Towards Intra-operative Monitoring of Ablation Using Tracked 3D Ultrasound Elastography and Internal Palpation

Pezhman Foroughi\textsuperscript{a}, Jessica Burgner\textsuperscript{b}, Michael A. Choti\textsuperscript{c}, Robert J. Webster III\textsuperscript{b}, Gregory D. Hager\textsuperscript{a}, and Emad M. Boctor\textsuperscript{a,d}

\textsuperscript{a}Department of Computer Science, Johns Hopkins University, Baltimore, USA;
\textsuperscript{b}Department of Mechanical Engineering, Vanderbilt University, Nashville, USA;
\textsuperscript{c}Department of Surgery, Johns Hopkins Medical Institutions, Baltimore, USA;
\textsuperscript{d}Department of Radiology, Johns Hopkins Medical Institutions, Baltimore, USA

ABSTRACT

B-mode ultrasound is widely used in liver ablation. However, the necrosis zone is typically not visible under b-mode ultrasound, since ablation does not necessarily change the acoustic properties of the tissue. In contrast, the change in tissue stiffness makes elastography ideal for monitoring ablation. Tissue palpation for elastography is typically applied at the imaging probe, by indenting it slightly into the tissue surface. However, in this paper we propose an alternate approach, where palpation is applied by a surgical instrument located inside the tissue. In our approach, the ablation needle is placed inside a steerable device called an active cannula and inserted into the tissue. A controlled motion is applied to the center of the ablation zone via the active cannula. Since the type and direction of motion is known, displacement can then be computed from two frames with the desired motion. The elastography results show the ablated region around the needle.

While internal palpation provides excellent local contrast, freehand palpation from outside of the tissue via the transducer can provide a more global view of the region of the interest. For this purpose, we used a tracked 3D transducer to generate volumetric elastography images covering the ablated region. The tracking information is employed to improve the elastography results by selecting volume pairs suitable for elastography. This is an extension of our 2D frame selection technique which can cope with uncertainties associated with intra-operative elastography. In our experiments with phantom and ex-vivo tissue, we were able to generate high-quality images depicting the boundaries of the hard lesions.

Keywords: Elastography, Ablation, Strain, Active Cannula, Frame Selection, Tracking, Intra-operative imaging, Monitoring

1. INTRODUCTION

Ultrasound elastography has the potential to become the primary imaging modality for monitoring ablation. The b-mode ultrasound depicts the acoustic properties of the tissue which may not be affected by ablation, whereas elastography is sensitive to the change in the stiffness of the tissue during ablation. Varghese \textit{et al.}\textsuperscript{1} showed that the zone of necrosis can be accurately depicted under ultrasound elastography. Boctor \textit{et al.}\textsuperscript{2} used a dual-armed robotic system for monitoring ablation. In another work, a finite element model of tissue with shape priors was optimized to determine the ablated region.\textsuperscript{3} This approach was successful in accurately determining the size and position of the ablation region given the shape estimate. A sophisticated 3D displacement estimation method based on dynamic programming was introduced by Rivaz \textit{et al.}\textsuperscript{4} to cope with high compression rate, noise, and signal decorrelation.

The main challenge associated with elastography for monitoring ablation is that the quality of the images depends on the type of the motion. Usually it is assumed that the compression is mostly in axial direction with minimal lateral and elevational (out-of-plane) motion. In the case of freehand compression, the user compresses or decompresses the tissue by applying force to the tissue via the ultrasound transducer itself. This means that the quality of the images depends on the expertise of the user. It also reduces the consistency of elastography.

To overcome this problem, various robotic manipulators were designed to control the motion of ultrasound transducer.\textsuperscript{5–7} Recently, the da Vinci surgical robot (Intuitive Surgical Inc., Sunnyvale, CA) has been employed...
to exert a controlled palpation using laparoscopic ultrasound. In another approach, the ablation needle was used as the compression/decompression to reduce the difficulty in providing controlled and repeatable results. This was further improved by the addition of 3D imaging. Minute perturbations were applied to the tissue in a controlled manner via the ablation needle to construct the strain images. The needle was fixed in place and a stepper motor controlled the motion. We have also shown that whenever the ultrasound probe is tracked, the localization information could be employed to reduce the dependency to the user expertise in freehand elastography. In this approach, the tracking information is exploited to find pairs of RF frame that are more likely to generate high-quality images. This frame selection scheme significantly enhances the quality and reliability of strain imaging.

In this work, we introduce two methods to enhance elastography results targeted for ablation monitoring. First, we employ a robotic device that controls an active cannula. The active cannula palpates the ablated region from inside providing local contrast independent of the depth of the ablation. Second, we extend our tracked ultrasound elastography to 3D imaging. Similar to the 2D case, the tracking information is used to select the best volumes for elastography. This method also obviates the need for pausing data collection when applying compression.

