High Flow Nasal Cannula: Influence of Gas Type and Flow Rate on Airway Pressure and CO_2 Clearance in Adult Nasal Airway Replicas

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Introduction and Aims

Background

High flow nasal cannula therapy (HFNC) is an increasingly used therapy in the treatment of respiratory failure. HFNC delivers heated and humidified gas through the nares, typically up to 60 L/min. Similar to constant positive airway pressure therapy, HFNC provides a positive airway pressure.[1] Additionally, HFNC has the ability to clear the airway deadspace of exhaled gas, replacing the CO_2 rich gas with O_2 rich gas.[1] Furthermore, novel applications of HFNC are being developed, utilizing gases other than air.[2]

Previous research established a quadratic relationship between pressure, flowrate, and cannula selection.[3,4] This research aims to use *in-vitro* experiments to understand the effects of gas, flowrate, cannula selection and airway geometry on airway pressure and exhaled gas clearance.

Methods

In-vitro Experiments

Five adult airway replicas were fabricated based on MRI scans of healthy volunteers, extending from the nares to trachea, with a closed mouth.[5] These replicas were connected to a lung simulator (ASL5000, IngMar Med. Inc.) at the trachea, via 22mm tubing. A constant flow of CO_2 was supplied simulating production during breathing. HFNC was delivered by placing one of three nasal cannula fully into the nares, and supplying 0-60 L/min of gas. The experimental setup is shown in Figure 1.

Two specialized (Adult Cannula, Vapotherm®) (Adult Small Cannula, Vapotherm®) and one generic (Adult Nasal Cannula 1104, Teleflex Med. Inc.) cannula were selected. Gases considered for testing were air, 99.9% O_2 and He/O_2 80/20. Gas content was sampled at the trachea using a laser diode gas analyzer (GA-200, iWorx Systems Inc.). Pressure parameters were recorded automatically by the lung simulator proprietary software.

Breathing was simulated for one minute in order to achieve steady state gas properties breath to breath. Nine breaths were recorded over 30 seconds. Breathing flowrates were set at the lung simulator. A sample capnograph and the selected breathing pattern are shown in Figure 2.

Additional breathing models were tested by increasing the tidal volume from V_t=500 mL to V_t=750 mL, and separately, by increasing the breathing frequency from f=18 min^{-1} to f=27 min^{-1}. Breathing pattern tests were limited to Vapotherm® Adult cannula, and air as a gas.

Statistical Model

4-factor ANOVA, as well as 1 and 2-factor was used to analyze the significance of HFNC flowrate, gas, cannula and airway geometry, as well as interaction between variables. Tukey post-hoc analysis was also employed to determine specific variable impacts.

A predictive model for PEEP was constructed using mult-variable linear regression. Statistical analysis was performed in the SPSS environment (SPSS 23, IBM Corp.)

