Contextually Enhanced 3D Visualization for Multi-burn Tumor Ablation Guidance

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Abstract. We introduce visualization methods for augmented and virtual reality displays that guide minimally invasive tumor-targeting interventions, such as radio-frequency ablation (RFA). Our experimental RFA guidance system performs virtual ablations that geometrically match the real ablations in statically registered phantoms. It provides a head-tracked stereoscopic display that shows a real-time, motion-tracked ultrasound scan, the avatar of a motion-tracked RFA probe, and a registered tumor, which is incrementally "carved" away with each successive ablation pass. An analog bar graph displays tentative ablation coverage fractions for tumor and healthy tissue in real time. We introduce our system, describe the visualization techniques, and present initial results.

1 Introduction and Motivation

Minimally invasive techniques are commonly used to treat a variety of cancerous lesions. The interventions include ablative methods such as cryo-ablation, microwave ablation, and radio-frequency ablation (RFA). These are characterized by the need to place percutaneously a needle-like instrument ("probe") in a precise location within the tumor, usually guided by real-time 2D ultrasound imaging and/or pre-operative scans such as computer tomography (CT) or magnetic resonance imaging (MRI). Here we focus on hepatic tumor RFA [1], the driving application in our work.

Ultrasound offers real-time visualization while advancing an RFA probe into the lesion, which may provide more flexibility than either CT or MRI in terms of approach angles. However, conventional 2D ultrasound presents only planar cross-sections of the scanned tissue, while tumors are three-dimensional and can have complex shapes. Thus, even for the most experienced physician, it can be difficult to position the RFA probe optimally to maximize the tumor ablation while minimizing collateral injury. When treating larger lesions, adjunctive techniques may be required for complete ablation of tumor cells. One strategy that is commonly employed is the use of multiple, overlapping (successive or simultaneous) ablations ("multi-burn"). Mathematical models have been developed to optimize this strategy [2] and illustrate its inherent difficulties. In addition, the ablation zone often is rendered obscure on the

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ultrasound image due to the release of nitrogen gas [3]. We expect therefore that an operator who views real-time, intra-operative ultrasound data that is annotated with registered pre-operative data (showing a 3D reconstruction of the target lesion) will optimally position the RFA probe and will perform RFA more efficiently and accurately than under conventional ultrasound guidance alone. Such a "contextually enhanced" 3D display can also show a dynamic, incrementally updated visualization of the tumor as it is being ablated.

In this paper, we describe first steps towards creating such a visualization for an RFA guidance system, which is currently based on 2D ultrasound and pre-operative MRIs. Our techniques are suitable for display methods with enhanced depth perception, preferably using stereoscopy and head-motion parallax, such as augmented reality (AR) see-through head-mounted displays (STHMDs), or head-tracked, "fish-tank" virtual reality (HTVR) systems [4]. After surveying relevant previous work, we give an overview of our guidance system and introduce the multi-burn visualizations. With the help of a newly developed, ablatable liver phantom, we demonstrate the visualization's potential for mirroring a real ablation procedure as it guides the physician through it. We conclude with suggestions for future investigations.

2 Previous Work

Medical instrument guidance is addressed by several commercial systems. These typically use optoelectronic or magnetic motion tracking for interventional tools. The tools' poses or trajectories are displayed in real time and superimposed on pre-operative scans, usually in 2D cross-sections. Manufacturers include *BrainLab, Medtronic, Stryker, Veran Medical* and *Ultraguide* (no longer operating). All commercial systems we know of use conventional 2D monitors as displays; some (*BrainLab, Stryker*) present perspective views of reconstructed patient data (3D scans) together with instrument pose. No commercial guidance systems we are aware of use stereoscopic and/or head-tracked displays, and we are also unaware of any commercial guidance systems that might be employing the type of visualization we propose here.

On the other hand, surgery simulation systems [5] incorporate virtual cutting [6] visualizations that are analogous to the methods we present below—with the difference that they are used in simulation, not interventional guidance. In contrast to the above-mentioned commercial guidance systems, surgery simulators may use displays with stereoscopic imaging and head-motion parallax. The same applies to guidance system research prototypes, e.g., the STHMD-based systems developed by Nassir Navab's team [7], as well as our own STHMD-based prototypes (referenced below).

Other relevant work includes an experimental AR guidance system [8] that combines real-time 2D ultrasound scans with segmented data from pre-operative CT scans (e.g., vessels). The developers report positive feedback from two experienced interventionists recruited to guide an RFA probe into a phantom using their system.

At the University of North Carolina, a team led by Elizabeth Bullitt has developed a technology for registering 3D vessel trees from pre-op scans with intra-op angiograms. This technique is integrated into a real-time guidance system for transthoracic intrahepatic portosystemic shunt (TIPS) placement, a difficult endovascular intervention. The TIPS project developed a head-tracked stereoscopic visualization system [9] that is similar to ours.

