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Feature Article

Oxygen Economics: The Use of Heated High-Flow Nasal Oxygen in Air Medical Transport of the Adult Patient

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A B S T R A C T

The use of oxygen via a heated high-flow nasal cannula (HHFNC) in transport of the adult patient experiencing hypoxemic respiratory failure is an emerging and successful adjunct. Although early intubation was thought to be the safest intervention early in the coronavirus disease 2019 pandemic, what we have learned over the past year was that it would serve the patient best to avoid intubation. We discuss an individual case study of a coronavirus disease 2019–infected patient who required subsequent interfacility air transport to our quaternary care facility. This patient presented to the receiving air medical team on HHFNC. Before January 2021, the capability of this program to transport these patients on HHFNC was not possible because our current ventilation platforms had to be upgraded to include the high-flow option and because of the relative infancy of the HHFNC platforms available for adult air transport. The previously noted approach to not intubate these patients, or to certainly use caution when making the decision to intubate, was not the common theme until late in 2020. Presented in this case discussion will be pertinent positive and negatives as they relate to transporting the patient on HHFNC to include the all-important issue of oxygen supply and demand. The authors would emphasize that the named products in this case are simply products used by the receiving air medical program and do not in any way support an endorsement of these products over any other platforms used to provide positive patient interventions and outcomes.

A heated high-flow nasal cannula (HHFNC) as an adjunct in the intensive care unit (ICU) environment has been in use for over 20 years. The physiology behind the concept of high-flow oxygen (flows 40-60 L/min, fraction of inspired oxygen [F_{IO_2}] up to 100%) for the adult population is it creates pharyngeal washout of dead space gas and can provide precise F_{IO_2}'s with small amounts of positive end-expiratory pressure (PEEP). The benefit of PEEP is small and can be argued based on many patient dynamics (obesity, amount of flow, "mouth open" breathing, etc) but is thought to be as follows: for every 10 L/min per flow, you can add +1 cm H_2O PEEP (4-6 cm H_2O total). This may provide some airway stenting to assist with improved laminar airflow through the airways while possibly contributing to a small increase in functional residual capacity.[1]

HHFNC in the adult population continues to be an underused intervention despite its potentially superior outcomes. Although HHFNC is not a new concept or therapy compared with noninvasive ventilation (NIV) and standard oxygen therapy, it has been shown to improve patient comfort as well as decrease mortality compared with other strategies when treating hypoxemic (nonhypercapnic) respiratory failure patients.[2]

Recently, HHFNC use in air medical and critical care ground transport has become a more acceptable standard of practice to delay or avoid intubation in patients with coronavirus disease 2019 (COVID-19). The demand for interfacility transport to centers of tertiary care remains high. The focus on this intervention appears more emphatic now as opposed to a year ago when COVID-19 infections somewhat precluded using this therapy, along with other noninvasive methods, in fear of aerosolizing infectious particles. The seemingly most common approach to treating COVID-19 patients experiencing hypoxemic respiratory failure was to immediately intubate them, setting such low thresholds that a patient on 5 or 6 L/min oxygen would buy an endotracheal tube and a ventilator.[3] Before the use of HHFNC delivery platforms for transport, such as the Airvo 2 (Fisher & Paykel Healthcare, Irvine, CA) and the Hamilton T-1 (Hamilton Medical, Reno, NV), air medical practitioners were left with making decisions as to what O_2 delivery method would be best to transport these patients. The available delivery devices could range from a

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nonrebreathing mask (NRBM) at 15 L/min, a NRBM at 15 L/min with a concomitant nasal cannula at 10 L/min, or transitioning the patient to mask continuous positive airway pressure or bilevel positive airway pressure (BiPAP). Certainly, there are issues with all of these alternative methods because the addition of NRBM and NC therapies does not ensure a definitive F_{IO_2} nor do they provide an adequate flow rate. Instituting continuous positive airway pressure or BiPAP presents the practitioner with the significant issue of what pressures are to be used with either mode. Whether protocol driven or physician ordered, adding positive pressure as a replacement for HHFNC is a “guesstimate.” BiPAP is flow variable based on patient respiratory demand and the patient’s tolerance of a tight, pressurized mask being strapped to his or her face. The addition of helmet-based NIV does appear to be an alternative.[4] However, because HHFNC limitations are noted to include having a fixed flow rate, mask or helmet-based NIV can have flow variability well over 60 L/min based on demand and the associated leak compensation, depleting the gas supply much faster. The use of helmet-based NIV versus HHFNC has shown no superiority for either method and hence should be subjectively driven when instituting such an intervention.[5]

The humidification piece of HHFNC includes a heater plate that can warm inspired gas to optimal temperature and humidity, which enhances patient comfort with such high gas flows. This helps to avoid the drying of the upper airway and decreases patient energy to warm and humidify this gas as well as expel secretions. The optimal humidity as described by Fisher and Paykel is the “natural balance of temperature and humidity that occurs in the healthy lungs.”[6] This optimal temperature (37°C/98.6°F) and humidity (44 mg/L) is believed to ensure the comfort of the patient and to aid in mucociliary clearance.