2. METHODS

In the first method “internal palpation” is applied to the tissue using an active cannula. This robot is composed of two concentric elastic tubes or cannulae the inner of which is precurved into a circular shape. The tip of the cannula is steered inside the tissue by rotating and translating the cannulae inside each other axially. The ablation needle is inserted inside the cannula with the smallest diameter. The first step in our workflow is to position the needle. In this step, the active cannula guides the ablation needle to a pre-defined target. When the needle reaches its target, the tissue is ablated for a few minutes to create a hard region. The robot then palpates the tissue from the inside in a predictable and repeatable fashion. The ultrasound probe collects raw RF data as the tissue is palpated, and elastography images are generated. With this method, the quality of elastography becomes independent of the depth of the image, whereas with outside palpation, the quality generally degrades as the depth increases. This is due to the fact that the pressure applied from the top fades out as the depth increases. The drawback is that the image is local, and the contrast reduces farther from the needle.

Figure 1 describes how the palpation is applied. The goal is to limit the tissue motion to axial displacement as much as possible to yield the best elastography results. For this purpose, the head of the ablation needle and the cannula is placed within the horizontal plane as shown in Figure 1. The inner tube of the cannula is rotated by a few degrees to approximate axial motion. A sequence of RF frames is collected as the cannula moves. In order to recover strain from this sequence, we use a fast and robust elastography technique which can solve for sub-pixel displacement both in axial and lateral directions.

Figure 1. The axial motion is approximated at the head of the ablator by the rotational motion at the base of the cannula.

In the second method, we incorporate the tracking information in the computation of strain images similar to our previous work. In this case, the palpation will be applied from outside the tissue providing a global view with the 3D probe in contrast to the palpation with the robot which gives a local compression in the center of the ablated zone. We are using a 3D ultrasound probe for our data gathering which is tracked with an optical tracker. Tracking information is readily available in our system for targeting purposes.
We have also extended our frame selection technique for ultrasound elastography to volumetric images. The 2D version exploited the localization information from an external tracker to find the best RF frames for elastography. The frame selection algorithm searched for frame pairs with minimal lateral and out-of-plane motion and optimal axial compression. In conventional 3D freehand elastography, usually two volumes are collected in the following order. First, the transducer is held still as the first volume is collected. The user is then signaled to apply compression to the tissue, and finally a second post-compression volume is recorded. This is a difficult task due to the weight of the probe, lack of feedback on the amount of compression, and the need for maintaining constant force during volume acquisition. Also, there will be only one pair of volumes available for elastography. In the presence of localization information, we can use the probe in “4D mode” in which a stream of 3D RF frames is obtained. The volumes with minimal unwanted motion are detected, and used for elastography. The user may also apply a series of compressions while for each compression level more than one volume is collected. There is thus no need to halt the data collection between two compression levels.

At this point, we reconstruct a 3D strain image by performing elastography on 2D slices. Since the lateral and elevational motions are minimized using the tracking information, we assume that the same 2D slices between the two volumes correspond to each other. The final 3D strain image is constructed by combining these 2D strain images. Considering the shape of the ultrasound transducer, we compute strain for “axial-elevational” slices rather than “axial-lateral” slices produced by the ultrasound array. The reason for this is that the curved shape of the head of the transducer produces a large elevational motion when compression is applied. Our 2D elastography technique\cite{14} can recover this motion when the “axial-elevational” slices are used.

![Figure 2. This Figure shows the components of our experimental setup.](image)

3. EXPERIMENTS

We conducted two experiments to preliminarily evaluate our elastography methods using ex-vivo tissue and an elastography phantom. Our experimental setup is a part of a novel guidance and monitoring system for ablation under development. Figure 2 shows the components of our experimental setup used in this work. It is composed of the active cannula, the robot control units, the ablation system, the ultrasound machine, the ultrasound transducer, and an optical tracking system. The tracking information was provided by the Polaris optical tracker (Northern Digital Inc., Waterloo, Ontario, Canada) with a passive marker attached to the transducer.
The robot base was also tracked using an active marker. Our custom software collected raw RF data from SonixCEP ultrasound system (Ultrasonix Medical Corp., Richmond, BC, Canada) and sent the data over a local network. The ultrasound data was obtained using a “4DL14-5/38” transducer with the center frequency of 6.7 MHz. The array of this probe is linear producing rectangular slices. The scanning head is, however, curved.

For synchronization purposes both RF data and tracker readings were captured on the ultrasound machine and time-stamped with the same timer. The data was then synchronized and sent over the network to another computer which recorded data. The developed programs were based on the “MUSIC Toolkit”,15,16 and the network connections were established via “OpenIGTLinkMUSIC”17 which is an extension of “OpenIGTLink” protocol18 adopted for transferring ultrasound data over local networks.

