Helium-3 phase-contrast velocimetry on a human airway model for validation of computational fluid dynamic simulation

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Introduction

A dozen years ago, hyperpolarized (HP) gas MRI appeared as a promising imaging technique for lung exploration [1]. Spin density, T_1, T_2 and diffusion weighted images were subsequently obtained leading to the evaluation of ventilation and to parameters related to parenchyma structure or oxygen consumption [2]. Combined with the use of dedicated MR sequences, even ventilation dynamics could be followed. Flow distribution, particle deposition and gas mixing within large respiratory airways highly depend on the convective patterns of the gas flow. Current knowledge of these patterns relies on in vitro measurements and simulations by computational fluid dynamics (CFD), both usually realized on idealistic geometries. This work introduces the first applications of a recently presented technique to map velocity on gases [3]. The technique used a dedicated MR sequence that combined the dynamic properties of radial *k*-space sampling with phase-contrast (PC) velocity encoding on HP gases. We first applied the technique on known flow patterns for quantitative validation. Measurements were then performed on a realistic phantom of a tracheobronchial tree and compared to CFD simulations performed on the same geometry.

Materials and methods

^{3}He was polarized on site [4]. For each experiment, ~50 mL of pure ^{3}He, polarized at 10% were mixed in a vector gas (air and N_2) and injected for few seconds in flow phantoms by means of a dedicated administrating system. MR acquisitions were performed at 1.5 T with an 8-cm surface coil (Q=300) used both for emission and reception. A spoiled gradient-echo sequence based on radial *k*-space sampling was combined to a PC velocity encoding strategy. 2D images of the three velocity components were obtained in a 1-cm thick slice (flip angle between 10 and 45°). For each projection, a diameter was acquired in *k*-space with 64 points sampled on the full-echo readout (FOV=100 mm, bandwidth=16 kHz, TR/TE=12/6 ms). The orientation order for projections was dichotomous [5] and interleaved by a four-point velocity encoding scheme (velocity encoding=3 m s^{-1}). Sequence was triggered when gas injection started, and projections were acquired continuously for 12 s (256 projections per velocity encoding). Reconstruction was performed off-line by complex filtered back projection and velocity was assessed by phase difference with the reference image. By grouping sets of 32 projections, dynamic images were obtained, each one having a temporal resolution of 1.5 s. Velocity maps were first obtained in a cross-sectional slice in the middle of a U-shape pipe and compared pixel-by-pixel to a CFD simulation (stationary and incompressible flow, no-slip condition on the lateral surface, parabolic entry profile, free outlet) with FIDAP (Fluent Inc., Lebanon, NH, USA). Airway geometry was segmented from CT thoracic lung scans of a patient [6] and materialized using rapid prototyping. Several bronchial cross sections up to the 4th generation were investigated and compared to a simulation with the same conditions.

Results

In the curved pipe, the three velocity components were measured by MR with a precision down to 0.025 m s^{-1} in comparison with the simulated data. The same asymmetrical through-plane velocity pattern was observed for MR and CFD (fig. 1) with a maximum velocity in the outer region of the pipe (triangle on fig. 1). Two in-plane symmetrical eddies directed toward the maximum through-plane velocity could be observed as expected and vortex centers corresponded within less than one pixel (circle and cross on fig. 1). Within the airway model, calculated through-plane velocity profiles matched in all investigated cross-sections whereas vortex positions and intensities agreed with the experiment (fig. 2). In the presented section here, asymmetry of through-plane velocity profile revealed high inertial effects while convective patterns could be quantified from in-plane motion.

Discussion and Conclusions

We successfully applied PC to flowing HP gas within different physiologically relevant phantoms. The method was first validated by a classical CFD simulation on the well-known curved pipe model. The technique was accurate and its precision depended on the factors affecting signal intensity (coil sensitivity, ^{3}He polarization and concentration, relaxation effects, flip angle, flow rate and velocity encoding). It was therefore less precise on the edges (partial volume effect, less inflow effect). The use of the radial strategy enabled a flexible reconstruction for dynamic velocity imaging. On the whole, results presently found demonstrate the ability of the technique to measure velocities on gas in a stationary flow within one second and to observe typical 3D convective patterns.

The airway geometry was accurately reproduced in an opaque material with rapid prototyping. MRI could however provide velocity maps in this complex geometry, hence validating an original patient-specific CFD simulation protocol starting from thoracic CT-scans to full 3D velocity field simulated in the patient airways. Physiological consistency of the chosen simulation conditions may be discussed but HP gas velocity mapping should provide answers to this point since in vivo feasibility was shown [3].

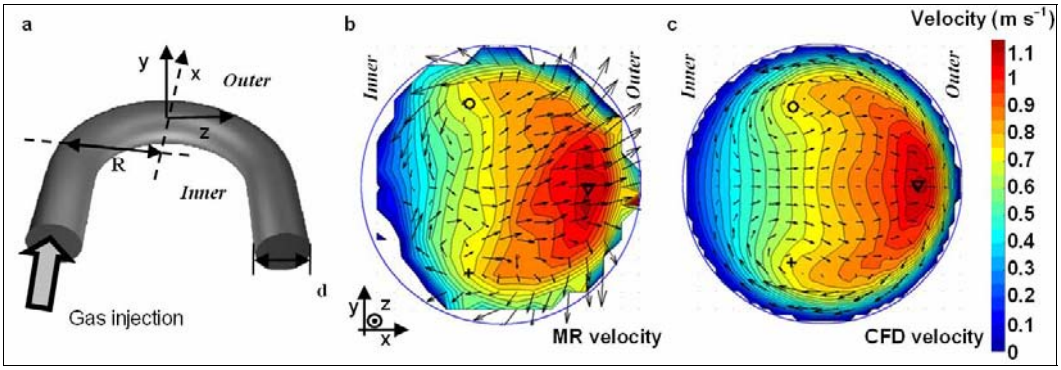

Fig. 1 U-shaped pipe (diameter d=25 mm, curvature radius R=200 mm), and measurement location (a). Experimental and numerical results (b and c) Reynolds number=956. Colors: though-plane velocities; arrows: in-plane velocities.

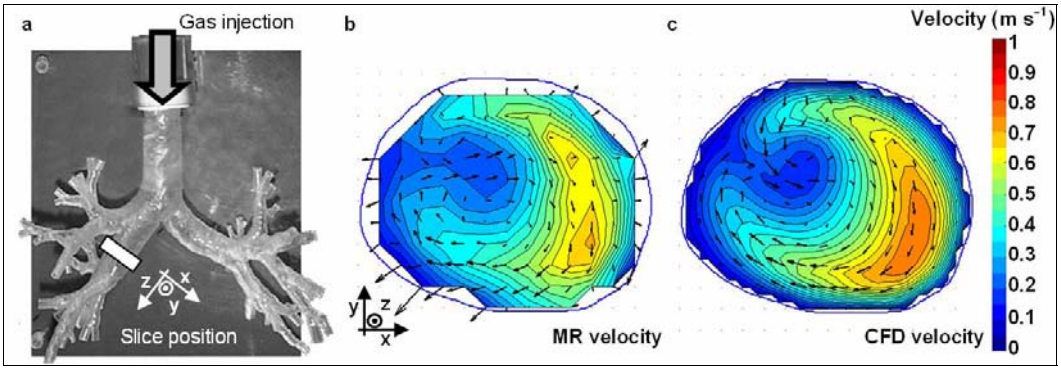

Fig. 2 Patient-specific airway phantom and measurement location (a) (second generation in the right main bronchus). Input flow rate was 270 mL s^{-1}. Experimental and numerical results (b and c).

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References

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