33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Evaluation of a Resectable Ultrasound Liver Phantom for Testing of Surgical Navigation Systems

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Abstract—**A formerly developed ultrasound liver phantom for testing of surgical navigation systems and liver resection trainings was evaluated experimentally. The phantom was scanned with CT and the dataset was analyzed with existing segmentation techniques. A virtual 3D model was generated on the basis of the segmentation; it was later used for phantom registration in a surgical assistance navigation system. Within an experiment, ten test persons have tried to touch three tumor models hidden in the phantom with the tip of a resection instrument. In 67% of overall 30 touch trials it was a successful touch at the first go. It means that the developed liver phantom is appropriate for testing of surgical navigation systems, as well as for computer assisted liver resection trainings.**

I. INTRODUCTION

THE purpose of surgical navigation is to support the surgeon by providing him detailed information about the position of his instruments in the patient's body. Therefore the positions of the instruments in relation to the patient's body are measured. By means of an organ model, testing of new surgical assistance systems is possible without the need of a real patient. Of course, the properties of an organ model should be consistent with those properties of a real organ, which are affected by the corresponding surgical intervention. In case of a liver resection these are:

- softness close to a real liver, because of the application of resection instruments such as scalpel or ultrasonic aspirator;
- ultrasonic imaging possibility with realistic appearance in ultrasound, because it is a major intraoperative image modality for liver resections;
- CT imaging possibility with realistic appearance in CT, because it is a very important basis for surgical intervention planning, simulation, augmented reality, registration, etc.

It is also very important, that the model reproduction is not connected with some essential expenses.

CT-phantoms for testing of medical systems and methods are already known since the past century [1]. In [2] an abdominal phantom on the basis of epoxy resin with tumors consisting of water and glycerol was developed, which was scanned with CT 9800 scanner (General Electric). The slice width was 5, 7 and 10 mm. The liver tissue of phantom in CT had an intensity of 52 HU (Hounsfield Units). The tumor models differ according to glycerol concentration about 4 – 26 HU. The phantom and its CT-scan were further applied for liver lesion detectability analysis with CT. In [3] a liver phantom from silicon was applied for registration algorithm testing. With this aim it was scanned with Mx8000 Philips CT-scanner.

In the area of ultrasound liver phantoms there are some low cost techniques of ultrasound feature modeling. In [4] and [5] gelatin is in use in order to imitate the ultrasonic properties of a human liver with low costs. In [6] a liver tumor modeling method is presented, which is based on the agarose gel with addition of graphite for echogenicity altering.

There are also some products on the market, which are oriented on the abdominal area simulation in various image modalities. For example the German company QRM GmbH [7] provides a phantom for the abdominal area, which appears in CT quite similar to real liver and tumors in different contrast phases. The US-American company Supertech [8] offers similar abdominal area phantoms with some more complicated structures and appearance in CT, as well as realistic ultrasonic properties. Abdominal phantoms from the Japanese company Kyoto Kagaku [9] also provide realistic appearance in CT and ultrasound.

The analysis of these works has shown that there is no such liver phantom, which has all properties needed for testing or training with usage of ultrasound and CT image modalities and resection possibility being easily reproducible at the same time.

In this work a liver phantom is evaluated, which can be resected with conventional surgical resection instruments. It provides realistic ultrasonic images and also quite realistic CT images. The manufacturing process of this phantom as well as its appearance in ultrasound have already been described in [10]. This process was not seriously changed in the presented work. Nevertheless, some details are necessary to introduce in this work for consistency.

In this paper the integration of the phantom in the complete workflow for testing of navigated systems for computer-assisted liver resections is presented. For this purpose, the phantom was scanned with CT. To do so, it was important to add a contrast agent into the phantom. For a practical correspondence estimation of the resulting CT-dataset to the scanned phantom an experiment was carried

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Manuscript received April 15, 2011.

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out, where the dataset was segmented and registered with a simple landmark technique. Three tumor models in the phantom were touched with resection instrument tip using just a graphical representation of the phantom's virtual 3D model and a model of the resection instrument in the corresponding coordinate system.

The experiment was carried out by ten test persons to show that the correspondence of the planning data (CT-scan and 3D model) to the liver phantom is suitable for navigated liver resection simulation and testing of surgical assistance systems.

II. MATERIALS AND METHODS

A. Phantom Structure, Materials and Production

The phantom described here consists of three tissue types: liver parenchyma, vessel trees and tumor models (Fig. 1).