Case Discussion

A transfer request was received by the transfer center for air medical transport from an outside hospital for a 49-year-old male patient currently in the ICU on HHFNC with a positive COVID-19 diagnosis confirmed by a respiratory polymerase chain reaction panel on 2 separate tests, 1 from admission and a subsequent positive result 7 days later. The patient presented to the outside hospital with progressive shortness of breath and dyspnea for 3 days’ duration, with an increased temperature (39.1°C/102.4°F) and general malaise. Pneumonia, acute respiratory distress syndrome (ARDS), and hypoxemic respiratory failure due to COVID-19 were diagnosed, and dexamethasone, remdesivir, and antibiotics were initiated. The patient’s respiratory status was supported with high-level BiPAP and subsequent HHFNC. The patient avoided endotracheal intubation up to this point, and the receiving physician expressed a directive not to intubate if possible. The patient was being transferred directly to the operating room (OR) at the receiving hospital for immediate cannulation for venovenous extracorporeal membranous oxygenation.

According to the bedside report, the patient was currently using a Vapotherm HHFNC (Vapotherm, Exeter, NH) at 40 L/min with 100% F_{IO_2}. The patient is “fine as long as he doesn’t move too much” per the sending nurse. The crew completed the receiving report and donned the appropriate personal protective equipment and presented bedside to find the patient in the semi-Fowler’s position. On examination, the patient was alert and oriented $\times$ 4, appeared flushed, and was tachypneic with a respiratory rate of 28 breaths/min. The bedside monitor showed a sinus tachycardia with a rate of 120 beats/min, and hemodynamics were unremarkable. Current oxygen saturations at rest were 90% to 92%. Breath sounds were markedly decreased with crackles. A chest X-ray from the morning of the transport showed “worsening ground glass opacities, greater in the upper lobes. New, small pneumo-mediastinum.” The patient has a triple-lumen peripherally inserted central catheter in the right upper arm and a 20-G intravenous line in the right wrist (in the event rapid sequence intubation/delayed sequence intubation was going to be an issue). The crew introduced themselves and explained the stepwise course of action to initially include transferring the patient’s oxygen support to the Hamilton T-1 ventilator in high-flow mode. This was to ensure the patient would tolerate the equipment change without any decompensation. Alternate treatment interventions could include oronasal BiPAP and emergent intubation as explained to the patient. The patient voiced understanding, and consent was obtained for transport. The patient was wearing a surgical procedure mask over his nose and mouth and over the HHFNC interface, which was continued after the changeover was complete.

The transport ventilator was placed on the high-pressure wall outlet and placed in the “HiFlowO2” mode with the flow set to 40 L/min and F_{IO_2} at 100%. A medium Optiflow (Fisher & Paykel Healthcare, Irvine, CA.) nasal prong interface was attached to the circuit, and the changeover was made to the T-1 transport platform. O_2 saturations were unchanged. A brief 5-minute period of no clinical patient changes was observed and the patient was transferred to the flight stretcherThe patient remained in sinus tachycardia with a heart rate of 121 beats/min. Oxygen saturations were at 86%, and the respiratory rate was 32 breaths/min. The air medical crew requested feedback from the patient to which he stated he was fine but “just short of breath,” also confirming this was not abnormal from previous times he moved. The flow was increased to 60 L/min, which is the maximum flow allowed on current HHFNC devices in the United States. The F_{IO_2} remained at 100%. This decrease in saturation of peripheral oxygen is indicative of the marked lack of functional residual capacity this patient has as a result of the current COVID-19 infection. His computed tomographic scan the day before transport is shown in Figure 1.

Once the patient was able to achieve a saturation of 90% or greater, the air medical crew placed the patient on an E cylinder at 2,000 psi. Obtaining an E cylinder from the sending facility would allow for more time to the aircraft with some reserve in the event loading was delayed for any reason. This sending facility’s medical ICU was on the first floor of a 5-story facility, and the route to the helipad was relatively unimpeded. Based on the current flow rate and F_{IO_2}, the full E cylinder offered approximately 9 minutes’ duration on the current HHFNC settings before running out of oxygen.

