritical care population. Determining the overall effect of HFOV, as well as each individual component of this therapy (permissive hypercapnea, improved oxygenation, sedation/paralysis, and mean airway pressure), on ICP and cerebral perfusion pressure will be important but difficult to assess. Whether HFOV should be used as an initial therapy in ARDS instead of a rescue therapy should also be explored, particularly if it may reduce mortality. In our small series of patients, we found no additional risk of HFOV over standard ventilation in brain-injured patients with severe hypoxemia due to ARDS, and in fact found improved oxygenation in all patients. Therefore, HFOV should be considered by clinicians for the management of patients with acute brain injury and concomitant ARDS.

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