# Validation of Phase-Contras MR Velocimetry of Hyperpolarized Rare Gases via Particle Image Velocimetry

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## Introduction

In recent studies phase-contrast MR velocimetry (PC-MRV) of hyperpolarized $^{3}$He has been used to validate computational fluid dynamic simulations [1]. Our aim is to validate PC-MRV of hyperpolarized rare gases (HpRG) by comparison with the well established Particle Image Velocimetry (PIV) technique [3] and to explore the potentials and limits of PC-MRV for medical as well as for fluid-dynamics applications.

## Methods

A home-built flow system was used to polarize $^{129}$Xe (natural abundance) by spin-exchange optical pumping. About 0.7 liter (normal conditions) of hyperpolarized $^{129}$Xe gas (HpXe) was accumulated as ice in a liquid nitrogen trap and thawed to fill a detachable Tedlar bag (A223-08 BOHLENDER GmbH, Germany). $^{129}$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, Germany) using a phase contrast flow measurement gradient echo sequence (*TE*=15.5 ms, *TR*=30 ms, *FOV*=12.8 cm, 128x128 matrix, $v_{enc}$=0.4 m/s). To perform 2D PC-MRV within the coronal *xz*-plane two separate scans were acquired having the flow-sensitized gradient (i.e. the read gradient) in the *z*-direction and in the *x*-direction, respectively. Velocities were evaluated only in pixels where the magnitude-signal exceeded 20% of the image's signal maximum.

To perform reproducible flow measurements on HpRG we used a hermetically sealed setup [2]. Flow conditions comparable to those at the bifurcation of the human trachea were generated within a phantom resembling the anatomy of one of the authors (taken from $^{1}$H-MRI). The area of the "trachea" and the two "main bronchi" were $A_{main}$=2.38 cm$^2$, $A_1$=0.81 cm$^2$ and $A_2$=1.12 cm$^2$, respectively and the branching angles $\alpha_1$=50° and $\alpha_2$=30°. To have the phantom suitable for both, PC-MRV and PIV, the flow channels were constructed and built within a dividable Plexiglas model with square profiles ($d_{main}$=15 mm, $d_1$=9 mm, $d_2$=11 mm, see Fig. 1). For an independent measurement of the total gas flow a pneumo-tachograph (PT; Fixed Orifice PT Neonat., KORR, USA) was put in front of the phantom inlet. The pressure drop generated by the all-plastic PT was measured with a differential pressure gauge (PCLA02X5D1, SENSORTECHNICS, Germany). The square-law dependence of the differential pressure drop was calibrated with a high precision flow generator (PWG System, MH CUSTOM DESIGN & MFG. L.C., USA).

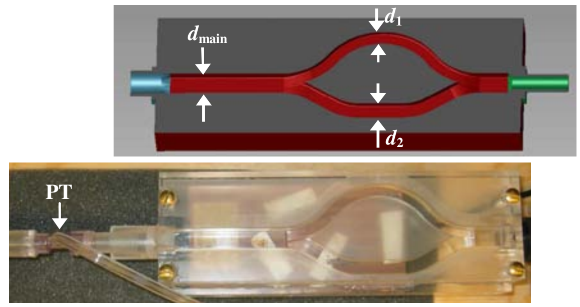


Figure 1: Flow phantom: design drawing and picture with the PT on the gas inlet and the NMR-coil underneath.

The PIV measurements were performed using a double cavity frequency-doubled Nd:YAG laser (PIV-Lite II, CONTINUUM, USA) and a synchronized CCD cross-correlation camera (SensiCam, PCO, Germany). An analysis software (INTELLIGENT LASER APPLICATIONS GmbH, Germany) was used to calculate the resulting velocity vector fields in the measurement plane. The particles (based on liquid Di-Ethyl-Hexyl-Sebacat - DEHS) were provided by an aerosol generator with particle sizes mainly below 1 µm. To match the flow conditions during PIV measurements to those during the MR measurements (performed with xenon at $Q_{Xe}$=0.056 ℓ/s) we used a total air flow of $Q_{air}$=0.2 ℓ/s yielding similar Reynolds numbers of ≈800 within the main tube for both cases.

