Finite element method simulations of gas flow dynamics in a small animal ventilator

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Introduction

- Constant-volume animal ventilator supplies a mixture of breathable gas and Hyperpolarized (HP) Xenon to small animals in HP *Xe* MRI experiment
- The quality of *Xe* MRI is determined by level of polarization
- HP *Xe* is depolarized in interactions with O_2
- Try to find a solution to prevent or reduce the polarization loss of HP *Xe*.

Methods

- COMSOL is a finite element method software that can be used to perform computation fluid dynamics
- Check by simulating with COMSOL if there is prolonged interaction between HP *Xe* and O_2
- Create CAD model of gas tubing
- Track the volume passed through the outlet and use it to adjust the pressure at the outlet to mimic the backpressure of lungs
- Perform consecutive time-dependent studies of the fluid dynamics and gas concentrations for typical breathing pattern (0.3 s of inhale, 0.3 s of breath hold, and 0.2 s of exhale)

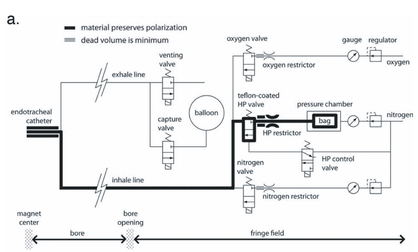

Figure 1: Schematics of Constant-Volume Animal Ventilator

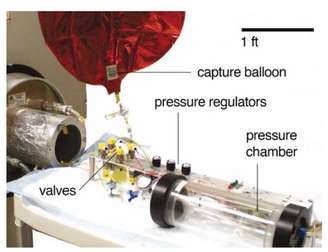

Figure 2: The Ventilator and all the valves are positioned close to the magnet

Results and Discussion

- The gas flow inside the conjunction is extremely sensitive to pressure difference at the inlets.
- O_2 completely dominated the tubes while *Xe* could not even get out.
- Under current setting, the gas velocity is too high, and the lungs are quickly filled up at t=0.008 s, which indicates the 0.3 s of inhale phase is not necessary.

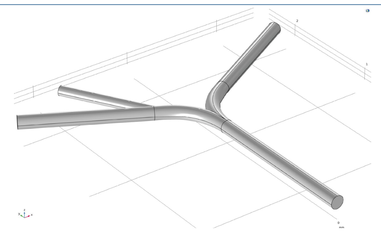

Figure 3: CAD model of the conjunction

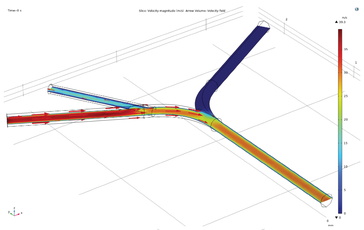

Figure 4: velocity plot at t=0s with $\Delta P = 1.5$psi

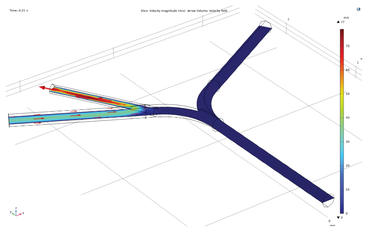

Figure 5: velocity plot at t=0.01s with $\Delta P = 1.5$psi

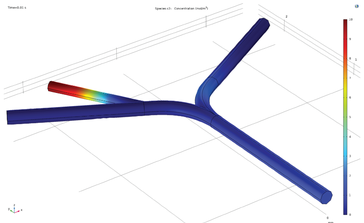

Figure 6: concentration plot of Xe/N2 gas at t=0.01s with $\Delta P \approx 60$Pa

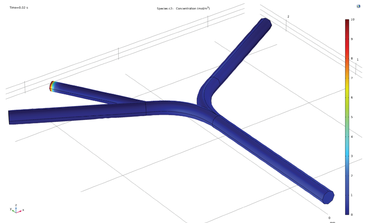

Figure 7: concentration plot of Xe/N2 gas at t=0.02s with $\Delta P \approx 60$Pa

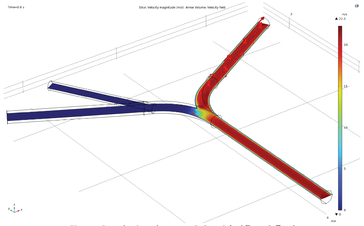

Figure 9: velocity plot at t=0.6s with $\Delta P = 1.5$psi

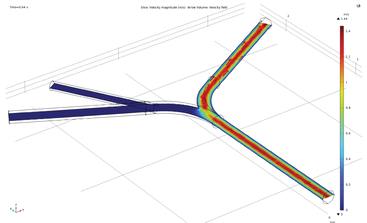

Figure 10: velocity plot at t=0.64s with $\Delta P = 1.5$psi

Conclusions

- Even with reducing the pressure difference from 1.5 psi to about 50 Pa, it is still hard for *Xe* gas to get out of its tube.
- The 0.2 s exhale period is not enough to clear out the conjunction completely because there is no gas flow in O_2 and Xe tubes.
- A possible solution to prevent or reduce polarization loss is to
  - Reverse the pressure setting so that P_{Xe} is higher than P_{O_2}
  - Reduce the pressure difference between the two gases so that both gases can enter the mouse's lung.

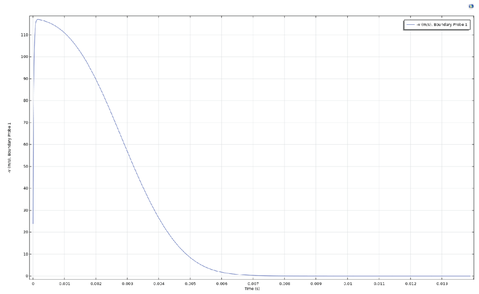

Figure 8: velocity monitored at the lung end of the conjunction with $\Delta P = 1.5$psi

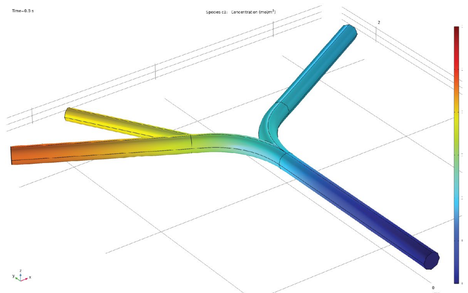

Figure 11: concentration plot of Xe/N2 gas at t=0.8s with $\Delta P = 1.5$psi

Acknowledgements

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References

1. Nouls, J. et al. A Constant-Volume Ventilator and Gas Recapture System for Hyperpolarized Gas MRI of Mouse and Rat Lungs (2011).
2. Limjunyawong, N, et al. Measurement of the Pressure-volume Curve in Mouse Lungs (2015).