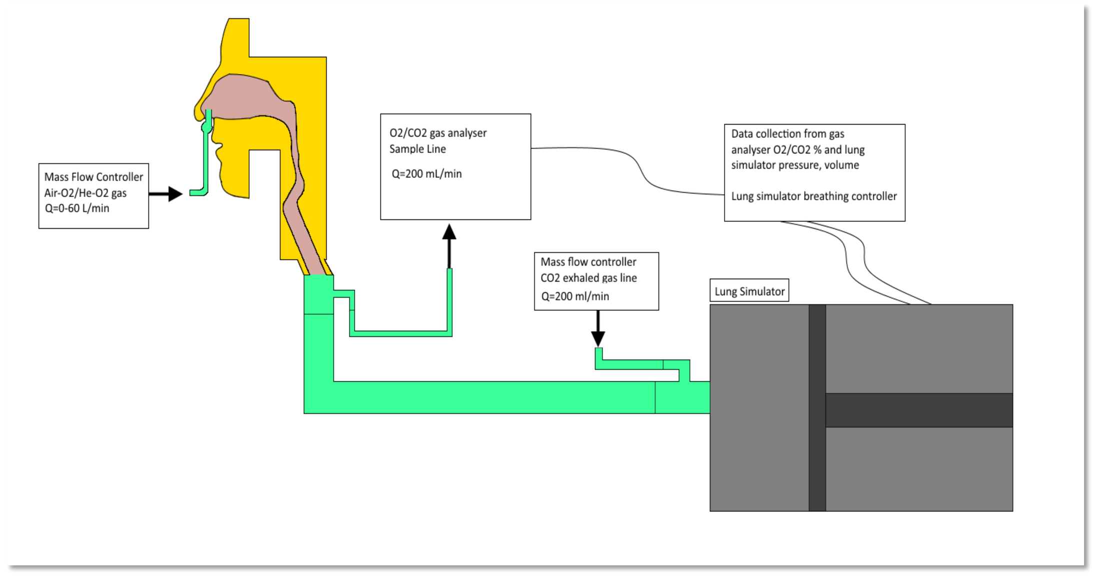

Figure 1: Schematic of experiment, performing HFNC therapy on adult upper airway replica, while breathing and supplying CO_2.

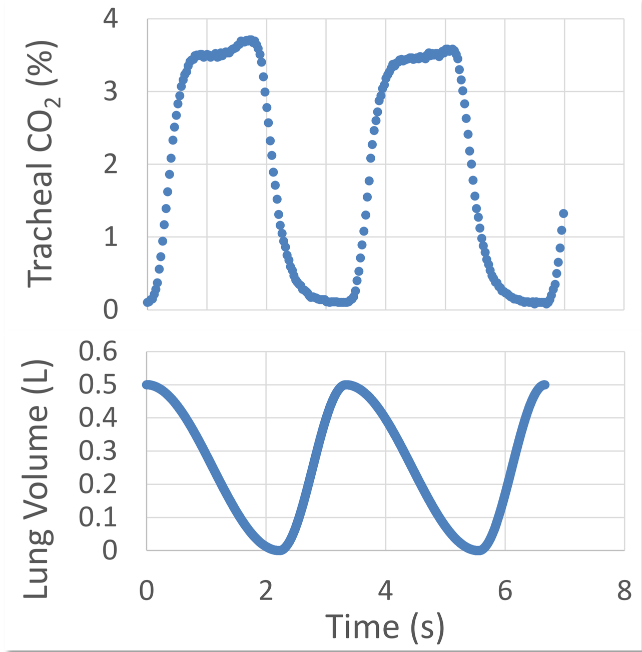

Figure 2: Lung volume waveform, coupled with sample capnograph. Aligned to start at exhalation.

Results

Deadspace Gas Clearance

➢Reduction in average CO_2/breath is shown in Figure 3. The trend appears to be asymptotic.

➢4-factor ANOVA shows airway geometry, gas, cannula and flowrate are significant indicators of average CO_2/breath ($p<0.001$). Variable interactions were also significant ($p<0.01$) in all cases except interaction of the 4 variables. Overall predictive power is R^2=0.993.

➢Repeated single factor ANOVA revealed flowrate, and gas to be individually significant ($p<0.05$). Flowrate was much more predictive (R^2=0.740 vs R^2=0.01).

➢2-factor ANOVA shows approximately equal influence of gas and airway geometry combined with flowrate (R^2=0.824 and R^2=0.819 respectively).

➢Gas influence on clearance is inconsistent subject to subject, as shown in Figure 4. This reflects strong interaction demonstrated in the multi-factor ANOVA.

Breathing Model

➢Increases in breathing frequency and breathing tidal volume both reduced overall average CO_2/breath approximately the same amount.

➢Normalizing average CO_2/breath to results of 0 L/min HFNC, Figure 5 shows negligible difference between breathing models.

