4D MR Pressure Difference Mapping: Comparison with Echocardiography and Invasive Catheter Measurements

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Introduction: Pressure gradients are an important clinical marker for the severity of cardiovascular disease such as aortic valve stenosis or aortic coarctation [1,2]. In-vivo blood flow measurements based on phase contrast (PC) MRI have been used to estimate regional pressure differences (PD) based on the Bernoulli equation or more advanced Navier Stokes modeling. Recently, 4D flow MRI has been employed to measure in-vivo 3-directional blood flow velocities which were used to calculate time-resolved 3D PD maps with full volumetric coverage of the aorta [3-5]. PD maps were derived using vessel boundaries (3D PC MR angiography) that were extracted from the 4D flow data. Time-resolved 3D velocity data inside the aorta was then used to estimate pressure gradients (Navier Stokes modeling) and finally to calculate iteratively refined PD maps. Previous applications include the validation of this approach in flow phantoms and in-vivo compared to echocardiography. However, phantoms studies represent and idealized situation. Moreover, it is known that PD estimation based on echocardiography using the simplified Bernoulli equation has limitations with respect to reproducibility and PD overestimation. It was therefore the purpose of this study to evaluate the potential of an optimized data analysis strategy for the assessment of aortic 3D PD maps compared to the gold standard, i.e. invasive catheter measurements. In 5 patients with aortic coarctation, 4D flow MRI based mean and peak pressure gradients were compared to the catheter and echocardiography measurements at the same location.

Methods: Five patients (mean age 11.4 years, 1 female) with aortic coarctation were included in our study after approval by the local ethics committee and written informed consent. All measurements were performed on a 1.5 (Avanto, Siemens, Germany) or 3T system (TRIO, Siemens, Germany) using an ECG gated and respiration controlled 4D flow sequence [6]. 4D flow MRI data were acquired covering the entire thoracic aorta (TE=2.3-2.5ms, TR = 4.8-5.0ms, spatial resolution = 2.0-2.3x1.8-1.9x2.0-2.8mm^3, temporal resolution = 38.4-40.0ms). Additionally, all patients were examined by echocardiography and cardiac catheterization 5.6 ± 8.3 months after the MR study as a part of their standard clinical care. In echocardiography, mean and maximal pressure gradients over the coarctation were measured. During catheterization pressure gradients were determined between ascending and descending aorta.

To evaluate the impact of dynamic versus static boundary conditions, two types of aortic segmentations were performed and compared. 1) 4D-PC-MRA: Time-resolved 3D segmentation of the vascular lumen of the aorta using feature extraction and cluster analysis [7]. 2) 3D-PC-MRA: Static 3D lumen segmentation based on the weighted sum of the velocity magnitude over all cardiac time frames [6]. Pressure differences were calculated based on the Navier-Stokes equation using 4D flow data in conjunction with the segmented 3D-PC-MRA and 34-PC-MRA aortic lumen. A reference point (Δp=0 mmHg) was set manually in the ascending aorta at the level of the lower edge of the pulmonary artery. For further analysis data were exported into 3D visualization software (EnSight, CEI, USA). For comparison of pressure gradients calculated from 4D flow MR data with catheter measurements and echocardiography, two analysis planes were positioned at the locations where the pressure gradient was invasively measured (figure 1): plane 1 in the ascending aorta (midway between the aortic valve and first supra-aortic branch) and plane 2 distal to the coarctation. Mean pressure differences between the two analysis planes were calculated.

Results: Results of pressure gradient analysis for all three modalities (MRI, echo, catheter) and different aorta segmentation strategies (3D-PC-MRA vs. 4D PC-MRA) are summarized in figure 2 and table 1. Mean pressure gradient determined by MRI showed moderate deviation from the standard method (catheterization) in 3 out of 5 patients (patients #1, #3, #4) by 15±11%. By using static segmentation (3D-PC-MRA), the deviation increased to 59±23% in the same patients. In patient #2, pressure gradients were overestimated by both echo and MRI compared to catheter measurement. In patient #5, the pressure gradient was underestimated by 45% even for 4D-PC-MRA (i.e. time-resolved) vessel geometry (60% for static 3D-PC-MRA aortic segmentation) compared to catheter results. In this case MRI data were acquired 2 years prior to catheter measurements which may explain differences in pressure gradients. Except for patient #1, PD estimation based on echocardiography showed similar differences compared to the reference standard catheter (table 2).

