Original paper

Videosurgery

Preparing the anatomical model for ablation of unresectable liver tumor

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Videosurgery Miniinv 2014; 9 (2): 246–251
DOI: 10.5114/wiitm.2014.43022

Abstract

Introduction: *Nowadays the best treatment of the primary and secondary hepatic tumor is surgical resection, but only 5–15% of all patient with hepatocellular carcinoma and 20–25% of all patients with liver metastases are indicated for resection. In these cases some kind of ablation and other technique could be used.*
Aim: *To present the methodology of preparing the anatomical model for ablation of unresectable liver tumor.*
Material and methods: *The presented method is based on abdomen computed tomography (CT) dynamic examination. Three methods of segmentation are used: rolling vector for liver volume, modified Frangi filter for liver vessels, and fuzzy expert system with initial region-of-interest anisotropic filtration for liver metastases. Segmentation results are the input data for creating 3D anatomical models in the form of B-spline curves and surfaces performing the surface global interpolation algorithm. A graphical user interface for presentation and evaluation of models, presented in color against DICOM images in grayscale, is designed and implemented.*
Results: *The proposed approach was tested on 20 abdominal CT obtained from the Department of Clinical Radiology of Silesian Medical University. The lack of a "gold standard" provides for the correction of the results.*
Conclusions: *Preparation of the anatomical model is one of the important early stages of the use of image-based navigation systems. This process could not take place in a fully automatic manner and verification of the results obtained is performed by the radiologist. Using the above anatomical model in surgical workflow is presented.*

Key words: *anatomical liver model, liver ablation, abdominal surgery planning.*

Introduction

Nowadays the best treatment of primary and secondary hepatic tumors is surgical resection, but only 5–15% of all patients with hepatocellular carcinoma and 20–25% of all patients with liver metastases are indicated for resection [1, 2]. In these cases some kind of ablation and other technique could be used: cryoablation (CA), radiofrequency ablation (RFA) [3], microwave ablation, percutaneous ethanol injection therapy (PEIT), high-intensity focused ultrasound (HIFU) and laser [4]. The major task of this procedure is needle placement in a desirable position achieved from pre-operative planning data. The goal is complete removal of the tumor and minimizing damage of the surrounding tissue. Conventionally ultrasound imaging is used for guiding needle placement, but due to a small size of tumor and quality of ultrasound image it is often difficult to identify it clearly [5]. Imprecise treatment of tumors causes complication and recurrence rates of 1.7–3.2% and 14–15% in PEIT, and 5.8–12% and 3.6–5% in RFA [6]. In order to improve results of tumor treatment, image-guided intervention (IGI) systems are used popularly in neurosurgery, otolaryngology, and orthopedic surgery, where rigid parts of the skeleton are used as

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reference points to register preoperative data and the position of surgical tools in the operating room (OR). The main advantage of IGI systems is presenting a model of the operation field including tumors and positions of surgical tools on an extra medical monitor, which shortens the intervention and improve safety in general [7] and for liver ablation [8]. Tracking points of the liver is a complex process, whose accuracy is also influenced by parameters of the stereo camera, which was set up by two laparoscopic monocular cameras and the calibration procedure [9]. Previous work has shown that mobility of the individual points of the liver reaches millimeters due to respiratory motion or even centimeters under pressure of laparoscopic tools [10].

Aim

The paper presents the methodology of preparing the anatomical model for ablation of unresectable liver tumor.

Material and methods

The presented approach can be divided into five steps: 1) preparing anatomical images, 2) anatomical structures segmentation, 3) creating models of anatomical structures, 4) presentation of the anatomical model and 5) verification.

Preparing anatomical images

In order to prepare a 3D anatomical model of the patient some anatomical images should be used. As regards liver metastases diagnosis, computed tomography (CT) is the most popular imaging mode, because it is cheap and relatively easy to apply – little collaboration with the patient is needed. The aim of the examination is to detect and determine resectability of the metastases. Usually a few series both with and without a contrast agent are performed [11]. The CT examinations are archived and stored in Digital Imaging and Communications in Medicine (DICOM) format.

Anatomical structures segmentation

For liver volume segmentation the semi-automatic method proposed by Juszczyk is applied [12]. The method requires one to indicate a single point within the spleen and one point inside the liver. The points indicated by the user are treated as the beginning of the rolling vector by which finding a common area in the liver and spleen in two-dimensional cross-section is performed. After assigning the labels of the object on the current cross-section, the shape of the image is transferred to the adjacent images. The stopping condition is to find the layer without the labeling of the object. Once you find the volume of the spleen, you remove it from the initial volume and the resulting volume is the correct volume of the liver. Photo 1 presents visualization of the liver surface model based on B-spline curves.