The patient was expeditiously transferred to the aircraft, cold loaded, and placed on the high-pressure main oxygen. The saturation fluctuated between 88% and 91% during this time. The aircraft uses 2

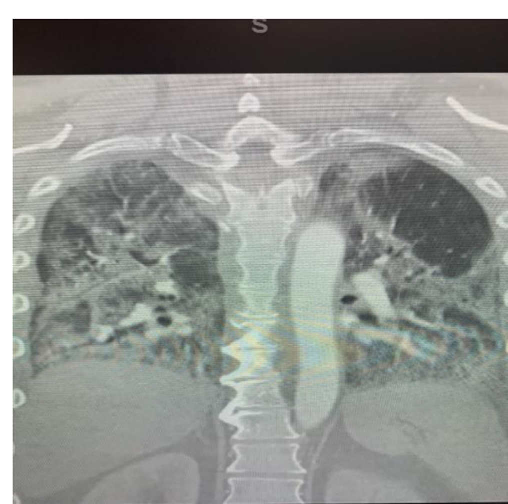

Figure 1.

oxygen tanks containing approximately 2,700 L when filled. The return flight from the sending facility back to the receiving facility was approximately 10 minutes, so the aircraft oxygen supply en route to the receiving facility would be sufficient.

The return trip was uneventful with patient oxygen saturations fluctuating between 90% and 94%. Upon landing on the helipad at the receiving facility, 2 D-size oxygen cylinders were obtained from the storage area near the helipad while the patient remained on oxygen inside the aircraft. Based on the quick reference flowcharts, with the current settings of 60 L/min and the F_{IO_2} decreased to 90% secondary to saturations being minimally improved, and for the small amount of oxygen able to be conserved, the team had approximately 12 minutes total between the 2 D cylinders to transport the patient from the helipad to the OR before both oxygen tanks were dry. Normally, this is about a 5-minute transport with 1 elevator trip up 2 floors.

The patient was safely cold off-loaded, and expeditious transport to the OR ensued. Once in the OR room, the transport ventilator was again placed on a high-pressure oxygen outlet. The operating surgeon was able to briefly discuss the plan with the patient before the anesthesia team was able to place an endotracheal tube and send the patient off to sleep. The transfer was completed with no adverse events recorded. The transfer from the helipad to the OR subsequently consumed half of 1 D cylinder to approximately 1,000 psi. The self-recorded transport time from the helipad to the OR once the patient was off-loaded took 3 minutes 38 seconds.

Discussion

The COVID-19 pandemic has presented unique challenges to not only the ICU teams but also to transport teams across the world. Regardless of the mode of transport, these patients required complex treatment modalities (prone positioning, inhaled pulmonary vasodilators, extracorporeal membrane oxygenation, etc) to combat significant insult to the lungs, causing profound life-threatening hypoxemic respiratory failure. Although some patients were being placed on NIV and HHFNC early in the pandemic, it was thought that this was harmful by way of aerosolizing infectious particles to the treating staff. There was significant concern among air medical crew and ground critical care teams regarding particle transmission. Proper personal protective equipment for the crews and mask coverings for patients were essential to help mitigate this concern. These patients presented like an ARDS insult, which, as we know about treating ARDS and hypoxemic respiratory failure, dictates to not delay intubation because delayed intubation in severe ARDS leads to negative outcomes.[7] These summations directed to intubate patients very early in their diagnosis, leading to many ventilator equipment shortages. When current lessons learned are factored in, we now know that we may have been able to mitigate some of those shortages had these patients not been intubated so early on and so frequently. Treating these hypoxic patients with NIV and HHFNC along with concomitant treatment therapies has shown benefit and positive outcomes.[5]

It should be noted that a significant transport concern, if not the major concern, for HHFNC and NIV patients is the oxygen supply and demand. This is tantamount to a safe and successful patient outcome and transport. In recognizing this demand, our single-aircraft interfacility program ensured all current ventilator platforms were upgraded and capable of the HHFNC option along with its accompanying equipment. The hurdle that remained was to ensure when transporting these patients that there were always sufficient resources, oxygen being the main one, in supply. Shown in Figure 2 is an example of a HHFNC set-up (Fig. 2).