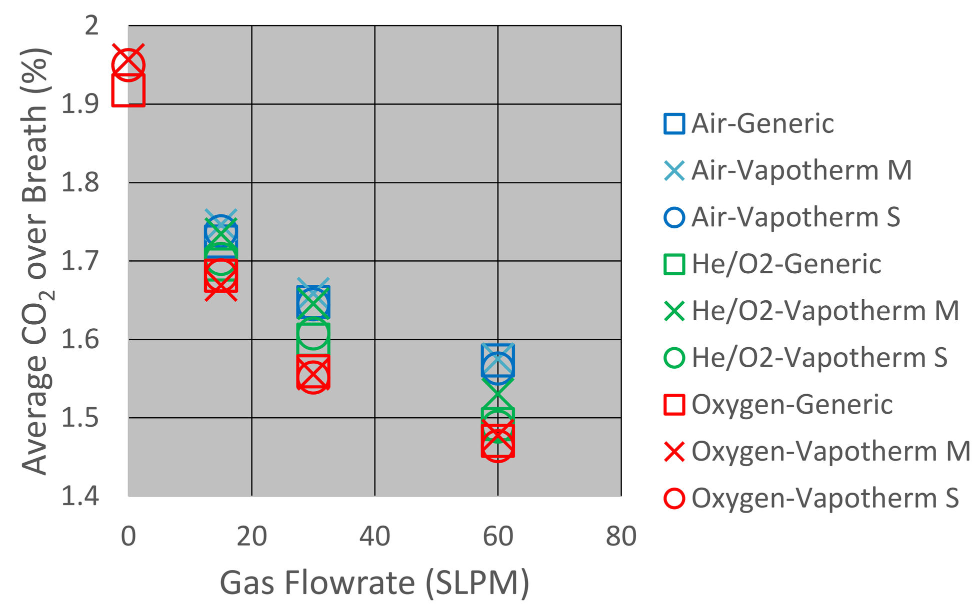

Figure 3: The average CO_2/breath averaged for all airway geometries, controlling for gas and cannula selection.

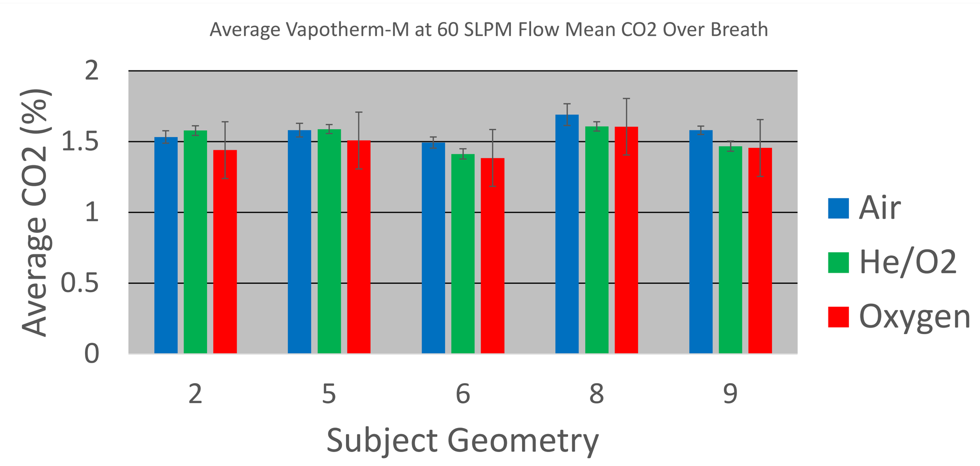

Figure 4: Effects of gas selection and subject geometry on average CO_2/breath. Sample case is for 60 L/min flowrate using the Vapotherm® Adult Normal cannula

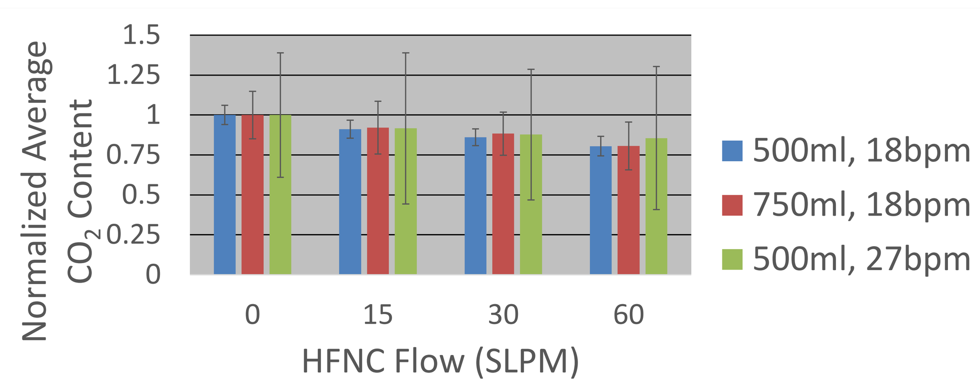

Figure 5: Average normalized CO_2/breath of subject 2 geometry, using Vapotherm® Adult cannula. Results normalized to CO_2 content for breathing type at 0 L/min.