Vascular structure segmentation applies the modification of vascular Frangi filter [13], based on the analysis of the eigenvalues of the Hessian matrix. The method consists of two stages. At the first stage the method determines the intensity characteristic of liver tissue, removes the “hard” structures (e.g. high-density structures) and smoothes the image using anisotropic filtering. Then the modified filter proposed by Rudzki is used, which is a modification of the vascular Frangi filter, and introduces sigmoidal response functions gaining better sensitivity and higher immunity to noise. Comparing the proposed approach with different methods of vessel detection [14–16] which detect all hyperintense cylindrical structures, irrespective of their intensity based on evaluation of Hessian eigenvalues, Rudzki uses an intensity range rescaling function together with the liver as the region of interest and in this way the problem of other hyperintense structure such as bones is eliminated [17].

Multiscale analysis is carried out on the basis of the theory of linear space scales for discrete

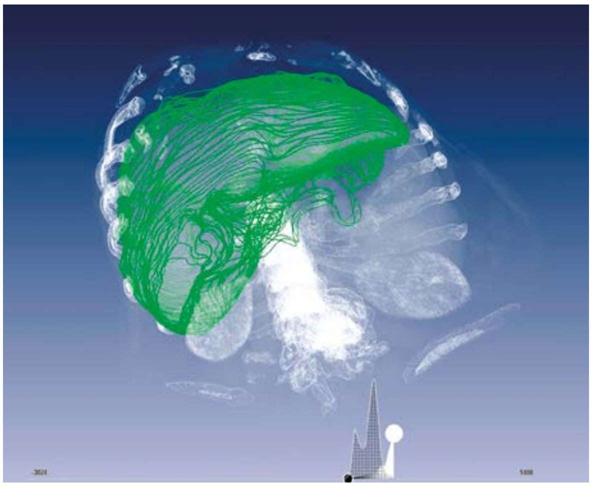

Photo 1. Example of liver surface model based on B-spline curves (green color)

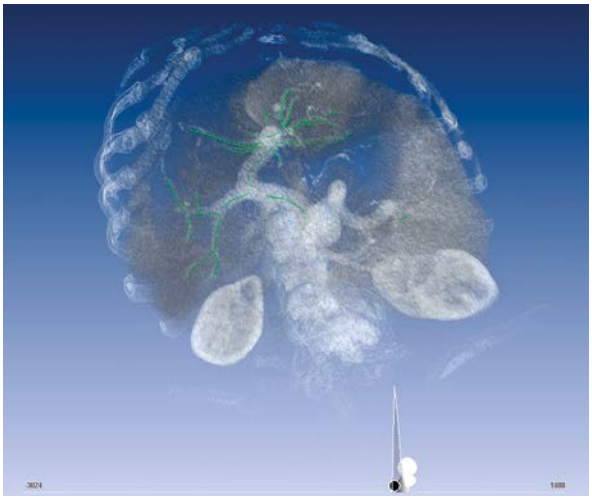

Photo 2. Example of liver vessels model based on B-spline curves (green color)

values of the scale corresponding to the rays of the hepatic vascular structures. Based on the filter response image vascular voxels are determined to start the segmentation process. The segmentation algorithm uses Fuzzy Connectedness, in which the fuzzy affinity relations are modified to take into account the result of the vascular response filter [18]. Central lines of received blood volume are created for presentation purposes. These central lines are interpolated by uniform cubic B-spline curves. Photo 2 presents an example of interpolated central lines of finding main branches of liver vessels. The presented method was tested on 40 abdomen CT in the portal phase with liver vessels contrast

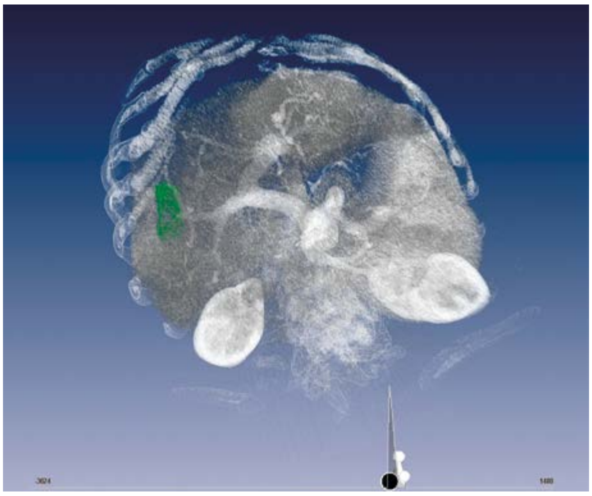

Photo 3. Example of liver nodule based on B-spline curves (green color)

from 35 Hounsfield units [HU] to 150 [HU] [19]. The evaluation took into account the number of bifurcations from the portal vein. In 1 case the vessel tree could not be detected. In 4 cases segmentation was of a poor quality and in the remaining 35 cases the vessel tree was segmented above the 1st bifurcation (2 cases), 2nd bifurcation (11 cases) and 3rd bifurcation (22 cases).

The segmentation of lesions in the liver CT study raises a number of problems well known and described in the literature [20, 21]. The changes, depending on the type, size, and stage of malignancy, are characterized by different levels of intensity. In this work the semi-automated method proposed by Badura is used. The data series is first interpolated to provide a specific voxel size. The size is selected by weighing time and the quality of the segmentation process and the best results can be obtained for a cubic voxel size of approximately 1 mm^3. Other resampling techniques such as downsampling to *unify* voxel sizes to the largest of them all have also been tested. Downsampling technique returns reasonable liver nodule segmentation results for a voxel size $\leq$ 2.5 mm.