An overall concern addressed by this team regarding portable and onboard oxygen supply was performing calculations and creating quick reference digital or pocket charts (Fig. 3) that we could use as a guide regarding fixed-flow interventions like HHFNC. These charts included the most common tank equipment used in transport from

Figure 2.

bedside to aircraft (D and E cylinder types, respectively) as well as the aircraft's (EC145, 2 tanks, slightly smaller than the "M" cylinder, carrying approximately 2,700 L) gas supply. These quick reference charts do not include the use of a liquid oxygen system. Because of the increased demand we would be seeing in transporting HHFNC patients, we wanted to figure out a way our team could be sure as to the supply and demand of the oxygen on board and further what we would need as it related to the bedside transports.

We used the air-entrainment mask ratio, which relates the air-to-oxygen ratios for common oxygen concentrations. The Hamilton T-1 transport ventilator allows for air inflow on the back of the device up to 260 L/min flow and uses an internal air-oxygen blender, which draws from the ventilator turbine. The air-to-oxygen ratio represents the relationship an air-entrainment device uses to produce a desired oxygen concentration.[8] Oxygen is always expressed as "1" in the ratio, or "1 liter" of oxygen. Thus, an air-entrainment device with a 7:1 ratio mixes 7 liters of air with each 1 liter of oxygen.[8] A constant liter flow and oxygen concentration associated with HHFNCs produced a more accurate table, which mitigated having to "guess" at the duration of a cylinder. Providing the ratios between the 2 gases remains constant, we can take 1 part oxygen and divide it by the total parts for each oxygen concentration. Table 1 lists the fraction ratios for each oxygen concentration, giving us the oxygen consumption factor.[8]

Using the oxygen concentration (F_{IO_2}) and flow (L/min), a calculation was devised to give the amount of time an oxygen cylinder would last at a desired HHFNC setting (in hours and minutes). The desired set flow is multiplied by the oxygen consumption factor for the desired oxygen concentration (F_{IO_2}) and then divided into the total amount of liters in the oxygen cylinder (tank psi × cylinder factor), equaling the minutes available.

$$\text{Minutes} = \frac{\text{Liters in Oxygen Tank (Tank psig } \times \text{ Cylinder Factor)}}{\text{Set Flow}\left(\frac{\text{L}}{\text{min}}\right) \times \text{ Oxygen Consumption Factor (for set Fio2)}}$$

Referring to a D cylinder, HHFNC set at 30 L/min at 30% F_{IO_2} with 2,000 psig available yields 320 L/(30 L/min × 0.111) = 96 minutes (1 hour 36 minutes).

To further confirm our duration times, we bench tested 3 different approaches to oxygen consumption and duration using 2 full (2,000 psig) D cylinders and 1 full (2,000 psig) E cylinder, all with the Hamilton T-1 transport ventilator with concomitant medium Optiflow nasal prongs. We used the Fisher and Paykel Optiflow RT232 circuit with passover humidification. We tested the E cylinder with the high-flow setting at 60 L/min and F_{IO_2} set at 60%. All of these tests were designed with a built-in 200-psig "cushion" so as not to completely use all of the cylinder gas available. Our second test used

E Tank

	FIO2% E Tank @2000psi x0.28 = 560L							
	30%	35%	40%	50%	60%	70%	80%	100%
30L/min	2h 48m	1h 52m	1h 15m	0h 50m	0h 37m	0h 30m	0h 24m	0h 19m
35L/min	2h 24m	1h 36m	1h 4m	0h 43m	0h 32m	0h 26m	0h 21m	0h 16m
40L/min	2h 6m	1h 24m	0h 56m	0h 38m	0h 28m	0h 22m	0h 18m	0h 14m
45L/min	1h 52m	1h 15m	0h 50m	0h 34m	0h 25m	0h 20m	0h 16m	0h 12m
50L/min	1h 41m	1h 7m	0h 45m	0h 30m	0h 22m	0h 18m	0h 15m	0h 11m
55L/min	1h 32m	1h 1m	0h 41m	0h 28m	0h 20m	0h 16m	0h 13m	0h 10m
60L/min	1h 24m	0h 56m	0h 37m	0h 25m	0h 19m	0h 15m	0h 12m	0h 9m

M Tank

	FIO2% M Tank @2000psi x1.54 = 3080L							
	30%	35%	40%	50%	60%	70%	80%	100%
30L/min	15h 25m	10h 18m	6h 51m	4h 37m	3h 25m	2h 44m	2h 14m	1h 43m
35L/min	13h 13m	8h 50m	5h 52m	3h 58m	2h 56m	2h 21m	1h 54m	1h 28m
40L/min	11h 34m	7h 44m	5h 8m	3h 28m	2h 34m	2h 3m	1h 40m	1h 17m
45L/min	10h 17m	6h 52m	4h 34m	3h 5m	2h 17m	1h 50m	1h 29m	1h 8m
50L/min	9h 15m	6h 11m	4h 6m	2h 46m	2h 3m	1h 39m	1h 20m	1h 2m
55L/min	8h 25m	5h 37m	3h 44m	2h 31m	1h 52m	1h 30m	1h 13m	0h 56m
60L/min	7h 42m	5h 9m	3h 25m	2h 19m	1h 43m	1h 22m	1h 7m	0h 51m