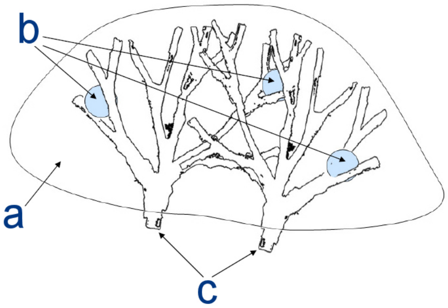

Fig. 1. Phantom structure: parenchyma tissue (a), tumor models (b) and vessel trees (c).

The parenchyma is produced using candle gel with cellulose addition for obtaining of necessary echogenicity. The tumors consist of a mix of agarose with glycerol for a lighter appearance in ultrasound or of pure candle gel for a darker appearance. The vessel trees are produced from silicon. The appearance of the phantom is shown in Fig. 2. Thereby, the pure candle gel is quite transparent and cellulose decreases tissue transparency and constitutes its echogenicity. There are also some agarose tumors visible within the phantom. In the implementation with tumors from pure candle gel they are almost invisible through the liver tissue.

The phantom is produced as follows. At first three tumor models from the agarose-glycerol mix or from pure candle gel are produced. In case of the agarose-glycerol mixture the agarose powder is added to distilled water, heated to 75°C and mixed with glycerol. This composite is then filled into three round silicon forms with a diameter of about 3 centimeter and hold in a fridge for 2 hours. In the other case pure candle gel is heated to 100°C and the tumor silicon forms are filled out with it. A thin polyethylene layer is laid in each form in case of pure candle gel to avoid mixing of tumor models with the phantom parenchyma because it also has a temperature of 100°C before the entire phantom is cooled down. The vessels are made from liquid silicon material, which can be hardened by polymerization of two mixed components. As the mix is yet liquid it is cast in a hard silicon form with a vacuum casting system. After casting it must be hardened for 30 minutes. The silicon was chosen because it does not melt down during further usage by production of the entire phantom and its echogenity is quite low, what is comparable with the ultrasonic properties of real vessels. After the vessels and tumor models are made, they are fixated in the phantom silicon form which was produced by means of vacuum casting using a 3D-printed liver model of a real patient. After these arrangements are made, the candle gel with cellulose solution is heated to 100°C and cast into the form using the vacuum casting system. The form with contents is held in a fridge for two hours. There can also be some pigments used, for example to fully avoid the visibility of tumor models within the phantom material because sometimes this can happen with the tumor models from pure candle gel while absolute invisibility of tumors is necessary within some experiments.

Fig. 2. Phantom appearance: cellulose decreases candle gel transparency and constitutes echogenicity, agarose tumors are visible inside of the phantom.

B. Phantom Appearance in Ultrasound

The phantom was scanned with a medical ultrasonic system and ultrasonic properties were close to such of a real liver. In Fig. 3 a comparison can be seen between the phantom and real patient ultrasonic images of liver tissue, tumors and vessels. The real patient images were recorded during a liver resection at the university hospital of Essen in Germany. As it can be seen from the comparison in Fig. 3 the phantom can deliver a quite good simulation of liver tissue and its structures in ultrasound. These ultrasonic properties were already used for development of an automatic blood vessel recognition algorithm [11] which is now used in a prototype of a surgical assistance system for operations on soft tissue. In present time, the phantom is used for development of soft-tissue registration and navigation techniques.

C. Phantom CT-Scan and Appearance in CT

For a CT scan a roentgen contrast agent was added during the phantom manufacturing. The phantom was scanned with a Siemens Somatom CT-scanner with a slice thickness of 1 mm and pixel size of 0.5×0.5 mm. The parenchyma tissue appeared in CT with a homogeneous texture with an element size of approx. 3 pixels. The roentgen density of the liver parenchyma tissue varied between -109 and -49 HU. The tumor models appear with a less grainy texture, the roentgen

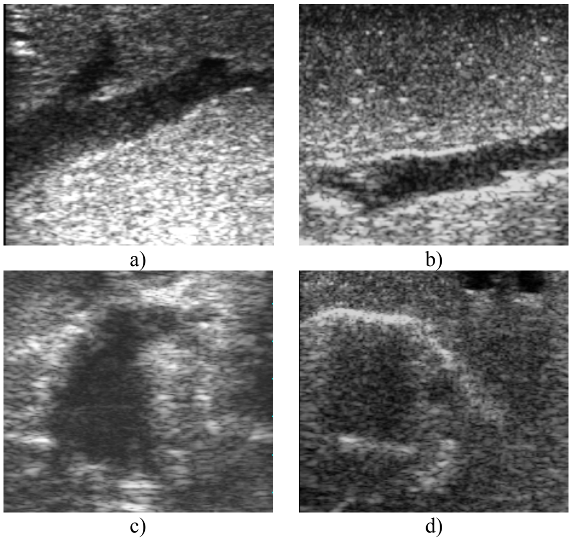
a) b) c) d)

