Phase Contrast MRI of ^{19}F and ^{3}He gas flow: Phantom Studies

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BACKGROUND

Since conventional (^{1}H-) MRI of the lung suffers from low signal, non-proton MRI with inhaled gases is being used to visualize pulmonary airspaces. Hyperpolarized ^{3}He has by now proven to be the most sensitive of these gaseous agents. However, fluorinated ^{19}F gases (SF_6, C_2F_6, C_4F_8) offer adequate signal without hyperpolarization and both approaches are successfully being used to study alveolar ventilation and diffusion [1,2]. ^{3}He and ^{19}F gases exhibit totally different flow behaviour which requires particular attention if ventilation is assessed quantitatively. Studies of ^{3}He gas flow *in-vitro* and *in-vivo* have recently been demonstrated using phase contrast velocimetry [3]. A similar method is desirable for investigating ^{19}F gas flow and was developed and validated in this study. Against the background of prospective *in-vivo* applications, experiments have been performed in a gas flow phantom for C_4F_8 as well as ^{3}He to contrast their behaviour.

MATERIAL & METHODS

Flow of C_4F_8 and ^{3}He gas mixtures was generated in a custom-made phantom and measured at various flow rates with a velocity encoding gradient-echo pulse sequence. Velocity maps were reconstructed from the MRI data and compared to independent measurements of the gas flow.

<u>*Phantom Design (Fig. 1):*</u> The phantom was constructed as a closed loop of tubes in which the gas was kept circulating during MRI measurements. To ensure a reliable prediction of the actual velocity profile, MRI measurements were performed 1.2 m (~ 75 diameters) downstream of a long acrylic glass tube (Fig. 1-1; Ø 16 mm, L = 2m), where the flow profile was supposed to have fully settled. For a continuous and stable flow, a radial blower in a special housing was driven by a shielded electric motor that was controlled by a LabView interface. The phantom was equipped with a differential-pressure sensor in such a way that gas flow could be monitored and recorded during MRI measurements.

<u>*Pulse Sequence and Imaging Protocol:*</u> A spoiled gradient-echo (FLASH) pulse sequence was modified to measure the through-plane velocity of the flowing gas. Velocity encoding was performed using a bipolar gradient that was combined with the slice re-phasing gradient. In order to reduce the minimum TE, asymmetrical echo readout was implemented. Imaging parameters for ^{19}F and ^{3}He experiments are given in Table 1. All MRI measurements were performed using four velocity encoding steps with aliasing velocities (VENC) of 0,±3,±6,±10 m/s, where VENC=0 m/s denotes velocity compensation.

Tab. 1: Protocol

Parameter	^{19}F	^{3}He	
Field of View	128x128	64x64	mm²
Resolution	2x2x15	1x1x15	mm
Bandwidth	80	160	Hz/Px
Echo Time	4,7	3,3	ms
Echo Asymmetry	25		%
Repetition Time	15,1	9,4	ms
VENC Steps	[0, ±3, ±6, ±10]		m/s
Averages	2	1	
Acquisition Time	8	2,5	s

<u>*Experimental Setup and Measurements:*</u> Experiments were carried out on a 1.5 T Magnetom Sonata (Siemens Medical, Erlangen) with a custom-made ^{19}F birdcage-coil (Ø 5 cm) and a birdcage-coil (Ø 60 cm, Rapid Biomedical, Würzburg) for ^{3}He, respectively. The phantom was centred in the magnet, evacuated and filled with ~80% of C_4F_8 and ~20% of O_2 for ^{19}F experiments. For ^{3}He measurements the phantom was initially flushed with N_2. The flow sensor was calibrated using a syringe with 1 L volume. The phantom was then operated at flow rates between 0 and 1500 ml/s, corresponding to mean velocities of up to 6.0 m/s in the tube. MRI velocity measurements were performed for each flow rate. For ^{3}He experiments a small bolus was injected into the N_2 stream directly upon start of the sequence.

<u>*Image Reconstruction & Analysis:*</u> Phase contrast reconstruction was performed offline using MatLab. For each measurement, complex raw data from four velocity encoding steps were subtracted and scaled to form velocity maps with VENC ranges of ±3,±6,±10 m/s. Since uncertainty of the velocity measurement inversely relates to the SNR, error maps were calculated on a pixel-by-pixel basis using the SNR in the magnitude images.

