Intraoperative Analysis of Locations for 3D Ultrasound-Guided Capture of Foreign Bodies from a Beating Heart

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INTRODUCTION

Free moving foreign bodies in the heart pose serious health risks, having the potential to cause arrhythmia, occlusion, and even death[1,2]. The condition is common in both civilian and military populations[3,4]. Thrombi can emerge following myocardial infarction, and debris can enter heart through the venous system after a soft tissue injury in the chest, abdomen, or extremities. Small caliber bullets and small shell fragments with low velocity tend to circulate freely in the right atrium and can become entrapped in the pericardial trabeculations and fatty tissue[2]. Symptomatic, free moving cardiac foreign bodies must be removed surgically.

Treatment traditionally involves open surgery via median sternotomy and incision of the pericardium to expose the pertinent heart chamber[3,5-7]. The highly invasive procedure requires a long recovery period and incurs numerous risks, such as bacterial mediastinitis, inflammation, and bone fracture. A standard surgical setting may employ cardiopulmonary bypass (CPB), which introduces additional health risks.

We propose a minimally invasive surgical approach using an image-guided robotic end effector, to avoid the disadvantages of sternotomy and CPB. In the envisioned scenario (Fig. 2), a robotic tool is inserted transapically into the heart after detection of the foreign body using preoperative imaging. Under intraoperative ultrasound guidance, the robot moves to secure the target.

In previous work we used 3D transesophageal echocardiography (TEE) to track a foreign body in a beating heart phantom; results suggest that the abrupt, irregular motion of a cardiac foreign body precludes robotic retrieval based on direct pursuit of the projectile. We thus proposed to have the robot wait at a *capture location* and ambush the particle upon its arrival. Salient capture locations were considered based on spatial probability[8], dwell time, and visit frequency[9] to support the viability of the approach. In this work, we address the irregular nature of the motion by examining the time dependency of the capture location measurements. Our study is aimed at quantifying the tracking duration required to produce actionable estimates of capture locations, as well as determining the predictability of future figures based on past measurements. In a broader sense, improved understanding of the problem will aid in the design of retrieval systems and strategies.

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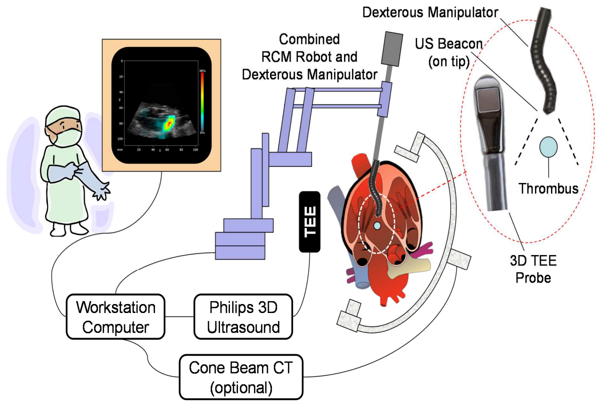

Fig. 2 Robotic fragment retrieval from the heart under 3D TEE guidance.

MATERIALS AND METHODS

As pictured in Fig. 1, the experimental setup consists of a Philips X7-2t 3D TEE probe and a heart phantom with programmable heartbeat in a water tank; a future goal is to transition to *in vivo* studies. A 3.2-mm steel ball representing a foreign body is placed in the phantom, and the scene is imaged using the probe at a rate of 20 volumes per second. Tracking of the foreign body is performed using a modified normalized cross-correlation method; previous reports[8] describe the setup in greater detail.

We previously defined different criteria for selecting a location at which to capture a cardiac foreign body, namely spatial probability, dwell time, and visit frequency, but reported measurements based on the full duration of the 20-second data sets (n=5). Here we present the time evolution of the figures in order to illustrate the intraoperative behavior of the foreign body and how the system might respond in real time.

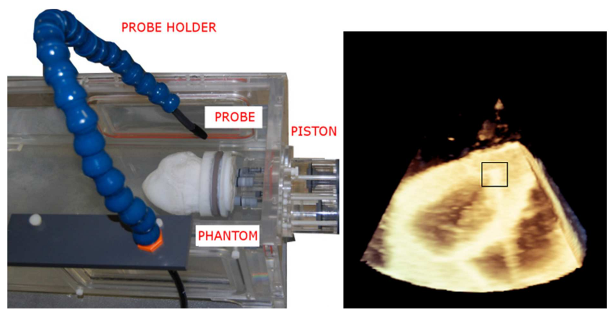

Fig. 1 (*Left*) Arrangement of the TEE probe and beating heart phantom; (*Right*) a sample 3D ultrasound image with foreign body outlined.

