Pressure gradient estimation from PC-MRI: acceleration versus velocity encoding

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Introduction: MRI can be used to estimate blood pressure gradients non-invasively [1-3] by solving the hemodynamic Navier-Stokes equation. Most applications use velocity encoded phase contrast (PC) MRI data to calculate pressure gradients and generate pressure difference maps. Pressure gradient estimation requires the derivation of local temporal and convective acceleration by calculating spatial and temporal derivates of the measured time-resolved velocity vector field [1]. As results, noise in the original velocity data may be severely amplified by error propagation and corrupt the final pressure gradients and differences. To reduce noise and improving accuracy of derived quantities, acceleration encoded MRI data can be used [4] to directly measure flow acceleration. However, previously reported acceleration encoded MRI measurements had long acquisition and echo times (TE) and thus low signal-to noise ratio (SNR) and high artifact sensitivity. Moreover, no application of a MRI technique with full three-directional acceleration encoding has been reported to date. A recently introduced optimized fast 3 directionally (3D) acceleration encoded PC technique with shorter TE [5] may thus offer more accurate pressure gradient estimation. In our study we used a stenosis model to systematically evaluate pressure gradient estimation using acceleration encoded versus velocity encoded [6] 3D PC-MRI data. Additionally 2 healthy subjects were included in our study to compare the performance of acceleration and velocity encoding PC-MRI for pressure gradient estimation in-vivo.

Methods: A recently reported acceleration encoded PC sequence with optimized gradient waveform design for efficient encoding and short TE and repetition times was applied [5]. For validation, phantom measurements on a 3T MR-System (Tim TRIO, Siemens, Germany) using a stenosis model (pipe Ø 33.5mm, stenosis Ø 10mm) and a pump with constant flow of 5.9 l/min were performed. Blood mimicking fluid (60% water, 40% glycerol, viscosity $4.96e^{-3}$Pa·s, density 1105 kg/m^3) was used. Two acceleration encoded (three-directional acceleration encoding, sensitivities aenc=100 m/s^2 and aenc=150 m/s^2, TE 6.23ms and 5.67ms respectively) and one velocity encoded (three-directional velocity encoding, sensitivity venc=1.5 m/s, TE 3.05ms) 3D MRI measurements (1 time point, spatial resolution 1.0mm^3) were performed. In each case a flow-off measurement was subtracted from the data in order to correct for eddy currents and Maxwell terms. Additionally volunteers' scans were performed on a 1.5T (Avanto, Siemens, Germany) and 3T (Tim TRIO, Siemens, Germany) systems. Time-resolved 2D acceleration encoded (sensitivities aenc = 50 m/s^2, 100 m/s^2, 150 m/s^2) and velocity encoded (sensitivity venc= 1.5 m/s) PC-MRI data (spatial resolution 2.1x1.4mm^2, temporal resolution 15 – 21 ms) were acquired for each volunteer.

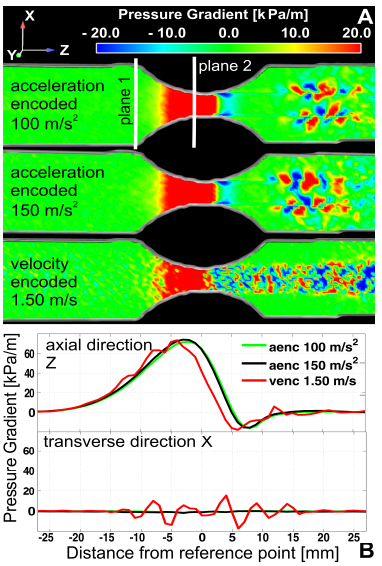

Fig. 1 *Pressure gradients in a stenosis model, **A**: distribution of pressure gradients in the central slice through the phantom for two acceleration and one velocity encoded measurement; **B**: mean pressure gradient across stenosis (ref. point at 0mm) for axial and one of the transverse encoding directions*

Data analysis: All in-vitro and in-vivo data were processed using Maxwell and eddy current correction. In-vitro data were segmented by thresholding the magnitude data, in-vivo data were segmented manually encompassing left ventricular outflow tract. The calculated masks were used in conjunction with MRI data for automated estimation of pressure gradients [1] using

$$-\nabla p + \rho g + \mu \nabla^2 v = \rho\left(\frac{\partial v}{\partial t} + (v\cdot\nabla)v\right) = \rho \cdot A \quad (1)$$

Navier-Stokes equation (Eq.1), assuming incompressible fluid, where p is pressure, ρ is the fluid density, μ the fluid viscosity; g is acceleration due to gravity, v velocity and A is acceleration. This equation was simplified by neglecting minor terms such as gravitational acceleration and viscous terms [4]. Based on pressure gradients, pressure differences were calculated by integration of pressure gradients and then iteratively refined [1]. For validation the expected pressure gradient across the stenosis in the phantom was estimated using the Bernoulli equation. For in-vitro pressure difference calculation in the in-vitro data the reference point (ΔP=0) was set in the center of the stenosis. Additionally velocity/acceleration data noise was calculated as standard deviation of the measured field in the model in the flow-off measurement. For in-vivo data a centerline was calculated from the mask. For pressure difference calculations a reference point was set at the starting point of in the centerline in the heart (Fig.2 lower right). In-vivo pressure gradients and pressure differences were calculated and then averaged over the line segment orthogonal to single pixels of the centerline (Fig.2 lower right). All pressure differences were interpolated to temporal resolution of 1ms and maximum ($peak_{max}$) and minimum ($peak_{min}$) peaks as well time to $peak_{max}$ and time to $peak_{min}$ were determined for each PC-MRI measurement for every volunteer and for all values Bland-Altman analysis was performed.