3 Guidance System Overview

We have been developing STHMD-based guidance systems aimed at minimally invasive interventions [10][11][12][13]. For this work, we have preferred an HTVR-based platform for a number of application-dependent reasons; these are discussed in an earlier paper [14], which also contains a brief description of our guidance system. We give a full overview here, with the understanding that our methods can also be applied to STHMDs (Fig. 1) or other AR devices, for example through-the-camera displays.

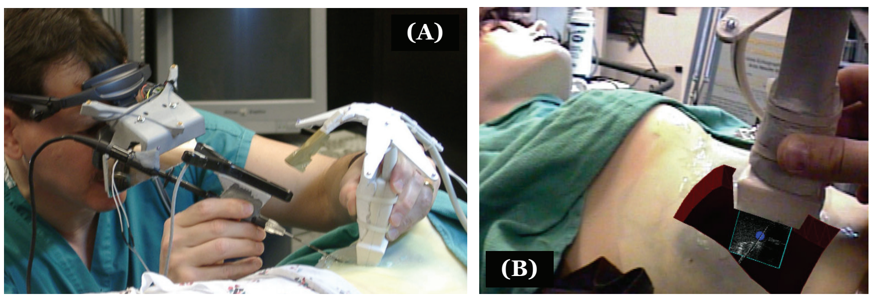

Fig. 1. (A) Our early prototype AR guidance system for liver RFA with video see-through HMD and motion-tracked tools (ultrasound transducer, RFA probe). (B) View through HMD: The ultrasound scan is below the transducer, within a synthetic opening into the phantom.

Our current HTVR-based prototype guidance system (Fig. 2A and 2B) targets liver RFA procedures. It integrates a 2D ultrasound scanner, a stereoscopic display (*Planar StereoMirror*™), an optoelectronic motion tracker (*NDI Optotrak Certus*) and a personal computer; it presents to the head-tracked physician (typically an interventional radiologist) a three-dimensionally merged, stereoscopic virtual environment (Fig. 2C) that represents an area within the patient. Within the display, the physician views a correctly scaled and dynamically updated ultrasound image that moves as if it were attached to the (schematically represented) handheld transducer; the physician also sees a dynamic representation (an avatar) of the RFA probe, which includes the (in reality invisible) part of the probe that is inside the patient. The estimated burn area of the RFA probe is shown as a wireframe surface (yellow sphere in Fig. 2C). We also calculate and display as a closed curve (not visible in these images) the burn area's intersection with the ultrasound slice. A set of 3D-guidance lines, visible at right in Fig. 2C, continually informs the physician about the current spatial relationship between RFA probe and ultrasound slice. This "contextually enhanced" view of the intervention scenario facilitates targeting using natural hand-eye coordination.

In contrast to STHMDs, the HTVR display does not provide registration between the computer-enhanced environment and the patient; however, we operate it with "orientation alignment," analogous to the "orbital mode" for HMDs [15], leaving only a translational offset between 3D display contents and patient internals. An earlier publication [14] provides more detail and also describes other modalities we use to map user-induced instrument translation to the fixed 3D display. Our head tracking and eye calibration techniques for HTVR-type displays are described elsewhere [16].

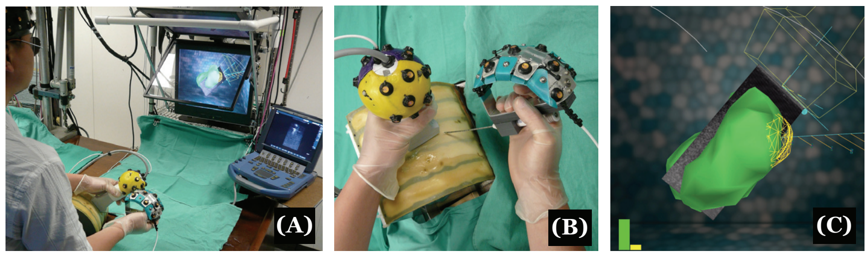

Fig. 2. (A) Guidance system for liver tumor RFA, in use on a liver phantom. (B) Motion-tracked ultrasound transducer and RFA probe. (C) The guidance system shows the pre-segmented tumor (green) within the phantom, registered with the real-time ultrasound scan, as well as the RFA probe and its 3D burn area (yellow wireframe sphere) intersecting the tumor. The bar graph at lower left shows the ratio of tumor (green) vs. healthy tissue (yellow) within the 3D burn area corresponding to the current probe placement.