RESULTS

Spatial Probability: The spatial probability of foreign body location is given by the histogram of its positions over time. This metric reveals that the foreign body has preferential regions of presence, as depicted in Fig. 3 (*top row*). Fig. 4 (*top*) shows how the most probable location develops over time; on average, 18.5 seconds of tracking is needed until the most probable location reaches an estimate of 50%.

Dwell Time: A retrieval system may require that the foreign body remain at a location for a certain amount of time to facilitate capture. The dwell time of a location in the heart describes amount of time the foreign body is expected to remain there before ultimately leaving. Based on Fig. 4 (*center*), the most dwelled location can be determined after 6–8 seconds of tracking.

Visit Rate: On the other hand, a foreign body may be more amenable to capture while in transit; in this case the chance of success can be increased by determining the location that the object traverses most frequently, without regard to how long it remains there overall. Fig. 4 (*bottom*) indicates that such a measurement stabilizes after 14–16 seconds of tracking.

Table 1 lists minimum time intervals for which capture location measurements repeat, determined by dividing the data into equal time intervals and finding the maximum correlation between intervals. Spatial probability prediction requires a longer observation period, implying that the behavior is fairly consistent, albeit along varying trajectories. This is a preliminary finding to be more rigorously examined in the future.

DISCUSSION

Though a foreign body in the heart moves erratically, existence of special capture locations suggest the feasibility of using a slow robot to retrieve it. This work explores the real-time evaluation of these locations.

The results provide insight on the time required to discover capture locations, a possible issue being the linearly increasing spatial probability over the 20-second dataset duration. Future work will examine the reachability of primary and secondary locations, as well as the tracking of heart walls to prevent damage by the robot.

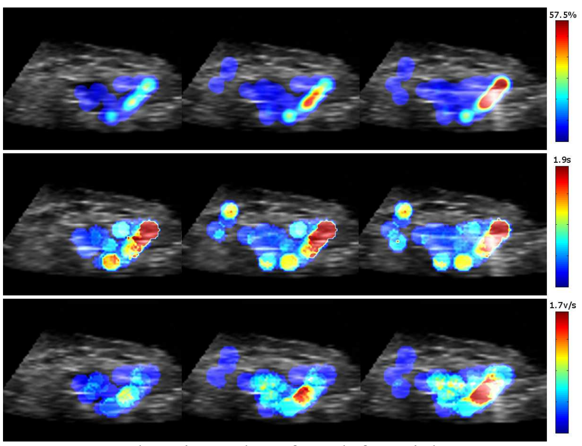

Fig. 3 Capture location values from left to right at t=6, 12, and 18 s. (*Top row*) Map of spatial probabilities, showing distinct regional preferences of the foreign body. (*Center row*) Map of dwell times showing faster evolution than spatial probability. (*Bottom row*) Map of visit rates; highly-traveled sections are not necessarily the most probable or most dwelled.

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Table 1 Minimum independent time intervals with repeating capture location estimates.

Spatial Probability	Dwell Time	Visit Rate
4.5 seconds	3.5 seconds	3.5 seconds

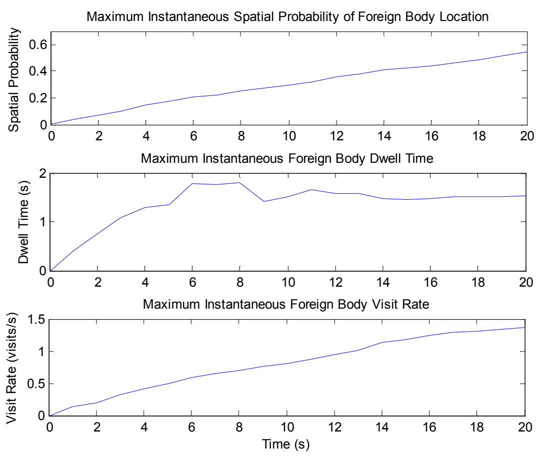

Fig. 4 Development of capture locations over time (averaged over five datasets). Previous work considered only the final estimates at t=20 s. (*Top*) Spatial probability. (*Center*) Dwell time. (*Bottom*) Visit rate; the slightly plateauing trend at t=14–16 s appears more clearly in plots of maxima, not shown here.