Velocimetry of hyperpolarized rare gases: Phantom studies and first *in vivo* results

W. Kilian[1], M. Strowig[1], F. Seifert[1]
[1]Physikalisch-Technische Bundesanstalt, 10587 Berlin, Germany

Introduction

For characterizing lung diseases or optimizing artificial respiration there is great interest in the dynamics of gas flow to and gas diffusion within the lungs. Several groups model these parameters numerically but no techniques have been available for a long time to compare their results to non-invasive *in vivo* conditions. Both quantities, flow and diffusion, are accessible by standard proton MR techniques. ADC measurements of hyperpolarized rare gases (mainly ^{3}He) are well described [1] and already used in clinical studies [2]. Up to now *in vivo* measurements of gas-flow velocities using phase encoding techniques are rarely shown.

Methods

For polarizing ^{129}Xe (natural abundance or isotopically enriched) by spin-exchange optical pumping [3] a home-built flow system was used. About 0.7 liter (normal conditions) of hyperpolarized ^{129}Xe gas (HpXe) was accumulated as ice in the liquid Nitrogen trap and thawed to fill a detachable Tedlar bag (GSTP001-0707, JENSEN INERT, Coral Springs, USA). ^{129}Xe polarizations of 10-15% were routinely achieved.

All MR measurements were performed on a whole body 3 tesla scanner (MedSpec 30/100, BRUKER BIOSPIN MRI, Ettlingen, Germany). A flow compensated gradient echo sequence (TE=15.5 ms, TR=30 ms, FOV=12,8 cm, 128x128 matrix) was adopted to acquire each k-space line twice. While acquiring a k-space line for the first time the gradients were set such that both integrals $M_0=\int^{TE} G(t)dt$ (zero-order moment of the gradients) and $M_1=\int^{TE} t\cdot G(t)dt$ (first-order moment) were equal to zero (flow compensation). During the second acquisition of the corresponding k-space line the gradients were set such that again M_0 was kept to zero whereas the first-order moment did not vanish. This results in an additional phase $\Delta\varphi=\gamma v M_1$ in the detection signal which is directly proportional to the velocity of spins moving with constant speed. By subtracting the phases of the flow compensated and the flow weighted images a map of particle velocity is obtained. The velocity yielding a 2π phase-shift gives the field of speed (FOS) which can be detected without phase wraps in the velocity map.

For testing the sequence and performing independent reference measurements we built a setup generating gas flow with constant velocities. When using hyperpolarized rare gases one has to hermetically seal off surrounding air from the hyperpolarized gas as oxygen drastically reduces the T_1 time of the non renewable hyperpolarized state. In Fig. 1 the setup with the measuring section is shown. During measurements it is mounted on the patient bed and hence has to be MR-compatible. Each Tedlar bag was housed in a box which could be pressurized. The bag outlets (fed through the walls of the boxes) were connected to the measuring section. A pneumatically controlled balloon valve (Hans Rudolph, Kansas City, MO) releases and stops the gas flow from one bag to the other. On a second board sitting outside the tomography room (not shown) several electro-pneumatic valves switch pressurized air flowing via flow restrictors (Lee, Westbrook, CT) to one box and from the other box thus maintaining a constant gas flow through the measuring section. The air flow to and from the boxes is controlled with variable area flow meters.

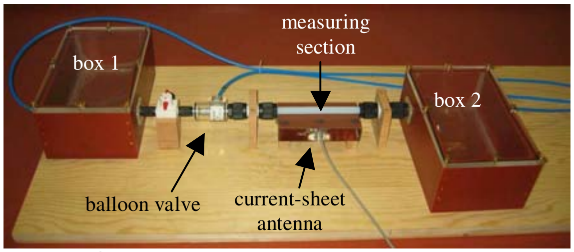

Figure 1: Setup for testing the flow measurement sequence

For the in vivo measurements a healthy volunteer lying supine inhaled about 0.7 liter of HpXe from the Tedlar bag. Due to its narrow valve the volunteer was not able to inhale the gas with different flow rates resulting in a total inhalation time of approximately 15 seconds. To flush the trachea from air a delay of 5 s was applied between inhalation and start of the MR-sequence.