4 Multi-burn Guidance Techniques

Virtual Ablation. In an initial multi-burn experiment (Fig. 3A and 3B), we introduced *virtual ablation*: by taking advantage of the known (tracked) position and orientation of the RFA probe, the system can "carve" out in the 3D display the area ablated from the target tumor, as the actual ablation takes place within the phantom. The virtual representation of the RFA probe within the 3D display thus acts as an "ice cream scoop," successively removing tumor fragments as they are being ablated (Fig. 3C)—provided the virtual ablation is initiated whenever a real ablation takes place, and provided that the exact shape of the RFA probe's burn area is known. We expect this technique to become an indispensable "blind navigation" aid for successive overlapping burns, given that, as already mentioned, the real-time ultrasound scan shows ever more artifacts with each successive burn, and so its utility diminishes rapidly. In contrast, our method continually tracks the RFA probe and virtually removes ablated tumor material, providing a clear visualization of un-ablated tumor tissue that is to be targeted for further treatment. For example, in Fig. 3C, the spherical tumor was virtually ablated several times.

The "carving" technique is currently implemented in MATLAB and uses volume transformation and subtraction calculations coupled with marching-cubes surface extraction. Because of that, each virtual ablation takes several seconds to complete. By switching to volumetric hardware-assisted rendering, we could eliminate the need for surface extraction and take advantage of parallelism within graphics processor units (GPUs). This would accelerate the virtual ablation to near-real-time speeds, which at first seems unnecessary given that the physical ablation takes minutes to complete. However, consider the utility of seeing in real time the potential effect of an ablation triggered at the current probe position in real time, while manually attempting to move the probe to the most suitable location for the next ablation pass.

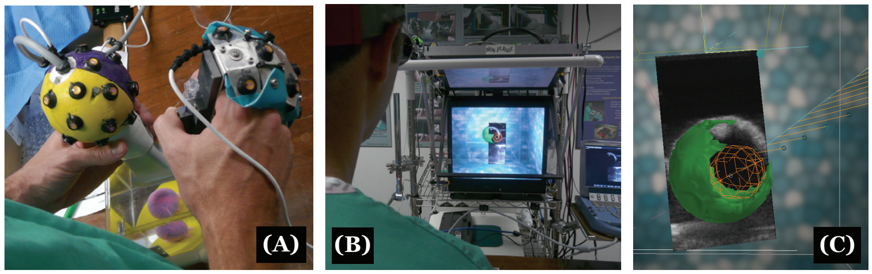

Fig. 3. (A) Simple phantom for initial multi-burn guidance experimentation consists of a Play-doh sphere affixed to the bottom of a water bath. (B) Using the multi-burn visualization technique in the guidance system. (C) Guidance system display during virtual ablation of the tumor with successive burns; after each burn, the ablated tumor area is "carved" away, showing only the remnant tumor.

Ablation Fractions Graph. The second enhancement is an analog bar graph display (lower left in Fig. 2C) that shows—in real time—the fractions of tumor (green) and of healthy tissue (yellow) that would be ablated if ablation were triggered at the current probe position. ("Fraction" implies a number derived from a scalar voxel count.) The additional calculations for this display component are easily supported by the data processing required for the carving visualization. The simple, but highly informative display should provide additional help for ablating as much tumor as possible, and as much surrounding healthy tissue as necessary for low recurrence probability. It is useful even for single-burn procedures, where it can confirm that the entire tumor is contained within the tentative ablation zone.

5 Matching Real and Virtual Ablation

In order to evaluate the new technique, we constructed a phantom containing ablatable tumor and background materials (Fig. 4A and 4B), based on acrylamide-albumin chemistry [17][18]. The phantom images realistically under ultrasound as well as MR, and allows segmentation of four tissue types: ablated and un-ablated tumor, as well as ablated and un-ablated background (Fig. 4C). This characteristic should enable systematic measurements of the performance of guidance systems such as ours. As Fig. 4A shows, we mounted water-filled tubes on the phantom to aid with (static) registration.

Using ITK-SNAP software, we segmented from the phantom's pre-RFA MRI the tumor (green in Fig. 4B) and the two water-filled tubes (blue in Fig. 4B). Before ablation, we calibrated the physical tubes with the Certus' measurement pointer. We obtained static registration between the phantom's pre-operative tumor surface and the real-time, motion-tracked intra-operative 2D ultrasound scans (Fig. 5A) by transforming the MR data such that the MR-segmented tubes coincide with the physical tubes.

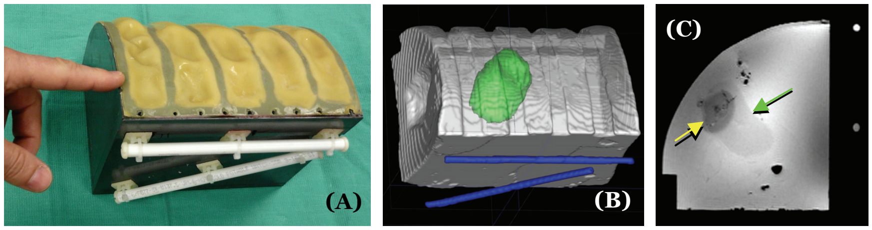

Fig. 4. (A) Liver phantom for multi-burn experimentation, equipped with (white) water-filled tubes designed to register the pre-segmented tumor—see pre-RFA MR data in (B), with tubes shown in blue—with the physical phantom (A). The post-RFA MR section (C) shows the elongated tumor (green arrow) and the intersecting burn area (yellow arrow, cf. Fig. 5B and 5C).

