Extending 4D Flow Visualization to the Human Right Ventricle

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INTRODUCTION: The right ventricle (RV) has a pivotal role in cardiovascular disease and its function may influence clinical outcomes. The RV has complex geometry and its function is significantly affected by the respiratory cycle, which makes imaging of the RV more challenging than the left ventricle.

MRI has been established as a powerful modality for functional assessment of the ventricular function. Particle trace visualization of the dynamic blood flow through the left heart has been performed using three-dimensional cine (3D + time = 4D) phase-contrast (PC) MRI data [1, 2]. In contrast, studies of right heart flow have been performed in only two dimensions [3]; this may largely be attributed to the limitations that respiratory effects and background phase errors create for 4D flow techniques.

We wanted to investigate whether recent advances in 3D cine PC-MRI data acquisition and post-processing would enable achievement of sufficient data quality for accurate particle trace visualizations of the 4D blood flow in the RV.

MATERIALS AND METHODS: Whole-heart 3D cine PC-MRI data were acquired during free breathing using a clinical Philips Achieva 1.5 T scanner. A flow-compensated gradient-echo pulse sequence with interleaved three-directional flow-encoding and retrospective vectorcardiogram gating was applied. Parallel imaging by sensitivity encoding (SENSE) was used to diminish scan time. To enable a trade-off between temporal resolution and scan time, a multiple of N_k sets of the four flow encoding segments per cardiac phase were interleaved. To suppress respiratory effects, a navigator gating method using a slowly adapting window position was applied; data were acquired at end expiration. On the scanner, all data were corrected for concomitant gradient effects. Automated post-processing made corrections for phase wraps and, using a fourth-order weighted correction [4], background phase errors.

Based on this basic configuration for data acquisition and post-processing, the effect of varying parameters known to affect the adequacy of 4D flow data were evaluated by making measurements in 6 healthy volunteers. We aimed at a scan time of 10-15 minutes, excluding the navigator gating efficiency. Evaluations of the in-vivo data quality were performed using pathlines emitted from the right atrium; data were considered to have sufficient accuracy only if the pathlines could be traced through the RV to the pulmonary artery without leaving the blood pool.

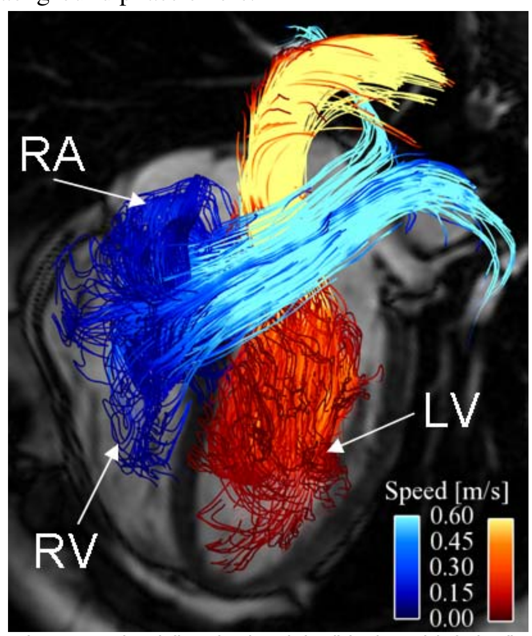

Figure 1. Blood flow in the right (blue) and left (red) side of the heart. Pathlines were emitted from the right and left atrium, respectively, at multiple time points and traced over one cardiac cycle. RA: Right atrium. RV: Right ventricle. LV: Left ventricle

RESULTS: With the constraint of a 10-15 minutes scan time, the best combination of scanning parameters for obtaining 4D flow data with sufficient accuracy for tracing pathlines from the right atrium, through the RV, and to the pulmonary artery (figure 1) included: TR/TE: 6.2/3.7 ms, flip angle: 8°, voxel size: 3x3x3 mm^3, VENC: 1 m/s, SENSE = 2, N_k = 2 k-space lines per cardiac phase, and navigator window size of 5 mm and 10 mm in the inner 25% and the outer 75% of the k-space, respectively.

The TE used here is 0.5 ms longer than the shortest possible on our scanner. In addition to a decrease in the signal-to-noise ratio via a shorter readout gradient, excessive shortening of the TE was found to amplify the background phase errors and resulted in aberrant particle traces that could be seen to leave the blood pool. In combination with a longer TE, the 4^{th} order weighted background phase correction scheme improved the elimination of phase offsets in a larger part of the field-of-view as compared to the conventional 1^{st} order correction based on a threshold generated mask.

DISCUSSION: Investigations of right heart flow with 3D cine PC-MRI present special challenges. It is important to minimize background phase errors, e.g. by using effective background correction and a longer TE. The lower velocities in the right heart may prompt the use of lower VENC, but this come into conflict with the simultaneous acquisition of left heart flow data. Finally, it is important to remember that the data are acquired only from end-expiratory beats, and therefore the flow visualizations will not be representative of all respiratory phases which may significantly impact RV volume and flow. The protocol presented provides whole-heart 4D flow data with sufficient accuracy for pathline visualizations of the transit of blood through the RV. Whole-heart 4D flow data has the potential to add to the understanding of basic RV and interventricular physiology in health and disease.

REFERENCES

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