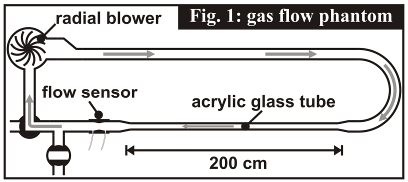


Fig. 1: gas flow phantom

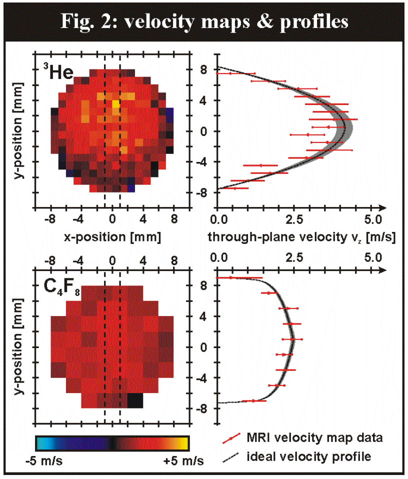
RESULTS

Magnitude images showed SNR values of 4-12 (C_4F_8) and 4-9 (^{3}He). SNR were lower at flow rates above 1200 ml/s (C_4F_8) and 550 ml/s (^{3}He) so these images were rejected. All velocity maps showed a non-uniform distribution tending to higher velocities towards the centre, where C_4F_8 profiles occurred more flat compared to ^{3}He.

Based upon the flow sensor data, Reynolds numbers were calculated for both gas mixtures at different flow rates. While a clearly turbulent flow pattern (Re >> 2320) was expected for the C_4F_8 mixture, laminar flow (Re < 2320) should be observed in N_2 with injected ^{3}He. The ideal velocity profiles may thus be described by a parabola for laminar and a more complex expression for turbulent flow. For comparison axial profiles were stripped from the MRI velocity maps and overlaid on the predicted idealized curves. Fig. 2 shows an example where depicted measurements of ^{3}He and C_4F_8 have comparable flow rates. It is obvious that velocities taken from MRI data are well described by their theoretical counterparts. This was observed for all datasets whereas agreement was better if the VENC corresponded to the expected range of velocities.

Further comparison was performed considering only the mean velocity of the MRI and flow sensor measurements. A circular region-of-interest (ROI) was placed on the velocity maps corresponding to the tubes cross-section. The mean velocity over the ROI was calculated whereas each pixel was error-weighted. Fig. 3 shows for C_4F_8 the mean velocity determined from MRI data plotted against the mean velocity measured with the flow sensor (for better illustration, data from different VENC were shifted parallel to the identity line). Excellent agreement of both methods is clearly visible as virtually all points touch the line of identity (R²=0.99). Results for ^{3}He were similar (data not shown), though fluctuations were higher probably due to the adverse mode of bolus-like application.

Fig. 2: velocity maps & profiles

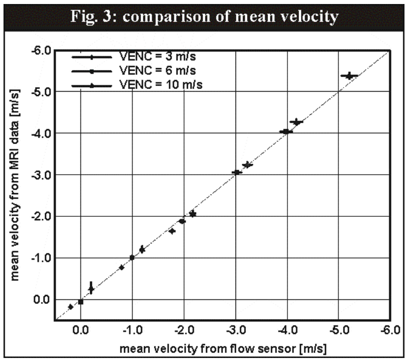


DISCUSSION

Corresponding to theoretical predictions, patterns of turbulent and laminar flow were observed with phase contrast MRI in C_4F_8 and ^{3}He gas mixtures respectively. Comparison of MRI data with independent flow sensor measurements demonstrated the high accuracy of phase contrast MRI for C_4F_8 gas flow. Results from ^{3}He experiments confirmed the methods validity previously shown in CFD simulations [3]. Experimental imperfections can be accounted for the slightly lower accuracy found in the ^{3}He studies. Images obtained with different aliasing velocities pointed out, that the choice of an adequate VENC is essential for precision of velocimetry, especially with low SNR. Though protocols and experimental setup were directed towards it, SNR may become critical for ^{19}F phase contrast MRI when moving to *in-vivo* applications. In this context it is noteworthy that – unlike in angiography – phase contrast velocimetry of non-proton nuclei is not biased by partial-volume-effects. Hence, if interest is directed towards flow or mean velocity rather than spatial distribution, the in-plane resolution can be further reduced.

It can be concluded from our results, that the employed method of phase contrast MRI is well suited to study the flow characteristics of ^{19}F fluorinated gases as well as of ^{3}He gas. In quantitative ventilation studies particular attention must be paid to their very different flow behaviour, which has been demonstrated in this study.

Fig. 3: comparison of mean velocity



<u>Acknowledgements:</u> Research was supported by the German Research Foundation (DFG FOR 474/Schr 687/2), MAIFOR and Forschungsfonds, Johannes Gutenberg University, Mainz, Germany.

<u>References:</u> [1] van Beek et al., 2004, JMRI 20(4): 540-45; [2] Schreiber et al., 2006, MRM 55(4): 948-52; [3] de Rochefort et al., 2006, MRM 55(15): 1318-25