Fig. 3. Phantom in ultrasound: a) vessel in a real patient ultrasound recording; b) ultrasound image of a vessel in a phantom; c) real hepatic tumor ultrasound image; d) ultrasound image of a tumor model in the liver phantom.

density varied between 176 and 276 HU. The vessel trees had something fuzzy texture in comparison to the liver. The roentgen density of vessels varied between 26 and 86 HU. The corresponding appearance values of these liver structures in CT scans of real patients are: liver parenchyma tissue with contrast agent from 90 to 125 HU, without contrast agent 50 HU, vessels with contrast agent from 150 to 350 HU and tumors with and without contrast agent 80 and 180 – 260 HU respectively. This means that all the phantom structures appeared darker as structures of a real liver. The example of phantom appearance in CT is given in Fig. 4.

D. Phantom Resection

Several trials (a total of approx. 20) to resect the phantom were made within some tests of the soft-tissue surgical navigation system prototype. It could be successfully resected with a conventional scalpel and also with an ultrasonic surgical dissector (CUSA Soering). The only problem, when resecting with the ultrasonic dissector was that the candle gel was melt down a little because the dissector was used without irrigation. But it has just a very small effect on the resection borders.

E. 3D Reconstruction from CT and Model Registration

A virtual 3D planning model was generated on the base of CT scan using the planning system described in [12]. For the processing time acceleration while performing the segmentation, the voxel size of phantom dataset was increased up to 1×1×1 mm.

The obtained 3D model of the phantom with tumors and vessels was registered in a common coordinate system with the resection instrument (CUSA) via a simple surface landmarks method (similar to [13]). For this purpose four distinctive places of the phantom were marked on its 3D reconstruction and touched with the resection instrument tip

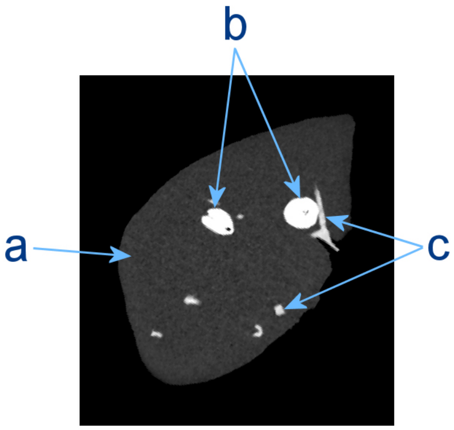

Fig. 4. CT-scan of liver phantom: parenchyma tissue (a); tumors (b); vessels (c).

on its real surface. Finally, a possibility to show the resection instrument orientation relative to the liver and its structures on the display was obtained (Fig. 5). This graphical representation was further the only allowed information source about the instrument orientation for the test persons within the experiment.

F. Experiments to Registration Evaluation

Within some experiments ten test persons had to touch all three tumor models in the phantom with the instrument tip. They were instructed not to look at the phantom itself, but to only use its graphical representation with the registered instrument on the display (Fig. 6). The number of trials until a tumor model was touched, was documented and used as evaluation criteria for the registration correctness: as lower the trial number is, as higher is the registration accuracy. A very similar technique was used in [10] for evaluation of intervention safety by real-time image navigation.

III. EXPERIMENTAL RESULTS

All the tumor models could be touched successfully. In 67% of all cases it worked at the first go. Sometimes it was only possible to puncture a tumor model at the fifth try, but it must be taken into consideration, that some of the test persons were using the system for the first time and no one had some familiarization possibility with the experimental environment. The results obtained form the experiments are

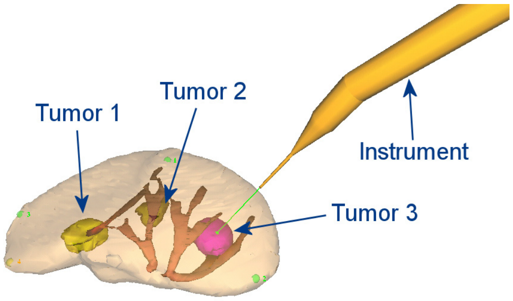

Fig. 5. Virtual 3D reconstruction of the phantom with registered instrument.

Fig. 6. Experiment: touching of tumor models in the liver phantom with registered instrument. A test person was only allowed to use the display (on the top) while puncturing the tumor models in the phantom (on the bottom) with the instrument tip.

presented in table 1.

TABLE I
EFFORT NUMBER FOR A TUMOR MODEL TOUCH

Number of Efforts	Appearance in Experiment			
	Tumor 1	Tumor 2	Tumor 3	Total
1	9	4	7	20
2	0	2	3	5
3	0	3	0	3
4	0	0	0	0
5	1	1	0	2

From table 1 the conclusion can be made that with the average effort number of 1.6 for a successful tumor model puncturing the intervention accuracy with a registered instrument can be considered as comparable to the intervention accuracy of a directly navigated instrument relative to the ultrasonic image, as it was made in [10], where the average attempt number was 1.1 – 1.3. It speaks about a successful instrument registration.

