3D Ultrasound Image Guidance System for Focal Liver Tumor Therapies

Derek J. Gillies[1,2], Jeffery Bax[2], Kevin Barker[2], Lori Gardi[2], David Tessier[2], Nirmal Kakani[3], and Aaron Fenster[1,2]

[1] Department of Medical Biophysics, Western University, London, ON N6A 5C1, Canada
[2] Robarts Research Institute, Western University, London, ON N6A 5B7, Canada
[3] Manchester Royal Infirmary, Manchester M13 9WL, UK

1 Purpose

Liver cancer is the 5th and 8th most common cause of cancer death among men and women, respectively, and is one of the few cancers that is continuing to increase [1]. The incidence of liver cancer has increased by more than a factor of three since 1980 and has a relatively low 5-year survival rate of approximately 18% using current treatment options. This survival rate increases to approximately 31% and has been observed up to 40% [2] when the disease is localized using the current standard of care, namely transplantation and resection. Although these therapy options are currently the most effective option for patients with liver cancer, these open surgical procedures are often associated with long patient recovery times and have been observed to result in traumatic hospitalization experiences for approximately 33% of liver transplant patients and 26% of liver resection patients [3]. This has motivated investigation into minimally invasive interventional techniques, such as radiofrequency ablation, microwave ablation, and irreversible electroporation, which have become alternative therapies for early-stage liver cancer. These techniques offer key advantages since they have reduced recovery times and complications, but can be limited since they rely on accurate placement of therapy applicators. This required accuracy is one potential source of the currently high local cancer recurrence rates that have been observed [4]. Typically, these procedures use an x-ray computed tomography (CT) image for planning and 2D ultrasound (US) to place therapeutic applicators. Occasionally, subsequent CT images are used to verify applicator placements prior to delivering therapy, but this is not standard of care at all centers. Thus, to reduce the currently high local cancer recurrence rates of interventional liver tumor ablation therapies, we propose the use of 3D US to provide intraoperative image guidance and placement verification of therapeutic applicators. This would increase the anatomical spatial context and field-of-view relative to 2D US without the need for additional CT imaging. In this work we present the initial development and system validation of a novel scanner with a mechanically assisted tracking system.

2 Methods

A three-motor mechanical mover was designed to provide geometrically variable linear, tilt, and hybrid (linear + tilt) geometries for variable 3D US fields-of-view (Fig. 1A). This mover can manipulate any clinically available 2D US transducer via probe-specific 3D-printed holders attached to a quick release mechanism. The scanner and housing were created such that the bulk of the scanner was positioned away from the US transducer to allow for a less restrictive interventional space for the physician. This also offers the advantage of maintaining the designed ergonomics of the commercial 2D probes. Linear, vertical, and rotational extents of 98 mm, 19 mm, and 90°, respectively, were designed to provide a large potential 3D scanning field-of-view (FOV). This large FOV allows for more anatomical landmarks and targets to be captured for anatomical context and potential registration to preoperative CT images.

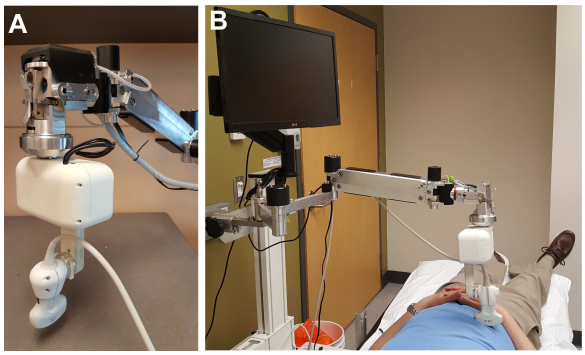

Fig. 1. (A) 2D US transducer attached to the three-motor mover mounted on a counterbalanced stabilizing system. (B) Mock clinical setup of the system mounted on a portable cart with a monitor to display visualization and guidance software.

The scanner was mounted on a counterbalanced stabilizing "arm" to provide a near weightless manipulation when performing image guidance intraoperatively. This mechanical system is tracked on five axes of rotation with magnetic encoders used to compute the pose of the US transducer for 3D visualization and guidance with foot released electromagnetic braking. The stabilizing system is mounted on a portable cart (Fig. 1B), which contains a foot-released vertical motion column to accommodate gross differences in patient sizes, a power supply for the brakes, and a monitor to interface with custom guidance software.

3D US images were acquired of: (1) a grid phantom to geometrically evaluate the reconstruction accuracy of the system, (2) an agar sphere phantom to assess volumetric reconstruction error, and (3) a human volunteer under IRB approval to assess clinical feasibility. Linear geometric measurements were performed after imaging 4 layers of 0.1 mm diameter monofilament polyester thread

regularly spaced 10 mm apart on each layer. The grid phantom was immersed in a 7.25% by volume water-isopropyl alcohol solution to match the approximate speed of sound in tissue at room temperature [5] and imaged using a curvilinear C5-1 transducer on an EPIQ 7G commercial US system (Amsterdam, NL). Measurements were compared to the expected 10 mm distance between strings with differences measured for the in-plane (lateral and axial) axes and the reconstructed (elevational) axis.

Optical tracking was used to assess the error in the magnetically encoded tracking system by replacing the 2D US transducer with a stylus via a 3D printed attachment that conserved the location of the tip (Fig. 2). As the tracking system was manipulated, transformation matrices were generated to compute the new tip position of the system relative to a starting position, generating a tip displacement. These displacements were compared against Euclidean distances between optically tracked tip positions with the initial starting position to assess error in the tracking system. Eight displacements were performed for each of the encoded axes independently prior to a trial combining all axes.

