Real-time 3D Catheter Localization System Using Ultrasound: Recent in Vivo Results Towards Endovascular Abdominal Aortic Aneurysm Repair

Jay Mung, Jesse Yen
Biomedical Engineering, Viterbi School of Engineering
University of Southern California

John Moos, Fred Weaver
CardioVascular Thoracic Inst, Keck School of Medicine
University of Southern California

Abstract—Surgeons have used localizers in minimally invasive procedures by combining 3D tool tracking with anatomical images obtained before or during the procedure. We previously reported on an ultrasound based 3D real-time locator system. The system determines location by measuring time of flight between a surgical tool-mounted ultrasound transducer and an array of external single-element transducers. Here we interfaced the localizer with 3D Slicer software for image guided surgery with preoperative CT images. We report on initial in vivo results and experience deploying an abdominal aorta stent in a porcine model using the ultrasound localizer. The system demonstrated real-time tracking in the aorta. CT images and direct inspection of the abdominal cavity showed bowel gas that likely caused poor signal propagation and thus erratic tracking. Despite this, we were able to use the 3D Slicer display to position the delivery catheter in the abdominal aorta. Abdominal aorta explant showed stent deployment within 3 mm of the target location. Future work will consider approaches to avoid bowel gas and improve registration.

Keywords - AAA; localization; image guided interventions; time of flight; locator; 3D tracking

I. INTRODUCTION

3D localizers are devices that provide the location of tracked objects in 3D space. Surgeons have used localizers for tool guidance in minimally invasive procedures by combining tool location information with anatomical images obtained before or during the procedure. Two types of commercially available surgical localizers are based on optical or electromagnetic (EM) technology. Optical localizers require line of sight between the tool and a set of cameras. Therefore they do not provide a solution for tracking catheters. EM localizers can be prone to error in the presence of metals. This has limited their utility in the operating room [1]. We previously reported on an ultrasound based 3D real-time locator [2]. The system determines location by measuring time of flight between a surgical tool-mounted ultrasound transducer and an array of external single-element transducers. We previously evaluated the system in vitro, showing that the localizer has zero bias and RMS error as low as 1 mm in water and 3 mm in the presence of tissue and a stent. Here we interfaced the localizer with 3D Slicer [3] software for image guided surgery with preoperative CT images. We report on initial in vivo results and experience using the system to deploy an abdominal aortic stent in a porcine model.

II. METHODS

A. Ultrasound Localization Device

A catheter placed inside the body is equipped with a single element 3.5 MHz transducer that transmits an acoustic pulse, which is received by an array of 7 single element transducers placed on the abdomen. A Verasonics system digitizes the signals which provide time of flight measurements to calculate location estimates at 20 Hz using a custom Matlab script. An OpenIGTLink [4] package interfaces Matlab with 3D Slicer for real-time localization display on preoperative images.

B. In vivo study part I: Preoperative imaging & registration

This experiment was performed with a 90 lb. female Yorkshire swine animal model (Irish Farms) in accordance with institutional IACUC protocol #11226. The animal was placed under temporary sedation for transport and CT imaging. Prior to imaging, button EKG leads were placed on the animal to serve as registration fiducials. The fiducials were positioned using a template corresponding to the array of 7 abdominal transducers and centered in the vicinity of the abdominal aorta/renal artery takeoff. This position was approximated using the location of the swine’s navel and nipples (figure 1).

A Siemens Biograph 64 PET/CT scanner acquired arterial phase contrast images and saved them at 1 mm slice thickness. Fiducial markers within the CT image were located using the fiducials module in 3D Slicer and manually clicking on markers. The CT image space locations of the fiducials markers are given in Figure 2. These coordinates were registered with the abdominal transducer array elements to provide coarse registration between the localizer and the CT space. Registration was performed with Procrustes analysis [5] and yielded a mean Fiducial Registration Error of 5.78 mm [6].

Figure 1. L: Animal with fiducial markers affixed, ready for CT scan. R: 3D volume rendering of CT data showing abdominal aorta and fiducial markers.
C. In vivo study part II: Live surgery and data acquisition

Following the imaging study, the animal was recovered from sedation and rested for 12 hours. The next morning, the animal was placed under general anesthesia with mechanical ventilation. A femoral cutdown was employed to gain access to the right femoral artery and place a 9 Fr introducer sheath inside the artery to facilitate introduction of the ultrasound catheter.

The EKG leads were removed and the abdominal array was placed and secured at the location of the markers (figure 3). Liberal amounts of ultrasound transmission gel ensured acoustic contact. The ultrasound tracking system was initiated and the catheter was advanced and pulled back inside the artery for several runs over the next several hours. For troubleshooting purposes frame averaging parameters, filtering parameters and abdominal array placement was varied while tracking was activated. Data was recorded in the form of time stamped coordinate outputs, intermittent raw RF data and monitor display video screen captures (figures 4, 5).