Results: Figure 1 shows a side-by-side comparison for pressure gradients (PG) calculation using acceleration and velocity encoded MRI data in the stenosis phantom. It is clearly evident that PG calculated from velocity encoded data was considerably noisier (transverse directions: standard deviation 3.9 kPa/m for velocity encoded data and 0.5 kPa/m for acceleration encoded data), since derivation of acceleration from velocity data amplified noise and inaccuracies. It is also evident from the lower plot in figure 1B that gradients in the transverse direction show higher standard deviation for velocity encoded data. From Bernoulli equation estimated mean PG (6.4 mmHg) between plane 1 and 2 (s.Fig.1) shows excellent agreement with gradients calculated from 3 PC-MRI data sets (6.2mmHg for 100 m/s^2, 6.6 mmHg for 150m/s^2, and 6.1mmHg for 1.5m/s sensitivities). In the volunteers' measurement pressure gradients calculated from direct acceleration measurements were also less noisy compared to velocity encoded data (s. figure 3 left). The comparison of peak and time to-peak values between acceleration encoded and velocity encoded data is summarized in table 1. The results of all acceleration encoded data compared to velocity encoded data were consistently lower for $peak_{max}$, $peak_{min}$ and time to $peak_{min}$, and consistently higher for time to $peak_{max}$ as velocity encoded data. Comparison only among acceleration encoded data shows a trend of data with higher aenc to have decreased maximum and minimum peaks and increased time-to-peak for increased aenc.

Discussion: The applied approach demonstrates the potential to derive additional quantitative information such as pressure gradients from directly acquired acceleration field. Compared to velocity encoded data parameters derived from acceleration encoded data were less noisy and my thus provide more reliable pressure gradient estimation. Future studies including a comparison with gold standard pressure measurements by catheters are needed to further validate acceleration encoded MRI.

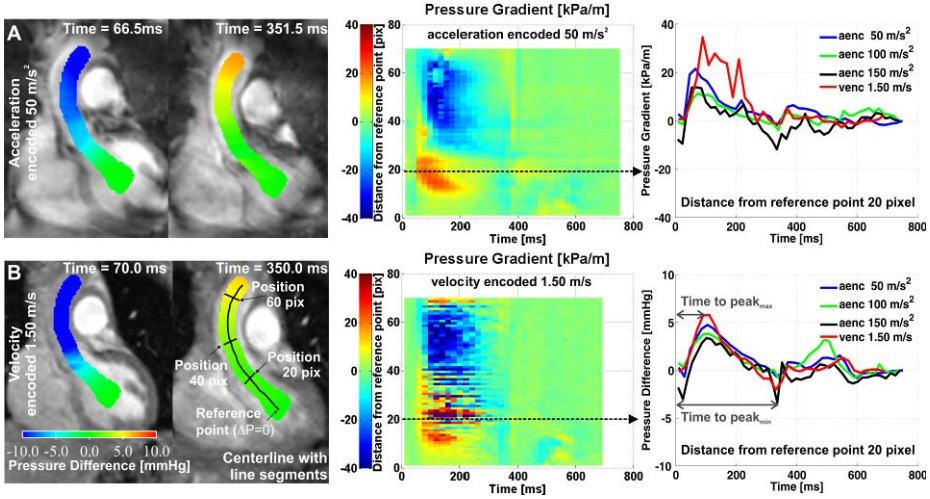

Fig. 2 *Pressure differences calculated in a volunteer; **A**: with acceleration encoded data; **B**: with velocity encoded data*

Fig. 3 *S patio-temporal distribution of pressure gradients and pressure difference for one volunteer. Left: temporal evolution ,of the pressure gradient along segmented centerline calculated from acceleration encoded data (upper left) and from velocity encoded data (lower left); Top right: pressure gradient, Lower right: pressure difference over time for one line segment, comparing of all 4 PC-MRI measurements*

A_{enc} 50m/s² vs. V_{enc} 1.50 m/s	Volunteer 1	Volunteer 2
$PEAK_{MAX}$ [mmHg]	- 12.8 ± 21.3	- 1.5 ± 3.8
TIME TO $PEAK_{MAX}$ [ms]	- 5.0 ± 222.1	12.5 ± 255.3
$PEAK_{MIN}$ [mmHg]	- 0.0 ± 1.7	- 0.9 ± 0.7
TIME TO $PEAK_{MIN}$ [ms]	- 41.3 ± 131.4	- 14.5 ± 103.0

Tab. 1 *Bland-Altman analysis results for comparison peak ant time-to peak between acceleration encoded (aenc 50m/s^2) and velocity encoded (venc 1.5 m/s) PC-MRI data for 2 volunteers.*

Acknowledgements: Deutsche Forschungsgemeinschaft (DFG), Grant # MA 2383/4-1, Bundesministerium für Bildung und Forschung (BMBF), Grant # 01EV0706.

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