Pressure

➢A quadratic relationship between flowrate and positive end expiratory pressure (PEEP) is found consistently when controlling for airway geometry, gas, and cannula, as shown in Figure 6.

➢Modifying pressure energy balance described in Moore et al.[3] a predictive relationship for PEEP (R^2=0.759) was developed as:

$$PEEP = 0.018\rho_g u_{cannula}^2 + 0.726\rho_g u_{nares}^2 + 23.837\text{Pa} \quad [1]$$

Where ρ_g is the HFNC gas density and u is the mean gas velocity exiting the cannula and nares.

➢This model is further improved (R^2=0.803) by modifying the power of the nares velocity:

$$PEEP = 0.015\rho_g u_{cannula}^2 + 22.2\rho_g u_{nares}^1 - 48.811\text{Pa} \quad [2]$$

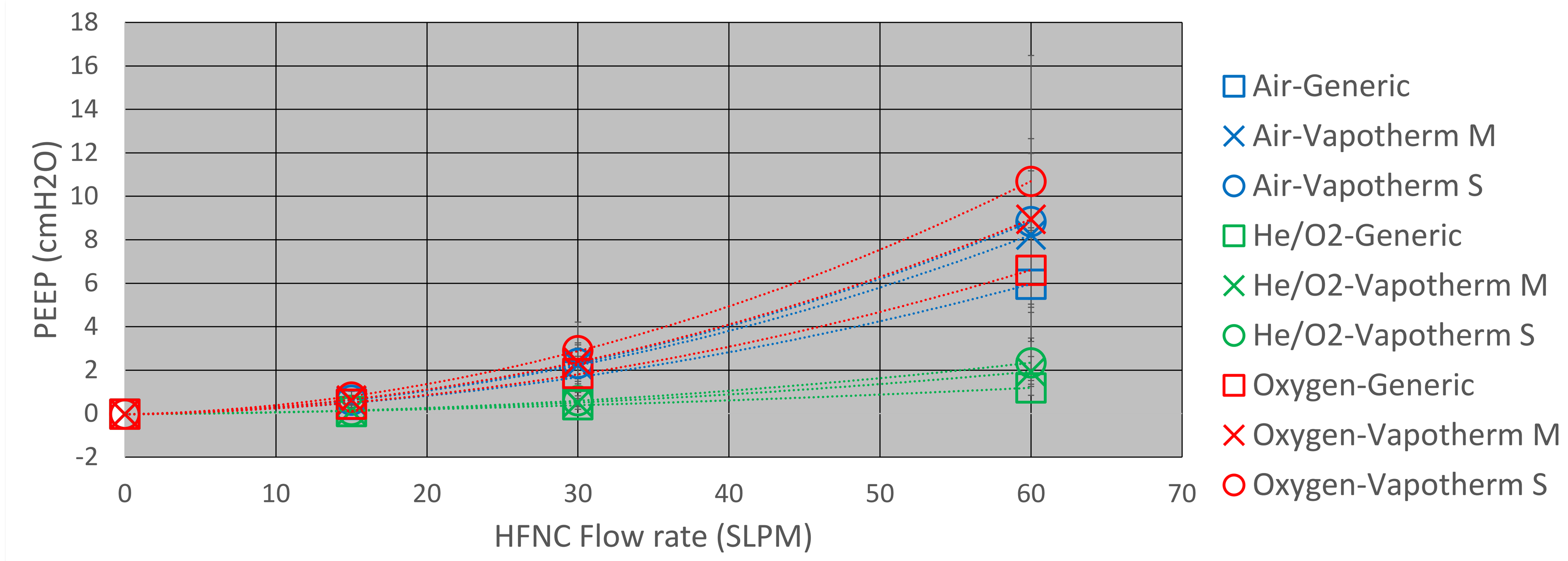

Figure 6: PEEP for the average of all airway geometries, controlling for gas and cannula selection.

Conclusions

➢Increasing flowrate had the strongest effect on deadspace CO_2. The rate of decrease in CO_2 decreases with increasing flowrate.

➢Cannula size and gas selection had a weaker effect on deadspace CO_2.

➢A predictive relationship for PEEP was made, based on flow energy balance.

➢PEEP increased with gas density, where O_2 had the greatest pressure and He/O_2 the lowest.

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