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Two dimensional and four dimensional hemodynamic and motion of the thoracic aorta – functional investigations prior to thoracic endovascular aortic repair

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To characterize aortic blood flow throughout the thoracic aorta and to determine physiological volumetric flow profiles 2D-PCMRI datasets from young healthy volunteers were analyzed. Measurement planes were manually placed at different aortic levels in the mid-ascending aorta (ASC), brachiocephalic trunk (BCA), left common carotid artery (LCA), left subclavian artery (LSA), descending aortic arch (ARC) and the level of the diaphragm (DES). After image analysis a cubic spline was fitted through the data points. Characteristic feature points were extracted by a semi automatic algorithm and archetypal waveforms were computed. Regression analysis was performed to identify the relationship of average volumetric flow (Q_{avg}) and peak volumetric flow (Q_{peak}). Finally it was investigated if supra aortic blood flow can be predicted based on supra aortic cross sectional area via a power law function.
Absolute blood flow was 6.7±1.9 l/min in the ASC and decreased to 4.1±1.1 l/min the DES. Relative to ASC flow, percentage volumetric flow was 16.5±3.0% at BCA, 7.0±1.4% at LCA, 7.3±1.6% at LSA, 68.6±4.8% at ARC and 68.6±4.8% at DES. In all volunteers and throughout all aortic and supra-aortic locations a triphasic flow profile was observed and archetypal waveforms showed similar characteristics. However the ASC waveform exhibited the highest systolic peak which decreased continuously through the DES. The highest diastolic antegrade peak was measured in the ASC, as well. The diastolic tail of the volumetric flow waveform was in general lower in the ASC and highest in the DES. In general the supra aortic locations showed a more pronounced diastolic minima and diastolic peaks. Visual assessment of the average volumetric flow waveforms revealed that a algorithmic feature point approach preserves the distinct triphasic flow characteristics. On the other hand simple grouped average approaches flatten the flow profile. Pooling the data for the aortic locations and the supra aortic locations showed a significant correlation between Q_{avg} and Q_{peak} (Aorta: $r^2 = 0.917$; $p < 0.0001$; SAA: $r^2 = 0.920$; $p < 0.0001$). Predicting Q_{avg} and Q_{peak} from the vessel area in the SAA based on a power law function resulted in a relative error of 29±24% for Q_{avg} and 25±15% for Q_{peak}. In 5 volunteers the calculated value was in a range <= 20% from the measured value.

A configurable, rigid phantom aortic arch model was operated within a pressure-stable, closed mock loop to study the influence of two distinct supra-aortic bypass configurations on blood flow distribution. The configurations were 1) a native aorta resembling physiological condition; 2) a surgical LSA bypass; 3) a surgical total arch approach with a RCA to LCA bypass and a LCA to LSA bypass. Furthermore accuracy of 2D-PCMRI and 3D-PCMRI, with and without phase offset correction, was investigated by comparing the obtained flow rates to flow rates acquired by gold standard ultrasound measurement.
Compared to the native aortic configurations measuring the supra-aortic blood supply by US, 2D-PCMRI and 3D-PCMRI the obtained relative flow volumes were not substantially different in the two bypass configurations. Volumetric flow waveforms and pressure waveforms didn't show realistic characteristics, especially in the supra aortic branches. MRI flow measurements in the

aorta showed good accuracies compared to the US measurements (2D-PCMRI: 6.47±4.19%; 3D-PCMRI: 4.53±3.78%) and errors without phase offset correction were not significantly different ($p>0.05$). In the small, off centered, supra aortic arteries accuracy of 3D-PCMRI measurements significantly increased by applying phase-offset correction (corrected: 17.10±15.18% vs. uncorrected: 297.33±377.21%; $p=0.007$). For 2D-PCMRI accuracy did not changed by phase offset correction (corrected: 12.77±9.17% vs. uncorrected: 11.78±10.27%; $p>0.05$)

The complex aortic dynamic was analyzed using a novel computational approach for assessment of thoracic aortic displacement and distension in their full four-dimensional (3D+t) extent. Computed tomography angiography (CTA) datasets of 24 patients without history of aortic disease were studied. Maximum displacement vectors (MDV) including its direction were computed at nine, characteristic aortic locations: left coronary artery (COR), mid-ascending aorta (ASC), proximal (prox) and distal (dist) at the origin of the supra aortic branches brachiocephalic trunc (BCT), left subclavian artery (LSA) and in the descending aorta (DES). To illustrate the overall amount of aortic motion ellipsoid representing the spatial variations of distinctive points were calculated using principal component analysis (PCA). Furthermore aortic distension based on aortic diameter and cross sectional area was calculated.
MDV decreased from COR to DISTLSA ($p<0.005$) and was highest for COR (6.2±2.0mm) and ASC (3.8±1.9mm). Displacement was clearly non-randomly directed towards left and anterior at COR and ASC. The craniocaudal component of displacement at COR and ASC was 1.3±0.8mm and 0.3±0.3mm. Maximum displacement occurred in the systole. Compared to the proximal aortic locations the length of MDV was negligible at the distal locations of the arch and in the descending aorta. In addition no predominant direction of displacement was observable. Distension was for COR 2.3±1.2mm and significantly higher compared with ASC, LSA, and DES ($p<0.005$).

Relative to blood flow in the ascending aorta about one third of stroke volume is distributed to the upper body through the supra-aortic arteries. Volumetric flow waveform feature point characteristics are similar throughout the thoracic aorta. Furthermore a high correlation between Q_{avg} and Q_{peak} is present whereby the former could be obtained from the latter with high accuracy. Therefore the archetypal waveforms in this study may be used to characterize normal aortic and supra aortic flow waveforms when scaled by an individual's cycleaveraged. On the other hand supra aortic volumetric flow could be derived from supra aortic area with adequate accuracy, assuming the applicability of a power law function.
The phantom experiment showed that adequate blood supply to the upper body might be provided by surgical bypass techniques. However, possibly due to the rigid nature of the phantom and the lacking windkessel effect volumetric flow and pressure waveforms could not be physiologically mimicked in the setup. Regarding 2D-PCMRI and 3D-PCMRI flow measurements, in particularly the accuracy of 3D-PCMRI measurements in supra aortic vessels highly benefits from phase-offset correction. Aortic displacement and distension predominately occurs within the proximal aorta and to a lesser extent in the aortic arch and descending aorta. As expected, the proximal aorta showed distinct non-random motion by retracing the left-anterior-caudal directed motion of the beating heart. However, contrary to previous assumptions the craniocaudal displacement of the ascending aorta is of lesser magnitude than its motion in the transversal plane.