## Results and Discussion

Typical PC-MRV results are shown in Figs. 2. a) and b). The better signal-to-noise ratio (SNR) in measurement a) is due to the larger slice thickness. As the phase gradient lay in the *z*-direction when measuring the $v_x$-component, aliasing is seen on top and bottom of the images.

In Fig. 2 c) and d) time-averaged velocity fields of two PIV-measurement are shown. Each of these series consist of 50 PIV measurements with 3 Hz repetition rate and 0.2 ms delay between the two laser pulses. Although flow channels with rectangular cross section were used, significant refraction of the laser light occurred within the plane of illumination. Thus each measurement series was performed twice, reversing the illumination direction. So the illumination was from the left hand side in Fig. 2 c) and from the right hand side in Fig. 2 d).

Concerning SNR, the comparison of MRV- and PIV-measurements gave similar results when slices with 10 mm thickness were used for MRI. As we have used xenon of natural abundance (only maintaining 26 % of $^{129}$Xe) comparable high SNR would also be achievable for the 5 mm slice thickness MRI using isotopically enriched HpXe or even better when using highly polarized $^{3}$He. It should thus be possible to obtain PIV-like spatial resolution by MR. The absolute flow profile for the two MR measurements are somewhat inconsistent referring to the velocities behind the bifurcation. From the PIV data it is clearly seen that the higher velocities occur in the wider channel which is also reflected in the 5-mm-slice MRI. This is obvious as these two measurements are reflecting the conditions in more or less the same plane. The MR measurement with the 10 mm slice does also integrate over gas velocities near the upper and lower walls of the flow channels where strong acceleration may occur due to the constriction of the channel.

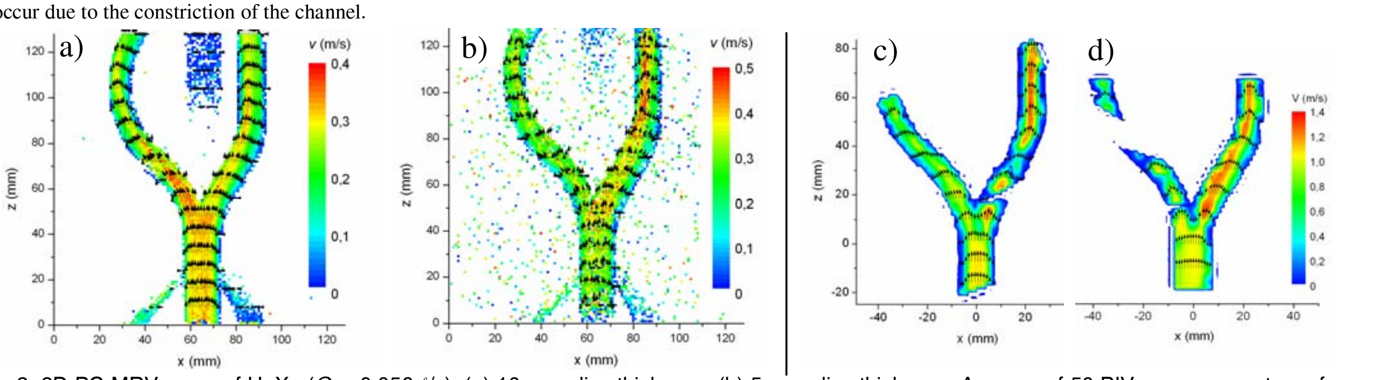


Figure 2: 2D PC-MRV maps of HpXe ($Q_{Xe}$=0.056 ℓ/s): (a) 10 mm slice thickness, (b) 5 mm slice thickness. Average of 50 PIV measurements performed with air ($Q_{air}$=0.2 ℓ/s): the laser-light illumination from the left (c) and from the right (d).

## Conclusion

The first direct comparison of PC-MRV and PIV were performed successfully. Our results reflect that MRV is capable to reach spatial resolution comparable to PIV. This shows that MRV of HpRG has great potential for velocimetry in non opaque structures, e.g., for in-vivo flow characterization within the airways.

## References

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