H Tank

	FIO2% H Tank @2000psi x3.14 = 6280L							
	30%	35%	40%	50%	60%	70%	80%	100%
30L/min	31h 26m	21h 1m	13h 57m	9h 26m	6h 59m	5h 35m	4h 32m	3h 29m
35L/min	26h 56m	18h 1m	11h 58m	8h 5m	5h 59m	4h 47m	3h 53m	2h 59m
40L/min	23h 34m	15h 46m	10h 28m	7h 4m	5h 14m	4h 11m	3h 24m	2h 37m
45L/min	20h 57m	14h 1m	9h 18m	6h 17m	4h 39m	3h 43m	3h 1m	2h 20m
50L/min	18h 52m	12h 37m	8h 22m	5h 39m	4h 11m	3h 21m	2h 43m	2h 6m
55L/min	17h 9m	11h 28m	7h 37m	5h 9m	3h 48m	3h 3m	2h 28m	1h 54m
60L/min	15h 43m	10h 31m	6h 59m	4h 43m	3h 29m	2h 47m	2h 16m	1h 45m

D Tank

	FIO2% D Tank @2000psi x 0.16 = 320L							
	30%	35%	40%	50%	60%	70%	80%	100%
30L/min	1h 36m	1h 4m	0h 43m	0h 29m	0h 21m	0h 17m	0h 14m	0h 11m
35L/min	1h 22m	0h 55m	0h 37m	0h 25m	0h 18m	0h 15m	0h 12m	0h 9m
40L/min	1h 12m	0h 48m	0h 32m	0h 22m	0h 16m	0h 13m	0h 10m	0h 8m
45L/min	1h 4m	0h 43m	0h 28m	0h 19m	0h 14m	0h 11m	0h 9m	0h 7m
50L/min	0h 58m	0h 39m	0h 26m	0h 17m	0h 13m	0h 10m	0h 8m	0h 6m
55L/min	0h 52m	0h 35m	0h 23m	0h 16m	0h 12m	0h 9m	0h 8m	0h 6m
60L/min	0h 48m	0h 32m	0h 21m	0h 14m	0h 11m	0h 9m	0h 7m	0h 5m

Figure 3.

Table 1
Air:Oxygen Ratios Chart with O2 Consumption Factors

F_{IO_2}	Air:Oxygen Ratios	Fraction Ratios	O_2 Consumption Factor
30%	8:1	1/9	0.111
35%	5:1	1/6	0.166
40%	3:1	1/4	0.25
45%	2:1	1/3	0.333
50%	1.7:1	1/2.7	0.37
60%	1:1	1/2	0.5
70%	0.6:1	1/1.6	0.625
80%	0.3:1	1/1.3	0.769
100%	0:1	1/1	1

An oxygen concentration of 60% has an air-to-oxygen ratio of 1:1 with the total parts equaling 2. This would give us an oxygen consumption factor of 0.5 (1/2 = 0.5). Adapted from Scanlon and Heuer.[8]

a full (2,000 psig) D cylinder with high-flow settings at 40 L/min and F_{IO_2} set to 100%. Our third and final test used another D cylinder with 50 L/min and F_{IO_2} set at 50%. All 3 bench-tested settings were correctly calculated with the built-in "cushion" based on the previously noted equation.

Conclusion

Proper planning prevents poor performance and a bad patient outcome. This, along with any respiratory intervention, is one that requires planning. As air medical crew, we find ourselves in unfamiliar environments, and receiving the patient on the 10th floor of a critical care unit with a ground pad on the opposite side of the facility can present an unknown challenge. Also, as air medical crew, we adapt and overcome, but if we are able, planning for these challenging transfers will prevent surprises and adverse events. As we enter this continuously evolving treatment paradigm, HHFNC will continue to become a mainstay for these patients, along with others who suffer respiratory insult that leads to hypoxemic respiratory failure, not limiting this insult to just COVID-19–infected patients. Because this treatment modality has shown benefit and appears to parallel the beneficial outcomes of NIV, therefore avoiding intubation and mechanical ventilation, at least for the interim, there will be continued demand for transport programs to be able to provide this intervention.

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