IV. DISCUSSION

The main disadvantage of the performed experiment is that the phantom has not been covered with a metal foil or something that could really conceal the real phantom and tumors position from the test person’s sight. Considering that fact that there were not so much puncturing trials, the experimental results can be assessed as preliminary. In future a more complex experiment concept should be proposed which would involve an entire tumor model dissection with its accuracy estimation.

V. CONCLUSION

The experiment has shown that the phantom registration was correct enough to function as a possible testing and training material for liver surgical assistance systems. Taking into consideration that fact that the phantom can be resected and easily reproduced, it can be said that it is a very suitable liver simulator for testing of surgical systems, where ultrasound, CT and navigation are in use at the same time. Future evaluation of the phantom could be a creation of tumor models with more realistic resection properties: better infiltration with surrounding tissue and at the same time a clear visible boundary. Some successful steps in this direction were already made. The phantom appearance in CT inclusive contrast phase modeling can be regulated with the contrast medium concentration and it was already ascertained within a single experiment.

ACKNOWLEDGMENT

We would like to thank Dr. Wilhelm Flatz (Institut für Klinische Radiologie – Klinikum der Universität München), Dr. med. Thorsten Johnson (Ludwig-Maximilians-Universität München) and Dr. Karin Tonn (Technische Universität München) for the given help for CT scanning of the liver phantom and informational support of any kind.

REFERENCES

[1] D. R. White, R. D. Speller, P. M. Taylor, “Evaluating performance characteristics in computerized tomography”, The British Journal of Radiology, March 1981, 54(639), pp. 221-31.

[2] H. M. Olerud, J. B. Olsen, A. Skretting, “An anthropomorphic phantom for receiver operating characteristic studies in CT imaging of liver lesions”, The British Journal of Radiology, January 1999, 72(853), pp. 35-43.

[3] L. W. Clementsa, W. C. Chapman, B. M. Dawant, R. L. Galloway, Jr. I. Miga and M. I. Miga, “Robust surface registration using salient anatomical features for image-guided liver surgery: Algorithm and validation”, Medical Physics, June 2008, 35(6), pp. 2528-2540.

[4] R. O. Bude, R. S. Adler, “An Easily Made, Low-Cost, Tissue-Like Ultrasound Phantom Material”, J. Clin. Ultrasound 23, John Wiley & Sons (1995), pp. 271-273.

[5] R. A. Nicholson, M. Crofton, “Training phantom for ultrasound guided biopsy”, The British J. of Radiology, 70, 1997, pp. 192-194.

[6] B. Luo, R. Yang, P. Ying, M. Awad, M. Choti, R. Taylor, “Elasticity and Echogenicity Analysis of Agarose Phantoms Mimicking Liver Tumors”, Proceedings of the IEEE 32nd Annual Northeast Bioengineering Conference, April 2006, pp. 81-82.

[7] QRM GmbH, Dorfstrasse 4, 91096 Moehrendorf Germany, www.qrm.de.

[8] P. O. Box 186 Elkhart, IN 46515 USA, www.supertechx-ray.com.

[9] Kyoto Kagaku Co., Ltd, 15 Kitanekoya-cho Fushimi-ku Kyoto, Japan 612-8388, www.kyotokagaku.com.

[10] J. Schwaiger, M. Markert, N. Shevchenko and T. C. Lueth, “The effects of real-time image navigation in operative liver surgery“, International Journal of Computer Assisted Radiology and Surgery, 5 May 2011, DOI: 10.1007/s11548-011-0557-5.

[11] N. Doerfler, B. Seidl, N. Shevchenko, R. Stenzel, T. C. Lueth (2011), “Blood Vessel Detection in Navigated Ultrasound: An Assistance System for Liver Resections”, 2011 IEEE / ICME International Conference on Complex Medical Engineering, May 22 – 25, 2011 Harbin, China, pp. 445-450.

[12] N. Shevchenko, B. Seidl, J. Schwaiger, M. Markert, T. C. Lueth, “MiMed Liver: A Planning System for Liver Surgery”, Proceedings of the 32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society “Merging Medical Humanism and Technology”, 2010, pp. 1882-1885.

[13] M. M. Goldsmith, R. D. Bucholz, K. R. Smith, N. Nitsche, “Clinical applications of frameless stereotactic devices in neurotology: preliminary report”, American Journal of Otolaryngology 16(4), 1995, pp. 475-479.