Presented at the 19th Annual Alberta Biomedical Engineering Conference. October 26-28, 2018, Banff, AB.

Experimental evaluation of pressure drop for flows of air and helium-oxygen through upper and central conducting airway replicas of 4- to 8-year-old children

Tyler Paxman, Michelle Noga, Warren H. Finlay, Andrew R. Martin*

Department of Mechanical Engineering, University of Alberta
**Department of Radiology & Diagnostic Imaging, University of Alberta*

Introduction

Background and importance

Respiratory diseases like asthma and cystic fibrosis are widespread among children.[1] These hinder lung function by affecting ventilation distribution, gas transport, gas exchange, and work of breathing.[2] An important quantity for understanding these effects is "airway resistance": the ratio of pressure drop to flow rate in the conducting airways of the lung.[3]

Previous work

Models of analytical airway resistance have been developed for predicting pressure drop in branching airways. The Pedley model (1970)[4], which assumes disturbed laminar flow is well-known and has been employed, modified, and assessed in other works.[5,6]

Limitations and current focus

The present work addresses two main limitations of these previous studies:

1. The effects of the upper airway on pressure drop in the branching airways were not considered previously. The current work involves experiments that include an upper nasal airway inlet condition.
2. Previous models were developed mainly based on adults and do not predict pressure drop in children well.[6] The current work focuses on model development based on child airways.

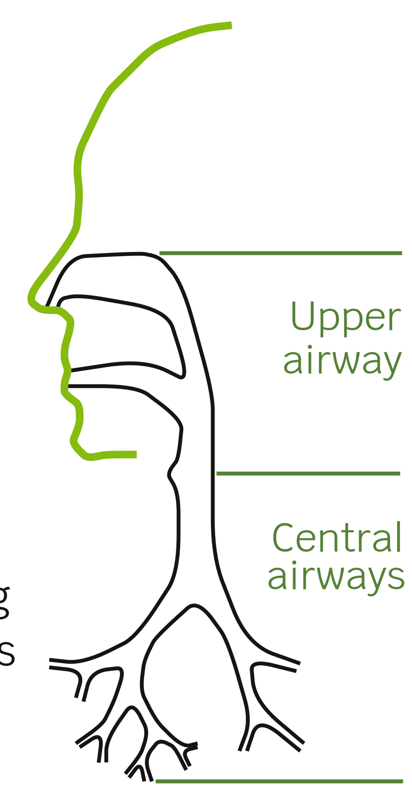

Fig. 1: Conducting airways sections

Methods

Pressure drop experiments

CT scan data from 10 subjects, ages 4–8, were used to produce and assemble 3D-printed replicas of upper and central airways (from the nostrils up to 3–5 generations of branching). These images were previously obtained and used by Borojeni et al. (2014), approved by the Health Research Ethics Board (HREB) of the University of Alberta.[6,7]

Pressure drop was measured for each replica with various constant inspiratory flow rates (5–60 L/min) and gases (air and helium-oxygen, 80-20 mixture) using an in vitro apparatus and nasal masks (Fig. 2). The branching airway segments were attached and detached to get values for nose-throat and branching airway pressure drop separately.

