Visualization of Flow in the Aorta Using Time-resolved 3D Phase Contrast MRI

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Introduction
The flow pattern in the human aorta has a complex three-dimensional (3D) shape [1]. A large range of pathology affecting the aorta, eg valvular stenosis, regurgitation and possibly plaques causes a change in the flow pattern. Furthermore, a better description of the flow in the aortic arch could improve our understanding of the arch as a source of cerebral emboli.

We here describe different ways of visualizing flow patterns in the aorta using a time-resolved 3D phase contrast technique that acquires all three velocity components in every point in a 3D grid encompassing the entire aorta. This makes it possible to retrospectively study the velocity information from anywhere within the acquired volume, without the need to position slices at the time of data acquisition.

Methods
Velocity vector information was obtained using a retrospectively gated 3D phase contrast pulse sequence [2]. We used a 1.5 T scanner (Signa Horizon EchoSpeed, GE Medical Systems, Milwaukee, WI, USA), and the following acquisition parameters: TR=18 ms, TE=7 ms, VENC=100 cm/s, FOV=300(SI)x300(AP)x128(RL) mm with a spatial resolution of 1x4x4 mm. 32 time frames were reconstructed. The phase contribution from concomitant gradient (Maxwell) terms and eddy current effects was subtracted. Data was acquired from young healthy volunteers.

The acquired velocity data was transferred to the Ensight® visualization program (CEI Inc, Research Triangle Park, NC, USA). Streamlines, based on the velocity information from a single time frame, were generated in order to visualize the instantaneous flow field in systole. Path lines were also calculated, which use the time-resolved data in order to trace the path of the blood flow, starting from a user defined location and time frame. Both these types of particle traces (streamlines and path lines), were calculated using a fourth order Runge-Kutta numerical integration technique. Flow profiles, extracted from a plane placed interactively within the 3D volume, were also created.

Results
Streamline created from the ascending aorta show the instantaneous flow field in a systolic time frame (fig 1). The streamlines were calculated both forward and backwards from the starting plane, displaying the flow all the way from the left ventricle to the descending aorta, including the flow to the neck vessels. The main direction of flow through the ascending aorta followed a clockwise rotation (right-handed helix).

Figure 1. Streamlines in the aorta in peak systole. The white arrow marks the plane where velocity profiles were extracted over time.

Using path lines, a more intuitive display of the blood flow is generated. Blood situated in the ascending aorta in early systole reached the neck vessels during the same systole (fig 3a), while blood ejected in late systole did not reach the neck vessels until the next beat (fig 3d).

Figure 3. Path lines started in the ascending aorta in early (a,c) and late (b,d) systole. During the first heart beat (a,b), the blood flow from early systole reaches the neck vessels (a). The lower panels depict the flow after the next ejection phase.

Discussion
The skewness seen in the flow profiles may be of importance when inserting mechanical tilting disc valves in the aortic position. It has been suggested that the valve be oriented with the largest orifice towards the non-coronary sinus in order to preserve the normal skewness of the aortic flow [3]. The interaction between aortic and neck vessel flow could be of importance for assessing a possible cardiac embolic source. The delayed arrival of late systolic blood flow seen will be dependent on the compliance of the aorta. This has previously been reported to give an age dependent variation in the flow pattern [1].

Flow patterns in the great vessels are complex in time as well as in space. Visualization based on 3D cine phase contrast data provides a non-invasive, three-dimensional approach for characterizing flow in the aorta and other vessels in the thorax. The upper ascending aorta is currently out of reach for other non-invasive imaging modalities like ultrasound. Time-resolved 3D phase contrast MRI can visualize and quantify flow in the aorta from a single acquisition. This non-invasive method opens for a new way to assess normal and diseased arteries within the thorax.

References