Results

Different types of Teflon tubes were used as measuring sections (Fig. 1). In Fig. 2 maps of the velocity v_z of the gas flow within a tube (inner diameter d=12 mm) are shown. For the experimental Xenon flow of 80 l/h (flow in negative z-direction) the Reynolds number is about $Re=\rho dv/\eta$~600, far below the critical value of Re_{krit}~2300 above which flow is normally no longer laminar. The inlet length l_e=0.03 $Re\,d$ ~20 cm defines the distance after which the laminar flow has formed its static parabolic profile within a cylindrical tube. In Fig. 2 a) it is clearly seen that the peak velocity along the tubes rises from the inlet (z=10 cm) to the top of the FOV (z=-6 cm). This is also seen in Fig. 2 c) where the z-component of the gas velocity derived from three axial measurements at z=5 cm; 0 cm and -5 cm is plotted along the tube radius r_x in x-direction. The peak velocity is more and more approaching the theoretically calculated values for a laminar-flowing gas.

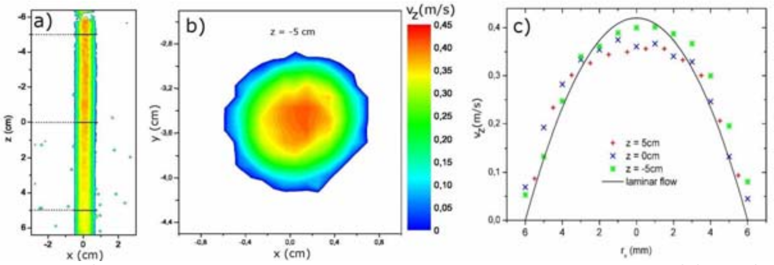

Figure 2: Coronal a) and axial b) maps of v_z (20 mm slice thickness, FOS=2 m/s) of flowing HpXe. Axial velocity profiles of three measurements (dots) and an ideal laminar flow (straight line) along the tube radius is shown in c).

In Fig. 3 a) an axial map of the gas velocity in z-direction v_z (20 mm slice thickness, FOS=0.6 m/s) is superimposed on a proton image about 10 cm downstream the larynx. The asymmetry in v_z with higher velocities toward the posterior parts of the trachea was seen in all axial images. In Fig. 3 b) a coronal map of the gas velocity in z-direction v_z (130 mm slice thickness, FOS=1.8 m/s) is superimposed on a proton image. As the FOV of the velocity map is smaller than that of the proton image the upper part of the trachea is not seen.

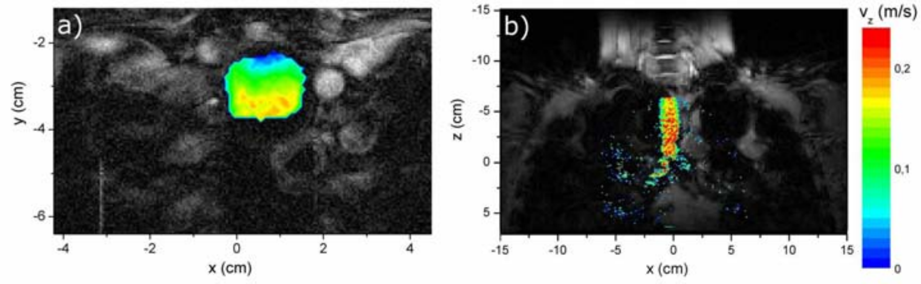

Figure 3: Axial a) and coronal b) maps of v_z of flowing HpXe within the trachea superimposed on standard ^{1}H images (10 mm slice thickness).

Discussion

In the phantom measurements we obtained velocity maps with very good reproducibility showing the robustness of the sequence. The very good match with theoretically calculated velocity distributions has shown that the velocities derived show the real speed of the gas flow. The *in vivo* measurements have shown very good velocity maps within the trachea. To advance the *in vivo* measurements further downstream to the bronchi we will have to test heart triggering to avoid movement artifacts of the bronchial tree due to the heart beat.

References

[1] Saam B.T. et al. MRM **44,** 174 (2000)
[2] Morbach A. E. et al. JMRI **21**, 765 (2005)
[3] Walker T.G and Happer W., *Rev. Mod. Phys.*, **69**, 629, (1997)