4D Aortic pressure difference mapping: an approach for the detection of pressure wave changes associated with atherosclerosis?

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Introduction: Time-resolved 3-directionally encoded phase contrast 3D MRI techniques (flow-sensitive 4D MRI) [1] allow for the analysis of vascular hemodynamics of the entire vessels such as the thoracic aorta. Furthermore, the spatio-temporal anatomic and flow information in such data sets can be used to derive additional functional parameters such time-resolved 3D pressure gradients (4D pressure mapping) inside the vessel lumen. The aim of this pilot study was to determine whether it is possible to detect the pressure wave changes associated with atherosclerosis (i.e. increased vessel wall stiffness) by applying 4D pressure difference mapping to patients with aortic high risk plaques and healthy young volunteers.

Methods, MR Imaging: 12 healthy subjects (mean age 24.5y) and 3 patients with severe aortic atherosclerosis (aortic plaques > 4 mm as demonstrated by TEE, mean age = 73.3y) were included in our study after approval by the local ethic committee and written informed consent. All measurements were performed on a 3T system (Magnetom TRIO, Siemens, Germany) using an ECG gated and respiration controlled rf-spoiled gradient echo sequence. Flow sensitive 4D MRI data were acquired covering the entire thoracic aorta (spatial / temporal resolutions ≈ 2x1.7x2.4 mm^3 / 40.8 ms, venc = 150 cm/s).

Methods, Data Analysis: For vascular lumen segmentation a processing chain including time-averaged PC-MRA calculation and a flood filling algorithm was used [2]. The segmented lumen was used in conjunction with the 4D velocity data for automated estimation of pressure differences based on the Navier-Stokes equation as described previously (assumptions: Newtonian fluid, viscosity = 1060 kg/m^3, density = $3.2x10^{-3}$ Pa·s) [3, 4]. In order to compare the data between subjects, 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 quantitative inter-subject analysis, 5 analysis planes were manually positioned at different anatomical landmarks as shown in figure 1. The resulting pressure difference - time curves were temporally interpolated to 1ms. Next, comparisons (unpaired t-test, p-value < 0.05 was considered statistically significant) of systolic and diastolic peak pressure differences as well as time to peak pressure values between healthy subjects and patients were performed for all 5 anatomical locations.

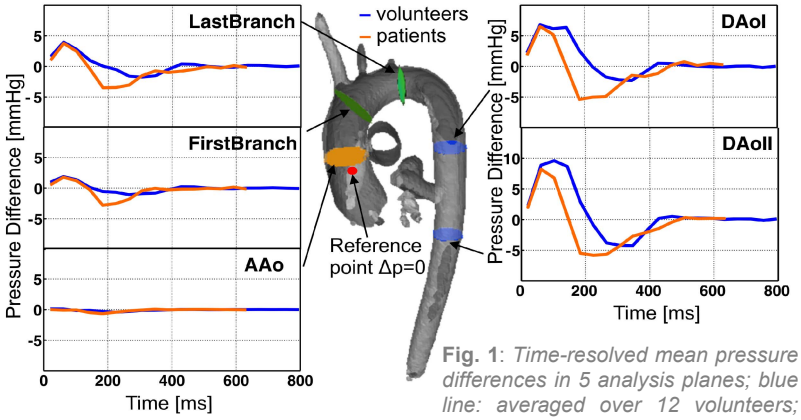

Fig. 1: *Time-resolved mean pressure differences in 5 analysis planes; blue line: averaged over 12 volunteers; orange line: averaged over 3 patients with aortic atherosclerosis.*

Results: The resulting pressure waveforms in volunteers and patients which were extracted from the 4D pressure mapping data are shown in Figure 1. Blue curves show the mean pressure differences averaged over 12 volunteers for all 5 aortic analysis planes. Increased systolic pressure differences along aorta followed by a pressure wave inversion in early diastole were clearly visible in all healthy subjects. The patients' data (in orange, averaged over 3 patients with atherosclerosis) demonstrated similar peak pressure differences but showed a clear trend towards an earlier inversion of the pressure wave. We assume that the altered waveforms dynamics reflect the expected increased aortic stiffness associated with atherosclerosis which results in increased pulse wave velocity, earlier waveform reflection at the periphery and thus earlier onset of the observed diastolic pressure difference inversion. The statistics of peak and time-to-peak pressure differences are summarized in table 1. Consistent, with figure 1, reduced systolic and diastolic "time to peak pressure difference" were found for patients compared to volunteers which were significant for systolic pressure differences for analysis plane locations DAoI and DAoII.

Discussion: The applied approach shows the feasibility to derive quantitative information such as 4D pressure gradients from flow sensitive 4D MRI velocity data. Comparison of volunteer and patient data demonstrated the sensitivity of the method for the detection of altered magnitude and dynamics of pressure differences in the presence of atherosclerosis. Future studies including larger number of patients and a three-dimensional analysis of the pressure difference distributions are warranted to evaluate the potential of 4D pressure mapping for the improved characterization of atherosclerosis and its progression during therapy.

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		Peak systolic PD [mmHg]	Time to Peak systolic PD [ms]	Peak diastolic PD [mmHg]	Time to Peak diastolic PD [ms]
Last Branch	**Healthy subjects**	4.7 ± 1.8	54.8 ± 27.1	-2.9 ± 1.7	269.5 ± 69.7
	Patients	4.1 ± 1.6	53.0 ± 26.9	-4.1 ± 2.1	225.3 ± 38.4
Dao I	**Healthy subjects**	9.3 ± 2.1	**90.4 ± 37.0****	-3.8 ± 1.8	291.4 ± 47.5
	Patients	7.2 ± 1.8	**57.3 ± 18.5****	-6.7 ± 5.3	274.3 ± 103.1
DAo II	**Healthy subjects**	12.5 ± 2.9	**89.7 ± 33.6****	-6.0 ± 2.0	291.5 ± 45.6
	Patients	8.8 ± 2.2	**56.7 ± 14.6****	-7.7 ± 4.6	231.3 ± 44.4

Tab.1 *Comparison of peak and time-to-peak pressure differences (PD) between healthy subjects and patients for three anatomical positions (Last branch, Dao I and DAoII as depicted in Fig.1). Values are given as mean ± standard deviation, statistically significant values are in bold and marked with ***