Feasibility of real-time MR based path planning for off-pump cardiac interventions

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Introduction

Recently, magnetic resonance imaging (MRI) has emerged as a meritorious modality for planning and performing minimally invasive intracardiac procedures [1-2] due to not only its excellent contrast mechanisms but also lack of ionizing radiation [3]. In this work, we evaluate the feasibility of a computational methodology, which combines preoperative cine MRI and intraoperative real-time MRI for guiding off-pump intracardiac procedures, e.g., aortic valve replacement (AVR) via transapical access in the beating heart [4-5]. Multislice preoperative cine data is used to generate a dynamic passage, (i.e., 3D path) inside left ventricle (LV), which is updated intraoperatively by registering it on real-time slices. We developed a novel virtual reality environment to test the method, for real-time 3D path registration and appropriate-sized catheter deployment, on datasets collected from 15 healthy volunteers.

Methodology

Initially, for every subject, a 3D dynamic left ventricular passage was generated using TrueFISP cine datasets with TR/TE = 2.3 ms/1.4 ms, alpha = 80°, interslice distance = 6.0 mm, and acquisition matrix = 224x256. Each dataset comprised 19 short axes (SA) and 5 long axes (LA) slices, capturing a full heart cycle in 25 sequential time frames (t). Our intraoperative datasets were also collected from the same subjects (n=15) using TrueFISP parallel imaging with effective repetition time = 48.4 ms, TE = 0.95 ms, alpha = 65°, slice thickness=6.0 mm, and acquisition matrix = 160x66. Those data include continuous real-time acquisitions of central three-chamber LA slice spanning consecutive 30 full cardiac cycle while the subjects were breathing. Figure 1 (A) and (B) shows the cardiac landmarks pertinent to the target operation, i.e., transapical AVR, on a three-chamber preoperative LA slice and its intraoperative counterpart respectively.

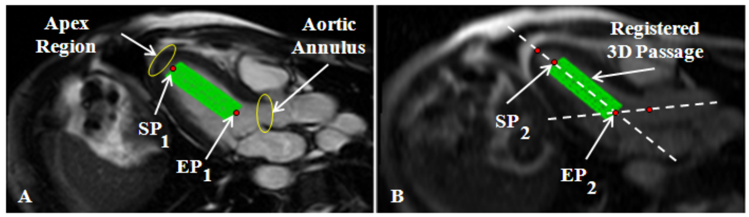

Fig. 1: A three-chamber cine LA slice (A), and corresponding real-time slice (B), depicting apical entrance, registered dynamic passage and aortic annulus.

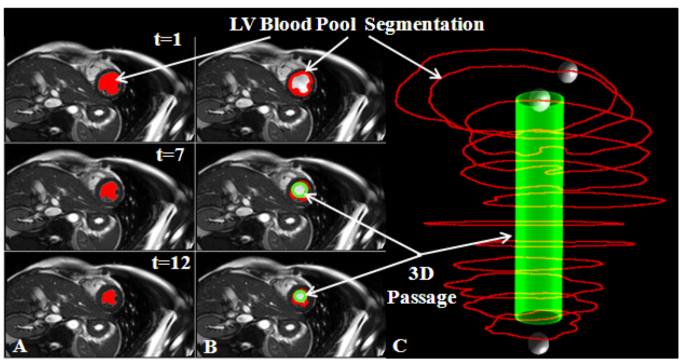

Fig. 2: LV blood pool segmentation (A), boundary contours and maximum circular common area (B), and 3D passage inside the contours (C).

In our transapical approach a prosthetic valve delivery catheter enters the LV via apex and deploys toward the aortic annulus along the passage without touching the endocardium. To extract the apex, the 3D passage, and aortic annulus for every single time frame ($\forall t$: t=1 to 25) from the cine images, LV blood pool was segmented in SA and LA slices by means of a semi-automatic custom region-growing algorithm [4]. Papillary muscles and chordae tendinae were included in segmentation for a realistic modeling of LV as shown in Figure 2. The passage was then created by projecting segmentation contours onto a single virtual plane parallel to SA; finding their maximum circular common area; and extending it along the LV for each heart phase [5]. Figure 2 (A) and (B) depict the SA slices and segmentation contours from top to bottom for three different heart phases (t=1, 7, and 12 respectively), while (C) shows the resulting 3D passage. The average diameter of passage base was 10 mm in systole and 21 mm in diastole for 15 subjects. The next major task was to register this 3D passage onto real-time LA slice on-the-fly. This was done in two main steps: (1) Determine the heart phase in which the real-time slice was collected (and thus match it with the corresponding passage); (2) Adjust the position and orientation of this passage to account for heart motion due to respiration, arrhythmias, etc. [4]. We have tested our algorithm to assess the accuracy of this real-time registration process. Specifically, the registered passages were compared to the ground-truth ones, which were created by manually locating them onto their correct positions in all the real-time images for 30 full heart cycles (n=15). The registration errors were defined as follows: $e_S=\| SP_1-SP_2 \|$, $e_E=\| EP_1-EP_2 \|$, where SP_1, SP_2 are start points, and EP_1, EP_2 are endpoints of the ground-truth passage and the registered one respectively (Figure 1). Based on our finding that the minimum base diameter of the passage was 10 mm, we have simulated the deployment process from the apex to the aortic annulus with tubular catheters of diameters: 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, and 9 mm.

Results

The average registration errors were: e_S =2.1 mm (min=1.6 mm, max=2.4mm), e_E=1.4 mm (min=1.0 mm, max=1.6 mm) for 15 subjects. This difference was mainly caused by the fact that the SP is nearer to the apex, the most dynamic point of heart, whereas EP is closer to the aortic annulus which undergoes relatively less motion. In order to guarantee safe deployment, we assumed both e_S and e_E took the absolute maximum value of 2.4 mm in either direction (i.e., total error of 4.8 mm at each side), and then omitting the outer parts, the diameter of the passage can drop to 5.2 mm in systole and 16.2 mm in diastole. Since the catheter can always follow the centerline of the passage, any device with diameter less than 5.2 mm can be deployed safely within such a corridor. In our simulations, the catheters with diameters 4mm and 5mm were deployed safely for all subjects (no collision), whereas the ones with diameters 6mm, 7mm, 8mm, and 9mm failed to be deployed safely (touching the endocardium) in 3, 6, 12, and 15 subjects respectively. Our immediate future work includes adapting another segmentation algorithm [6] for comparing with ours and testing the methodology in a dynamic cardiac phantom which can realistically simulate the size and motion of the apex, LV and aortic annulus [7].

References

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