Using the guidance system as described above, we placed the RFA probe with the goal of ablating a fragment of the tumor within the phantom (Fig. 2C). Virtual ablation was triggered as the RFA probe was energized. The remnant tumor calculated by virtual ablation is shown in Fig. 5B. After ablation, we re-imaged the phantom and segmented the phantom's remnant tumor from the post-MRI data (Fig. 4C). The result of the segmentation (Fig. 5C) closely resembles the virtual ablation. The remnant virtual and segmented tumors (Figs. 5B and 5C) are similar in shape, and both the virtual and MR-segmented ablation volumes contain approximately 15 cm^3 (slightly less than a cubic inch). This represents an initial confirmation that our method can be applied to multi-burn guidance, since we can expect that with accurate tracking and registration, as well as with exact calibration of the RFA probe's burn area, the virtual and real ablations will not "drift" too far apart after multiple successive burns.

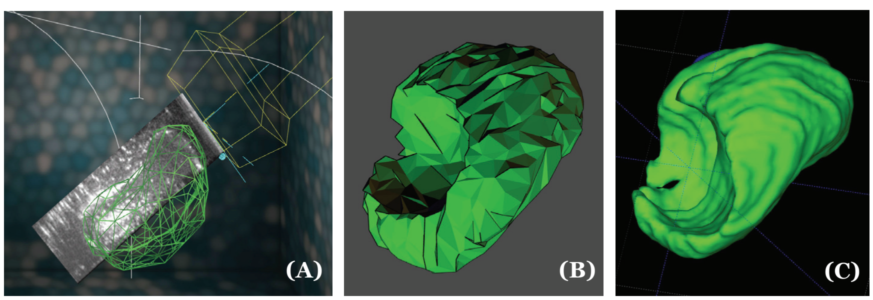

Fig. 5. (A) Accurate registration between pre-segmented tumor (green wireframe) and real-time ultrasound scan. The partially ablated tumor calculated by the guidance system (B) approximately matches the remnant tumor (C) segmented from the post-ablation MRI.

6 Conclusions and Future Work

We have demonstrated intuitive visualization methods suitable for guidance of multi-burn ablation procedures. As a result of accurate instrument tracking, and by using a realistically imaging, registered phantom, we can perform virtual ablations "in sync" with real ones, as compactly demonstrated by the companion images in Fig. 5B and 5C. The new visualization techniques (three-dimensional virtual ablation and dynamic ablation fractions graph) were integrated into an experimental liver RFA guidance system that uses a head-tracked fish tank VR stereoscopic display; they are equally suitable for AR systems employing see-through HMDs, as well as for other 3D display modalities. Furthermore, they can easily be adapted for simultaneous ablations (which use multiple RFA probes energized at the same time), where they can guide pre-RFA probe placement such that the multiple, overlapping burn areas encompass all tumor tissue.

We can currently use these methods only on motionless, rigidly registered phantoms. To maintain registration with a moving, breathing patient, our rigid, static preoperative registration is insufficient. Other researchers have used methods such as skin-mounted fiducials [19] to track patient motion. But for highest possible accuracy, one has to "attach" the pre-operative data to the tumor tissue itself, or rather, given that real-time ultrasonic imaging in the ablation area degrades after the first ablation, to the tumor's immediate neighborhood. Real-time 3D ultrasound echography (or "4D ultrasound" by its commercial name) can image the entire surroundings of a tumor and is therefore more suitable for dynamic intra-op/pre-op registration than its "ambiguously two-dimensional" counterpart. We are considering techniques such as vessel-based feature-to-image registration [20], which can match pre-operative MR imagery to intra-operative 3D ultrasound. This method can be extended to non-rigid deformations and has the potential of eventually operating in real time (in a GPU-based implementation), as an integral component of a future guidance system. We expect that as tracking, miniature-display and -camera technologies advance, such systems will ultimately be based on see-through head-mounted displays.

Acknowledgments

This work was funded by the National Institutes of Health (1 R01 CA101186-01A2). John E. Thomas and Kurtis Keller provided mechanical engineering support. We also thank Stephen Aylward, John Cullen (VMD, PhD), Sashi Gadi, Matthew Mauro (MD), Sharif Razzaque (PhD), Herman Towles and Ginny Turner. The guidance system's software incorporates *libwave* by Dave Pape (ported to Windows by us).

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