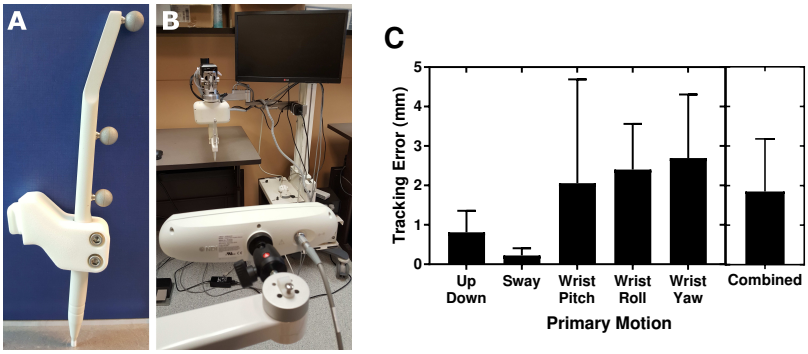

Fig. 2. A 3D printed holder (A) was used to place the tip of an optical tracking stylus at the intended tip location a 2D US transducer. Differences in computed displacements between encoder determined tip positions and observed optical tracking (B) tip positions were computed to assess error (C).

3 Results

3D US grid phantom images resulted in a mean geometric error of 0.29 ± 0.34 mm for 60 mm linear, 60° tilt, and hybrid combination (i.e., 60 mm + 60°) scan geometries acquired in 6 s. Volumetric measurement error was measured as -0.93 ± 0.73 cm^3 (4.14%) for a sphere of volume 22.45 cm^3 (Fig. 3A). 3D US images of the human volunteer scans (Fig. 3B) produced clinically usable images. Tracking system errors relative to the optical tracking system are shown in Fig. 2C.

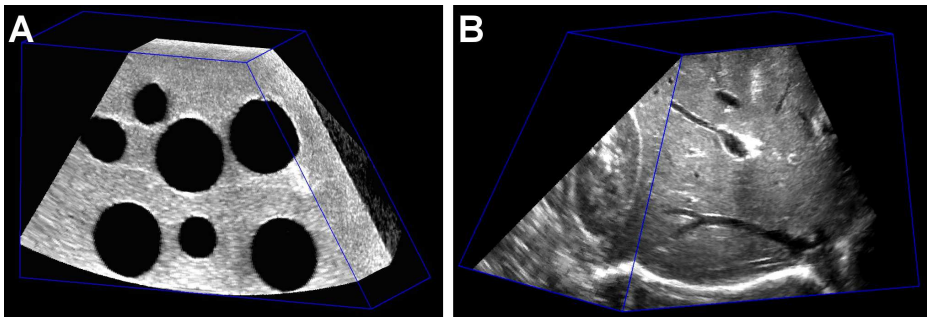

Fig. 3. 3D US images of an agar phantom with embedded spheres (A) and a healthy volunteer (B) using our 3D US system. In the volunteer image, relevant structures were viualized including the kidney, portal vein, and diaphragm.

4 Conclusion

A mechanically assisted 3D US system is proposed to provide image guidance and applicator verification during interventional liver cancer therapies. The system was evaluated for geometric and volumetric 3D US reconstruction accuracy in addition to evaluation of the tracking system error. These errors were considered reasonable for focal liver tumor therapies and future work is focused on performing a mock interventional procedure on a phantom to assess applicator image guidance accuracy.

Bibliography

1. American Cancer Society: Cancer Facts & Figures 2018. American Cancer Society, Atlanta (2018)
2. Choti, M.A., Sitzmann, J.V., Tiburi, M.F., Sumetchotimetha, W., Rangsin, R., Schulick, R.D., Lillemoe, K.D., Yeo, C.J., Cameron, J.L.: Trends in long-term survival following liver resection for hepatic colorectal metastases. Annals of surgery **235**(6), 759–766 (2002). https://doi.org/10.1097/00000658-200206000-00002
3. Schoenberg, M.B., Bucher, J.N., Vater, A., Bazhin, A.V., Hao, J., Guba, M.O., Angele, M.K., Werner, J., Rentsch, M.: Resection or Transplant in Early Hepatocellular Carcinoma: A Systematic Review and Meta-analysis. Deutsches Aerzteblatt Online **114**(31-32), 519–526 (2017). https://doi.org/10.3238/arztebl.2017.0519
4. Tanis, E., Nordlinger, B., Mauer, M., Sorbye, H., van Coevorden, F., Gruenberger, T., Schlag, P.M., Punt, C.J.a., Ledermann, J., Ruers, T.J.M.: Local recurrence rates after radiofrequency ablation or resection of colorectal liver metastases. Analysis of the European Organisation for Research and Treatment of Cancer #40004 and #40983. European journal of cancer (Oxford, England : 1990) **50**(5), 912–9 (2014). https://doi.org/10.1016/j.ejca.2013.12.008
5. Thouvenot, A., Poepping, T., Peters, T.M., Chen, E.C.S.: Characterization of various tissue mimicking materials for medical ultrasound imaging. In: Proc. of SPIE. vol. 9783, p. 97835E (2016). https://doi.org/10.1117/12.2218160