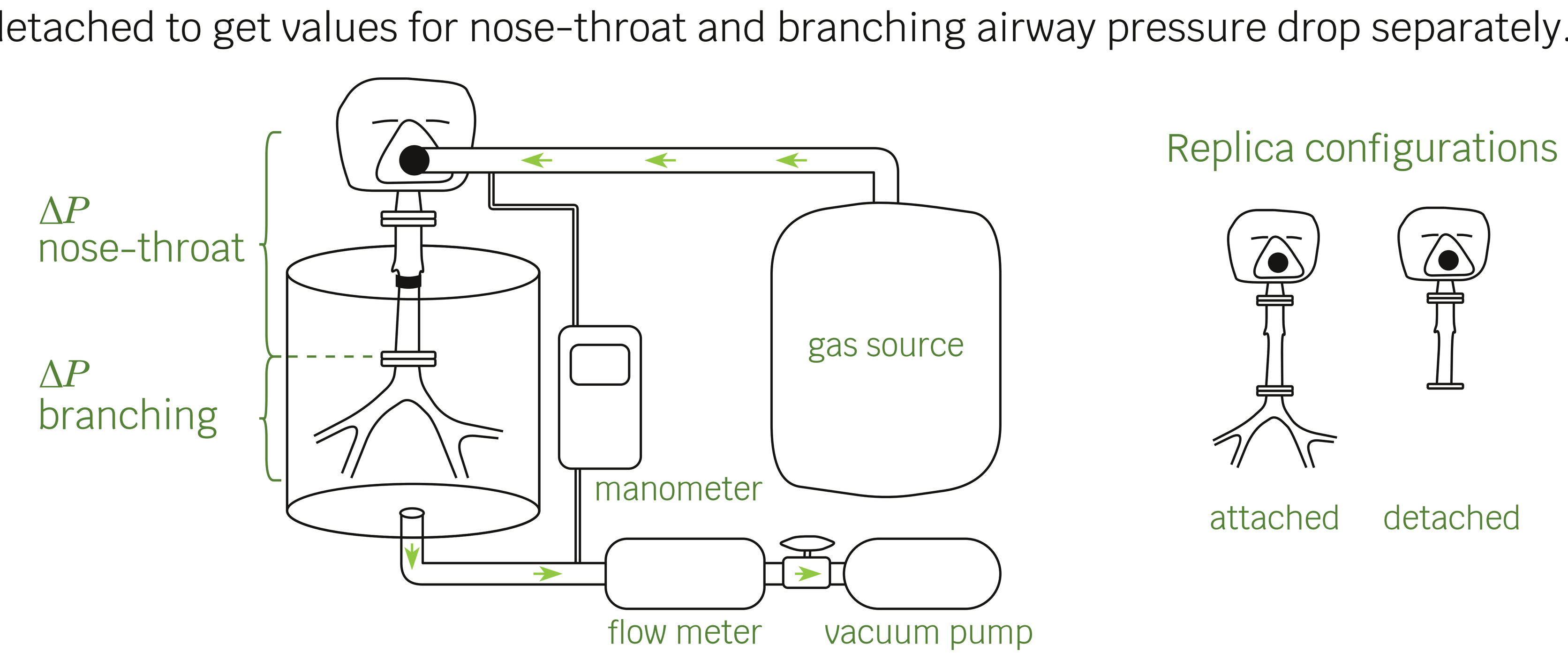

Fig. 2: Experimental in vitro apparatus for measuring pressure drop

General form of pressure drop equations

The experimental data relates pressure drop (ΔP) to gas density, viscosity, and flow rate (ρ, μ, Q) or in non-dimensional terms, coefficient of friction (C_F) to Reynolds number (Re)[8], as shown in Eqs. (1) and (2).

$$\Delta P = f(\rho, \mu, Q) \quad (1)$$

$$C_F = \frac{\Delta P}{1/2\rho v^2} \qquad Re = \frac{4\rho Q}{\pi \mu d}$$

$$C_F = \beta Re^{-\alpha} \quad (2)$$

Determining flow regime

The pressure drop for each flow regime (i.e. laminar, turbulent, etc.) is characterized by the exponent α. Values of α were obtained by plotting and fitting Eq. (2) using experimental data. These were then compared with those of known pressure drop equations for various flow regimes (Table 1) to determine which flow regimes occur in the nose-throat and branching airways of the replicas.

Table 1: α for pressure drop models

Flow type (ΔP *model*)	α
Laminar (*Hagen-Poiseuille*)	1.00
Disturbed laminar (*Pedley*)	0.50
Turbulent (*Blasius*)	0.25

Making absolute value predictions

A coefficient is needed for making absolute value pressure drop predictions. A computer calculation was set up to replicate the experiment by calculating expected pressure drop through the branching airways. The resultant non-linear system can be solved knowing that pressure drop must be equal across all paths (see Fig. 3).