We conducted our first experiment using the active cannula on turkey breast tissue. Figure 3 shows the results of ablation with the robot. The procedure described in Section 2 was followed in this experiment. The elongated ablation is created due to the thermal conductivity of the cannula. The picture also depicts the steered needle showing the rough placement of the needle during ablation.

After the ablation, the cannula induced a periodic motion with an amplitude of 15 degrees and a period of 3 seconds. The arc between peak-to-peak had an approximate length of 3.88mm (see Figure 1). This is based on the kinematics model of the cannula. Although the cannula tubes were rather stiff, the tissue might have slightly impacted the actual motion. While the robot palpated the tissue, a stream of ultrasound data was acquired. The ultrasound array was positioned perpendicular to the needle to minimize the shadowing and other image artifacts caused by the needle.

In the second experiment, the CIRS elastography phantom model 049 (Computerized Imaging Reference Systems Inc., Norfolk, Virginia, USA) was used. The phantom contained a spherical hard lesion not visible in the B-mode image. The size of the sphere was 20mm in diameter, and its center were located at the depth of 35mm from the top of the phantom. The elasticity of this lesion was 80 KPa (kilopascal) which was stiffer than the background (25 KPa). The user was asked to apply axial compression in a stepwise fashion (Figure 5). At the same time, sequences of tracked 3D RF data were collected from this hard lesion to form 3D strain images. The final 3D strain image was constructed by applying 2D elastography to “axial-elevational” slices as described in Section 2 and stacking the resulting 2D images together.

4. RESULTS

A sample of acquired ultrasound B-mode image is shown in Figure 4(a). The needle is visible as a bright reflection with a shadow underneath. The beveled line at the bottom of the image is the boundary of the tissue.
As expected, the axial displacement caused by robot motion is maximal close to the needle (Figure 4(b)). In Figure 4(c), the resulting strain image displays the hard lesion around the needle with clear edges. The dark intensities map stiff tissue whereas bright intensities represent soft tissue. Note that the range of strain includes negative numbers in Figure 4(c). This is due to the fact that the tissue is pushed and pulled from the inside, and the strain values are relative.

![Figure 4](image)

Figure 4. The B-mode, displacement map, and strain image of the ablated liver tissue are shown. The motion is maximal around the needle and diffuses as the distance from the needle increases. The strain shows the hard lesion created by ablation.

Figure 5 shows the stepwise hand motion of the user captured in the tracker readings. The vertical lines signal the beginning of the acquisition of a new 3D image. With this information, volumes with minimal hand motion during data acquisition which maintain the desired compression could be selected. The key point is that there is no need to delay the data acquisition when the user decides to increase or decrease the level of tissue compression. Although the overall time for data acquisition is increased, several volumes would be available for elastography.

![Figure 5](image)

Figure 5. The motion of transducer during a series of stepwise freehand compression is shown. The vertical lines represent the beginning of a new volume. Cyan and black colors represent forward and backward sweeps.

Three cross-sections of the 3D elastography created from pre- and post-compression volumes are presented in Figure 6. The plane of each cross-section approximately passes through the center of the hard lesion. Figure
6(b) is the direct output of strain estimation whereas (a) and (c) are the result of re-slicing the strain volume. The volume is not scan-converted which means that the pixel spacing varies with depth. In Figure 6(b), the curvature of the probe is visible at the top of the image. The curved head of the transducer prevents direct contact with tissue in the two sides of the probe which creates white corners in the elastography image. The gap between the probe and tissue is filled with ultrasound gel which appears as white regions at the top of the image.

Figure 6. Three cross-section images of the elastography image showing a hard lesion. Note that the image is not scan-converted. This is clear in (b) where the curvature of the probe is visible at the top of the image. The white corners in image (b) show ultrasound gel which is soft.

5. CONCLUSIONS

In this paper, we introduced two methods of elastography for monitoring ablation. These methods were designed to address the difficulty of generating reliable and consistent images in intra-operative procedures. The tracking information was utilized to find the best pairs of volumes for elastography, limit the search range of the displacement estimation algorithm. The palpation with active cannula provides a very controlled palpation which is applied directly to the target. Our preliminary results suggest that palpation with a robotic arm (in this case internal palpation with an active cannula) and/or the extra information from an external tracker can produce elastography images with high contrast for monitoring ablation. In future, we aim for a real-time monitoring system that can be used intra-operatively. We will also test the completed system in animal experiments for in-vivo ablation.

6. ACKNOWLEDGMENTS

Pezhman Foroughi is supported by Department of Defense Predoctoral Traineeship Award W81XWH-10-1-0326. This work was also supported by National Institute of Health (NIH) Small Business Innovation Research (SBIR) award 1R44CA134169 (PI Dr. Clif Burdette, Acoustic MedSystems, Inc). The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the NIH. We would like to thank Daniel Carnegie, Hyun-Jae Kang, Nishikant Deshmukh, Xiaoyu Guo and Hassan Rivaz for their help with this work.

REFERENCES