Discussion: Comparisons between catheter and 4D flow MRI indicate the potential of MRI to non-invasively determine the pressure gradients across aortic coarctation. To our knowledge, this is the first study proving an in-vivo validation of 3D pressure mapping by 4D flow MRI compared to the current gold standard. Limitations of this study include the small number of subjects and variable intervals between catheter measurements and 4D flow MRI. Increased differences between MRI and catheter based pressure gradients for 3P-PC-MRA compared to 4D-PC-MRA indicate the importance of dynamic boundary conditions for accurate PD estimation.

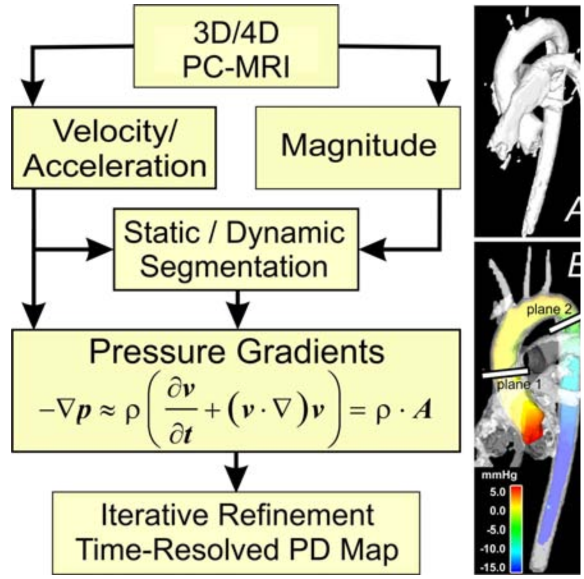

Fig. 1: Schematic illustration of the data analysis workflow used for the calculation of time-resolved 3D pressure difference maps. **A:** result of aortic and pulmonary vessel lumen segmentation based on 3D-PC-MRA **B:** Pressure difference distribution in the aorta for a systolic time frame and planes used for the calculation of pressure gradients for comparison with invasive catheter measurements.

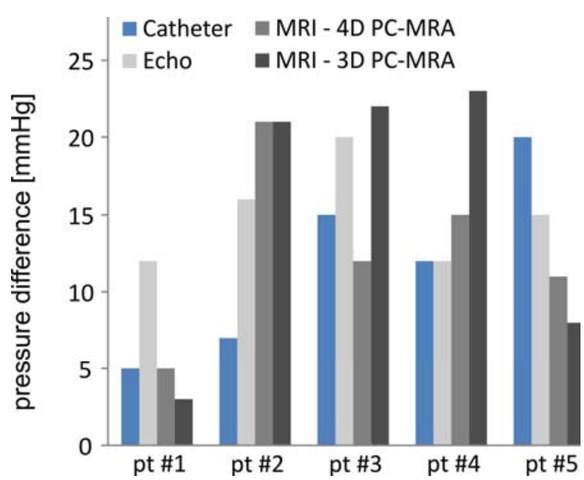

Figure 2: Comparison of pressure gradients measured using different modalities (catheter, echocardiography and MRI) in five patients with aortic coarctation.

Diffrence vs. catheter	patient #1	patient #2	patient #3	patient #4	patient #5
Echo	140%	129%	33%	0%	-25%
MRI - 4D PC-MRA	0%	200%	-20%	25%	-45%
MRI - 3D PC-MRA	-40%	200%	47%	92%	-60%

Table 1: Differences in pressure gradients between 4D flow MRI, echocardiography and the gold standard invasive catheter.

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