A final catheter tracking run was performed to place the catheter at the intended stent deployment site, just below the renal arteries (figure 1). The proximal end of the catheter was marked at the lip of introducer sheath to measure the length of the catheter from the femoral access site to the stent site. This length was used to mark the stent deployment catheter. The ultrasound catheter and introducer sheath were removed and the stent deployment catheter (Gore Excluder AAA Endoprosthesis, W.L. Gore & Associates, Inc.; Flagstaff, AZ) was introduced into the access site. The deployment catheter was advanced to the length as measured from the ultrasound catheter and the stent graft was deployed. The animal was then euthanized and the operation was converted to an open surgery to expose the abdominal aorta. The abdominal aorta and stent graft were then explanted to evaluate stent placement location.
III. RESULTS

A. Intraoperative experience

Figure 6. Thick orthographic projection CT slices showing bowel gas (green arrows)

Large pockets of bowel gas were visible in the preoperative CT images (figure 6) and later confirmed by direct surgical visualization. The raw RF data showed that ultrasonic signals with adequate SNR were only consistently available at sensors 1, 3 and 4, which corresponded to the upper right quadrant of the abdominal array. This corresponded to a position largely occupied by the liver. Moving the array towards the head, away from the bowels showed increase signal magnitude on the sensors but invalidated the pre-operative registration.

The real time nature of the system provided immediate feedback on system performance. When the catheter was not being actively manipulated, respiratory motion oscillation was detectable and could be suppressed by imposing a breath-hold with the mechanical ventilator. Qualitatively, axial tracking up and down the aorta appeared more accurate than left-right or anterior-posterior tracking, which appeared erratic around the image. This could have been due to user perception, as the axial position selected axial slices on which L/R and A/P positions were displayed.

B. Post euthanasia evaluation

Figure 7. Photo of bowel gas balloning from intestines upon opening abdominal cavity

Opening the abdominal cavity showed large amounts of bowel gas present in the intestines, consistent with the preoperative CT images. Direct surgical exposure of the abdominal aorta showed that the stent was successfully deployed. Explantation of the aorta with stent showed that the upper lip of the stent was 1-3 mm below the renal bifurcation (figure 8). Note that the process of cutting the aorta released tension on the vessel which caused it to relax and shrink from its in vivo state.

Figure 8. Top L: Photo of stent, in situ, deployed just below the renal arteries. Top R: Explanted aorta containing stent. Bottom: Explanted aorta and stent showing renal artery clearance.

IV. DISCUSSION & FUTURE WORK

We performed this pilot study to assess feasibility and troubleshoot the ultrasound localization system in vivo. It is clear that bowel gas is a major impediment to implementing the system in the porcine model, as gas reflects almost the entire ultrasound signal. Humans have less bowel gas than pigs, but nonetheless bowel gas is an important consideration. Barring any solutions to remove bowel gas, we must consider a different approach to acoustic access of the abdominal aorta. Image data as well as preliminary RF data suggest that bowel gas can be avoided by placing sensors on the flank and back the animal, transmitting signal through the liver and back muscle. Although the current abdominal array fits the animal well, the transducers must be reconfigured in order to facilitate acoustic access, avoiding both gas and bone. Dilution of precision can provide insight on optimal transducer placement given these constraints [7]. As such, we have built a prototype “cradle array” to hold transducers against the back and flank of the animal for our next study.

Registration between the preoperative image, patient and localizer also remains an unresolved issue. The current accepted method to ensure correspondence between the preoperative image and the patient in the OR is to position the patient exactly as he was positioned in the imaging scanner. To
this end, we will investigate custom patient positioners/immobilizers such as the Alpha Cradle (Smithers Medical Products) [8]. However, this does not address the issue of registering the localizer coordinate frame to the image/patient. Our current method provides coarse registration but it is inadequate in that it depends on the accuracy of replacing the transducer array as it is marked in the CT image. We will investigate a more rigorous registration scheme where the ultrasound localization device itself is used to locate a series of fiducials in order to bring the patient and image into registration. At this stage, we will not consider soft-tissue deformation due to respiratory motion as the abdominal aorta remains relatively static in relation to the spinal column.

Further technological improvements include provisions to address noise within the system. To this end, we will implement a custom hardware interconnect between the transducers and the Verasonics system. We note that the system does become contaminated with RF noise when the electrocautery device is in use, though this is not an issue because the device is used only to gain access to the artery. We will also implement extended Kalman filtering to ensure smooth, realistic position outputs [9].

V. CONCLUSION

Preliminary in vivo experience with the ultrasound localizer demonstrated real-time but erratic tracking in the aorta. CT images and direct inspection of the abdominal cavity showed bowel gas that likely caused poor signal propagation, thus responsible for the erratic tracking. Still, tracking was sufficient to navigate the catheter to the target position for stent deployment. The 3D Slicer display was used exclusively to position the delivery catheter. Abdominal aorta explant shows stent deployment within 3 mm of target location.

Our in vivo pilot study highlighted two major issues that need to be addressed in future studies: bowel gas/acoustic accessibility and registration. The long term goals for this work are to demonstrate feasibility for interventional procedures and demonstrate that ultrasound technology may be a viable option for surgical localizer systems.

ACKNOWLEDGMENT

Special thanks to Sukgu Han, Grace Huang, Gabriel Herscu, Linda Kirkman, Paul Kirkman, Ryan Park, Grant Dagliyan, Kristin O’Leary for previous work, logistics, imaging and surgery help. Jay Mung is supported by a fellowship from the Alfred Mann Institute.

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