This calculation was done iteratively while updating the coefficient value to optimize correlation with the experimental results (with Lin's concordance coefficient, ρ_c, where 0 = no correlation, 1 = complete correlation).[9]

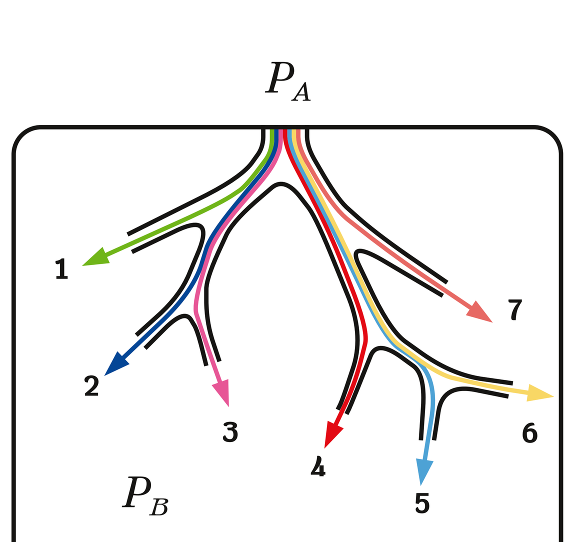

Fig 3: Paths in branching airways

Results

Finding functional form of pressure drop equation

Values of α were calculated for each subject by fitting the experimental data (C_F vs. Re). An example is shown in Fig. 4. Average α values for each airway were:

Branching: **0.24** (± 0.01)
Nose-throat: **0.22** (± 0.02)

Compared with previous models (Table 1) both airway regions most closely follow the turbulent Blasius equation form (i.e. α = 0.25), suggesting the presence of turbulent flow.

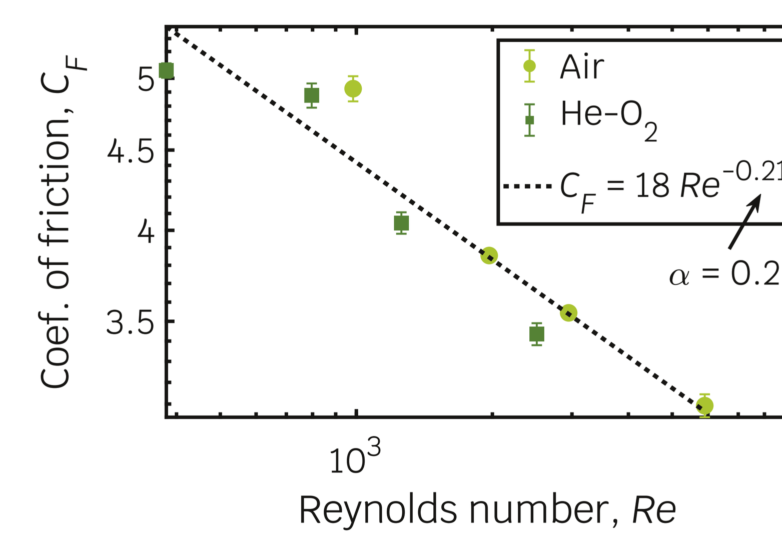

Fig. 4: C_F vs. Re for (branching airways, sub. 10)

Comparing pressure drop of helium-oxygen vs. air

Taking the pressure drop ratio of both gases (i.e. $\Delta P_{He\text{-}O_2} / \Delta P_{air}$) gives a simplified equation that depends on gas properties (ρ, μ) and α only.[10] When α is 0.25, the ratio is **0.455**. The ratios of the experimental data were:

Branching: **0.43** (± 0.03)
Nose-throat: **0.39** (± 0.03)

This again confirms that the turbulent Blasius equation form best captures the flow behavior seen in the experiments.

