Segmentation of aortic flow in real-time spiral phase-contrast MRI for assessment of stroke volume variability

Gustavo Maia Queiroz Mendonça[1] and Joao L. A. Carvalho[1]
[1]*Department of Electrical Engineering, University of Brasília, Brasília, DF, Brazil*

Introduction: Real-time spiral phase contrast MRI is uniquely capable of non-invasively measuring the stroke volume associated with each individual heartbeat[1-6]. The quality of these measurements depends on how good the segmentation of the interface between aortic wall and lumen is. Such process is hampered by the low-resolution and low-contrast nature of real-time images, especially at high field. Image segmentation using traditional techniques such as thresholding, denoising, filters, and morphologic operations — has proven not robust[1-3,7]. We propose a novel model-based approach, which is capable of very accurately segmenting aortic flow. Instead of attempting to achieve a millimetrically-accurate segmentation of the wall–lumen interface, the proposed algorithm focuses on separating the aortic flow from neighboring flows. This provides robustness, even when this interface is not visually distinguishable.

Imaging: Studies were performed on a GE Signa 3T EXCITE HD system. Slice prescription was performed perpendicular to the ascending aorta. Real-time spiral phase contrast was used to measure through-plane velocities, with 3 mm spatial resolution and 57 ms temporal resolution[1-3]. Seven healthy volunteers were studied.

Processing: During reconstruction (in MATLAB), zero-padding was used to obtain images enlarged by 2-fold. The radius (R) of the aorta, and an initial centroid value (x_o,y_o) were manually prescribed for each dataset, only for the first frame.

Centroid Tracking: An iterative process for automatic tracking of the aortic centroid, was designed (Fig. 1, g-k). Two "template images" are centered at the current centroid (x_n,y_n). *Template I* (Fig. 1h) is a 2D Gaussian function, and highlights the aortic lumen in a low-pass version of the image (Fig. 1g), by pixel-wise multiplication. *Template II* (Fig. 1i) is the difference between two Gaussians, and highlights the aortic contour in a high-pass version of the image (Fig. 1j). The two resulting images are binarized (using 60% and 10% thresholds, respectively), and combined with *Template I* by weighted averaging (the combined images are shown in Fig. 1k). The barycenter (displacement Δs from position $\vec{s}_\mathrm{n} = (x_n, y_n) = \{\sum_i \sum_j (i \cdot B[i,j], j \cdot B[i,i])\} / \{\sum_i \sum_j B[i,j]\}$ to position $\vec{s}_{\mathrm{n}+1}$ is then calculated. The centroid tracking process stops when Δs is smaller than ε_S.

Segmentation: The segmentation is actually performed on a model image (Fig. 1e), obtained by pixel-wise multiplication of an offset high-pass image (Fig. 1c) with a 2D Gaussian (Fig. 1d), centered at the estimated aortic centroid (Fig. 1k). The model image is normalized to the [0, 255] interval, and then binarized (Fig. 1f). The threshold level is $L = 255 \cdot e^{-R^2/2R^2} = 154$. The aortic flow associated with the current temporal frame is calculated by multiplying the binarized mask's area by the average blood velocity within it. In order to adjust to radius variations associated with vessel dilatation and contraction, L is adaptively adjusted based on the standard deviation of the images' pixel intensities. This seems to consistently increase/decrease with blood velocity, and, therefore, with aortic area.

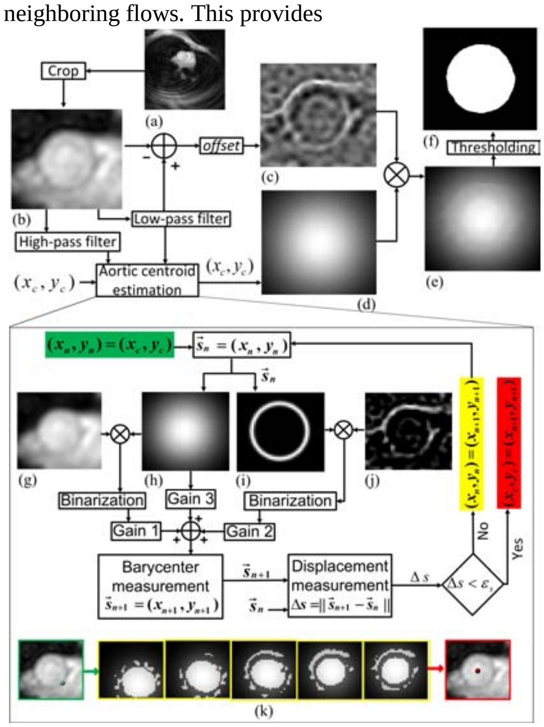

Fig.1: Block diagram of the proposed segmentation method (top); its iterative aortic centroid tracking algorithm (bottom); and the evolution of this iterative process (k).

Results: Due to the high temporal resolution requirements of flow measurement, and the use of real-time spiral MRI at 3T, all images display low resolution and low contrast. Fig. 2 shows segmentation results for six temporal frames (covering systole) from three different subjects: one presenting reasonably good image quality (Fig. 2a); one presenting medium image quality (Fig. 2b); and one presenting very poor image quality (Fig. 2c). The proposed segmentation algorithm was consistently able to track and isolate the aortic flow from neighboring flows, even when the wall–lumen interface was not visually well-defined.

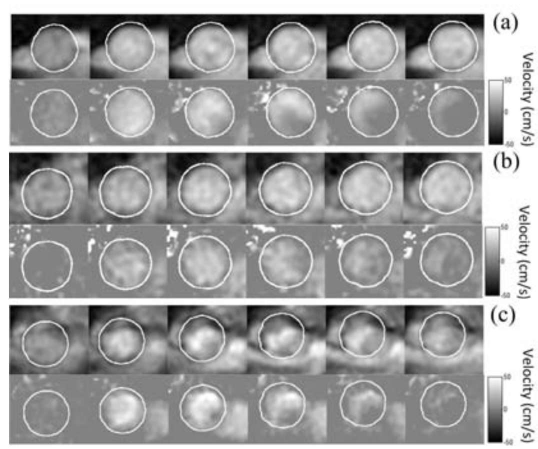

Fig.2: Segmentation results for six temporal frames (covering systole) from three different subjects: (a) one presenting reasonably good image quality; (b) one presenting medium image quality; and (c) one presenting very poor image quality.

Discussion: Segmentation errors are typically caused by an overestimated L, or by inaccurate aortic centroid estimation. However, pixels near the aortic wall — which would be neglected if there is underestimation of the aortic area — are very likely to present very low velocities, and, therefore, generally do not significantly contribute to the overall aortic flow. Assuming a parabolic profile, a 10% underestimation of the aortic radius or a 10% error in aortic centroid estimation would result in only 3.6% error in flow estimation.

Conclusion: We presented a robust model-based approach for segmenting aortic flow in real-time spiral PC-MRI images. The proposed segmentation method takes real-time MRI one step further towards becoming the non-invasive gold standard for assessment of stroke volume variability.

References: [1] Carvalho JLA, et al. Proc. 15th ISMRM, p. 248, 2007. [2] Carvalho JLA, et al. Proc 11th SCMR, p.1138, 2008. [3] Carvalho JLA, et al. Proc 16th ISMRM, p. 383, 2008. [4] Steeden JA, et al. MRM 64:1664, 2010. [5] Jones, et al. JMRI 33: 448, 2011. [6] Kowalik GT, et al. JMRI, early view, 2012. [7] Gondim GM and Viana TZ, B.S. thesis, University of Brasilia, 2008.