An integrated small-animal ventilator and recycling system for small-animal hyperpolarized gas MRI

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Introduction

Hyperpolarized (HP) gas MRI in small animals is challenging and generally requires a dedicated ventilator system. Moreover, the use of expensive rare isotopes such as ^{3}He and ^{129}Xe make it desirable to minimize cost by recycling these gases after they have been used for imaging. We present a constant-volume ventilator that offers precise control of gas delivery, permits high-resolution imaging, and captures the exhaled mixture containing ^{3}He or ^{129}Xe. The captured gas is then compressed by a piston and stored in a cylinder to be sent for re-purification.

Ventilator

The ventilator has been used for hyperpolarized MRI and further developed in our laboratory for 8 years, and was only partially described in the literature [1]. The ventilator uses off-the-shelf valves and standard pneumatic components (figure 2), eliminating the need for a custom-built, integrated pneumatic valve for gas mixing close to the animal [2,3]. The tidal volumes of N_2, O_2, and hyperpolarized gas are precisely controlled by flowing through non-depolarizing sapphire constrictors (O'Keefe Controls, Trumbull, CT). These flow restrictors exhibit a significantly larger impedance than the animal's airways to guarantee the delivery of a constant tidal volume even during bronchoconstriction, for example induced by a methacholine challenge [4].

Three-way, solenoid-actuated valves (ECO-3-12, Clippard, Cincinnati, OH) deliver nitrogen and oxygen to the lungs, or allow the animal to exhale (figure 3). During hyperpolarized gas imaging N_2 is replaced with HP gas, which is administered from a pressurized bag by a two-way pneumatically actuated valve (Parker PV-1-1134, Cleveland, OH) to preserve polarization. To capture the exhaled gas during HP gas imaging, a separate exhale valve directs the gas to a capture balloon (figure 3). The same ventilator can achieve tidal volumes ranging from 0.05 ml (small mice) to 5 ml (large rats) simply by changing the flow constrictors.

HP gas capture and compression

The exhaled mixture of air and ^{3}He or ^{129}Xe gas is collected by a balloon which is then attached to a gas-actuated piston (figure 4) that first withdraws the gas and then compresses it into a gas cylinder for storage (figure 4).

Imaging

Imaging was done as described in [5] on a C57BL/6 mouse instilled intratracheally with 50 µg lipopolysaccharide in a model of acute lung injury. A ^{3}He image array was acquired using a respiratory gated radial acquisition (5 minute acquisition, TE 0.9ms, TR 5ms, matrix 128×128×128, resolution 156×156×156 µm^3). In order to achieve such high-resolution imaging, the ventilator must deliver HP gas in a highly reproducible manner and it must repeatedly position the diaphragm at breath-hold at the same location (figure 1).

Conclusion

The ventilator described here enables high-resolution imaging of HP gases by controlling tidal volume consistently and minimizing motion artifacts. The ventilator design is straight-forward and the system is inexpensive to duplicate. By recapturing exhaled gas, it alleviates some of the costs associated with HP gas imaging.

Acknowledgements

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References

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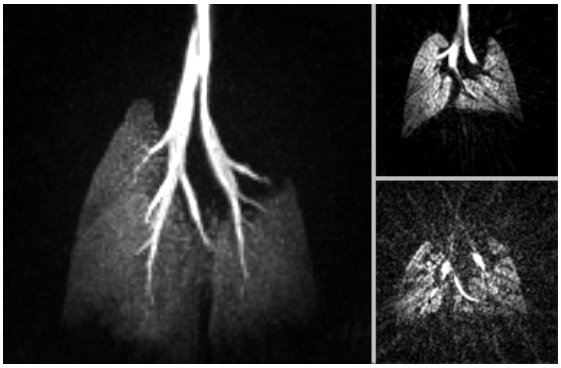

Figure 1: (Left) Maximum intensity projection of a 128x128x128 ^{3}He image array acquired in 5 minutes. The upper left lung is not ventilated, in a model of acute lung injury. (Top) Single slice at 156 µm isotropic resolution. (Bottom) Respiratory motion degrades a high-resolution image when ventilation is not reproducible.

Figure 2: The ventilator uses off-the-shelf components only. No integrated valve is required close to the animal trachea inside the magnet.

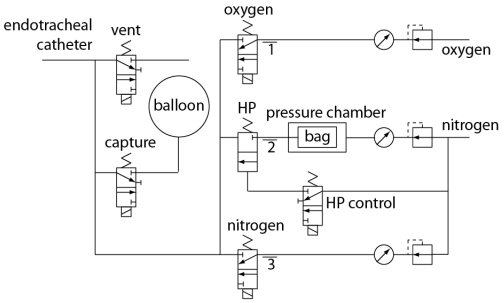

Figure 3: Pneumatic components of the ventilator. The constrictors are marked 1, 2 and 3.

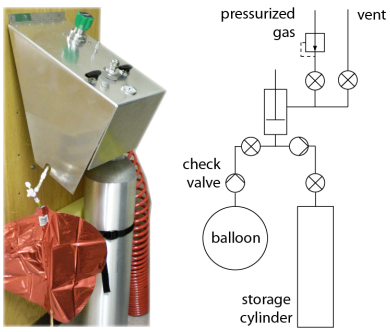

Figure 4: a gas-actuated piston collects HP gas from a balloon and compressed it into a cylinder for storage.