Quantitative MR Imaging of 3He Gas Transport in Model Airways

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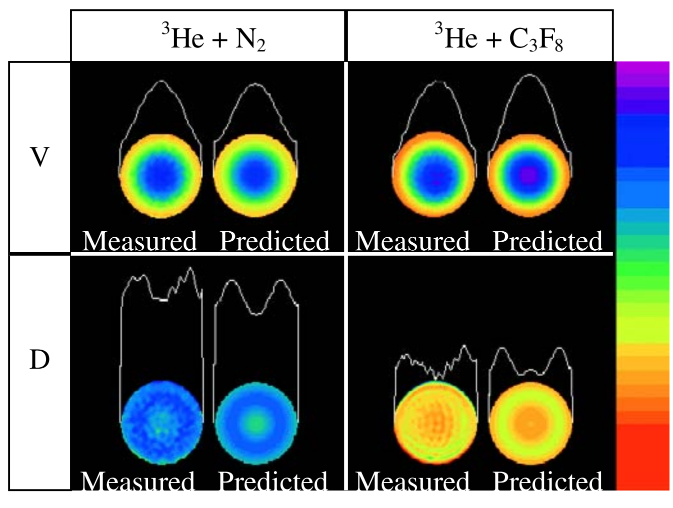
Abstract: The feasibility of quantifying gas transport in the major airways of adult rats is examined by employing two-dimensional (2D) constant-time imaging (CTI) for measuring the dynamics of hyperpolarized (HP) ^{3}He in a straight pipe with a diameter comparable to the rat trachea. At physiological flow rates, measured maps of axial flow and diffusion are accurately predicted using a simple transport model that describes ^{3}He's statistical dynamics. Since the model is generally applicable to any flow conduit, results provide a basis for gas transport studies with noninvasive ^{3}He MRI.

Materials and Methods: CTI was performed at 2.0 Tesla using a UNITYPlus console (Varian, Palo Alto, CA), a home-built birdcage coil having a 7-cm-diameter, and a 30-cm-diameter horizontal-bore magnet (Oxford Instruments, Oxford, UK) equipped with actively shield gradients (Resonance Research Inc., Billerica, MA). Prior to MR imaging ~300 ml of ^{3}He gas was polarized to ~40% using spin-exchange optical pumping. During MR measurements the HP ^{3}He gas was diluted to ~10-volume-percent by mixing it with either N_2 or C_3F_8 upstream of a Tygon hose that was ~1 meter long, had an inner diameter of 3.2 mm, and ran straight through the magnet bore. During gas delivery the volumetric flow rate was measured to be ~240 cc/min by bubbling the binary gas mixture into a graduated cylinder filled with water. Repeated measurements confirmed steady flow conditions. Constant-time images were collected using a 1.0 cm x 1.0 cm field of view and a 6.0-mm-thick slice that was transverse to the central axis of the flow tube. The CTI pulse sequence utilized a single 90° radio-frequency excitation, velocity-compensated slice-selective gradient pulses, two orthogonal phase-encoding gradients, and a bi-polar gradient-pulse-pair to encode axial motion. In all cases, the bi-polar gradient-pulse pair was characterized by a leading-edge-separation (Δ) of 1.0 msec and a pulse-duration (δ) of 300 μsec, and CTI images were acquired using a 16 msec repetition time, a 1600 Hz receiver bandwidth, and 64 phase-encoding steps along each axis. After data collection 2D maps of axial flow velocity and diffusion were created using two phase-sensitive images acquired with different bi-polar gradient strengths (0 and 4 Gauss/cm).

Results: The figure shows a comparison between measured and predicted maps of axial velocity (V) and diffusion (D). Results are presented in pairs with measured and predicted maps appearing adjacent to one another. To highlight differences between maps acquired with different binary gas mixtures all are rendered using the same color scale. The scale consists of 31 colors and ranges from 0 (red) to 100 cm/sec (purple) for velocity (V) maps, and between 0 (red) and 2 cm^2/sec (purple) for maps of axial diffusion (D). One-dimensional profiles across the center of the pipe are rendered in white and are based on values for each transport coefficient.



Measured maps of ^{3}He transport show a laminar-like structure that is accurately predicted. Predicted maps are formulated using a Gaussian approximation that relates the CTI-response to both gas dynamics and data collection. Conceptually, this approximation describes the effects of rapid gas diffusion across the pipe when excited nuclei traverse different flow lamina on the time-scale of CTI measurements. Since all transport measurements were performed at low Reynold's numbers using the same volumetric flow rate, results illustrate how differences for ^{3}He diffusion in each binary mixture mediate apparent values in transport maps. Additional results will be presented that illustrate the effects of CTI acquisition parameters and how findings can be generalized for studying gas transport in more complicated conduits; including, bi-furcating tubes and scaled models of the rodent nasal-sinuses.

Conclusions: This work shows that diffusion and flow both have a significant impact on MR measurements of ^{3}He gas transport and that a simple model of ^{3}He's statistical dynamics accurately describes maps of apparent flow and diffusion in straight pipes of comparable size to major airways in the rat lung.