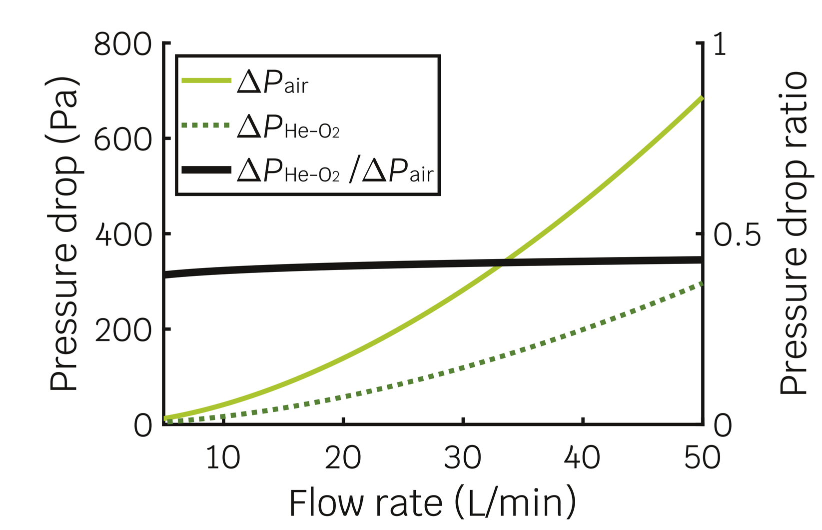

Fig 5: Pressure drop ratio (branching airways, sub. 10)

Finding coefficient to allow absolute value predictions

After determining that the model should have the form of the turbulent Blasius equation, its coefficient (C) was found by iteratively optimizing the correlation between analytical and experimental results, resulting in a modified-Blasius equation, shown in Eq. (3). Subject-specific coefficients (C_{ideal}) were obtained for each subject, and their average (C_{avg}) was found to be **3.0** (± 1.0).

$$\Delta P_{mod\text{-}Blasius} = C\left(\frac{L}{d}\right)\frac{\rho v^2}{2} Re^{-0.25} \quad (3)$$

Using the subject-specific coefficients allowed for accurate pressure drop predictions (ρ_c = 0.997), since it is a fit parameter. However, use of the average value for all subjects resulted in less accurate overall predictions (ρ_c = 0.909) and should be done with caution.

Conclusions

- Comparison of C_F and Re indicates that pressure drop in both the nose-throat and branching airways of children are best described by an equation in the form of the turbulent Blasius equation.
- The inclusion of a realistic nasal inlet condition is important, as turbulence generated in the nose-throat region is convected into the branching airways.
- A modified-Blasius model was proposed for describing pressure drop in the central airways of children.
- It is intended that these results will help other researchers better understand flow behaviour in the airways of children as they develop models in the future, which would ultimately assist with the advancement of clinical treatments.

References

1. Ferkol et al. *Ann Am Thorac Soc.* 2014, 11(3), 404–406.
2. Tgavalekos et al. *Eur Respir J.* 2007, 29(6), 1174–1181.
3. West. *Respiratory physiology: the essentials.* Lippincott Williams & Wilkins, 2012.
4. Pedley et al. *Respir Physiol.* 1970, 9(October 1969), 371–386.
5. van Ertbruggen et al. *J Appl Physiol.* 2005, 98(3), 970–980.
6. Borojeni et al. *J Biomech.* 2015, 48(10), 1988–1996.
7. Borojeni et al. *J Aerosol Sci.* 2014, 73, 39–47.
8. Slutsky et al. *J Appl Physiol Respir Environ Exerc Physiol.* 1980, 49(3), 417–423.
9. Lawrence et al. *Biometrics.* 1989, 255–268.
10. Litwin et al. *J Biomech.* 2017, 58, 217–221.

Thanks

Many thanks to The Canadian Natural Sciences and Engineering Research Council (NSERC) for their funding and support, as well as Fraser Bulbuc, for his major help with producing the replicas.

Contact Tyler Paxman | tpaxman@ualberta.ca