An anisotropic diffusion filter is applied to the three-dimensional region of interest (volume of interest – VOI). For these results in the image data areas of uniform intensity are smoothed while maintaining selectivity and a clear edge at a good level. Each tumor must be indicated by the starting point of the system which starts with the segmentation procedure of the growth area. The above-mentioned problems associated with the twofold nature of the changes and low contrast in the liver require the use of segmentation with *adaptive criteria selection*. For this purpose fuzzy expert system inference, monitoring the shape, size and nature of the intensity of the tumor region, is used [22]. The method has been evaluated on 30 nodules of various types in terms of density, size and shape, described and outlined by the radiologist. The method produced 77% (23/30) correct results, which means that the distance did not exceed 2 mm. In 7 cases the algorithm produced under-segmentation results. Photo 3 presents an example of a liver nodule based on B-spline curves.

Creating models of anatomical structures

The 3D models of anatomical structures supply a comprehensive description of anatomical features and are used for creating anatomical atlases [23] and physiological models (e.g. breathing model of lungs) [24]. The model should be represented as point clouds, polygonal mesh, implicit surface equation or parametric equations [25]. The parametric representation was selected due to a few advantages [26]:

- the parametric method on the plane can be easily extended to represent an arbitrary curve in three-dimensional space,
- the parametric curves feature a natural direction of traversal – an ordered sequence of points along a parametric curve can be generated and the cross-sectional area of the surface can be presented,
- the parametric form is more natural for designing and representing, because curves factors have a direct visual interpretation,
- the parametric form can represent a surface by introduction of a second parameter.

The tensor product surface is used. A B-spline surface $S(u, v)$ is obtained by taking a bidirectional net of control points $P_{i,j}$, two knot vectors u and v, and the products of univariate B-spline functions [27]:

$$S(u, v) = \sum_{i=o}^{m} \sum_{j=o}^{n} N_{i,p}(u) N_{j,q}(v) P_{i,j}$$

where $N_{i,p}(u) = N_{i,4}$, $N_{j,q}(v) = N_{i,4}$ denotes cubic B-spline function. As regards the surface fitting algorithm there are two approaches: approximation and interpolation [27]. In the interpolation case, which is used here, a surface which passes directly through the given points is constructed. To find unknown spline curve coefficients a *global surface* interpolation algorithm [28] is calculated, assuming a uniform distribution of control points.

Presenting the anatomical model and verification

The goal of using the patient's anatomical model is to highlight most important structures to simplify the planning phase. Usually the selected structures are presented in color against DICOM data presented in a grayscale map. Before an anatomical model of the patient is used for planning interventions it should be reviewed by the radiologist. In general, the model verification process is complex. All selected and segmented structures should be validated separately. To simplify this process the advantages of the model representation of space in the form of B-spline curves and surfaces are used. As mentioned earlier, in the equation surface splines of the 4th row and the local control property are used. Moving the control point of a portion of the curve will only affect three local segments. Control points are presented in the user interface as small cubes which can be directly moved by mouse movements (Photo 4).

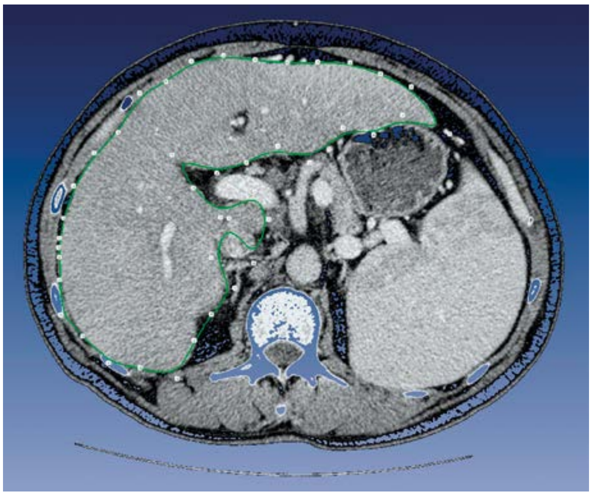

Photo 4. Manual improvement of segmentation result by moving control point (white cubes)

Results

The proposed approach was tested on 20 abdominal CT obtained from the Department of Clinical Radiology of the Silesian Medical University. The lack of a "gold standard" provides for the correction of the results. The individual segments of the vascular structures were represented in the form of spline segments. The verification of the results takes place in the volumetric mode, due to the variation in the direction of the vessels. It is also possible to insert an additional control point into the curve if the radiologist considers it necessary (Photo 5). After the verification the results are recorded as the patient's anatomy model for further use.

Discussion

Preparation of the anatomical model is one of the important early stages of the use of image-based navigation systems. This process could not take place in a fully automatic manner and verification of the results obtained is made by the radiologist.

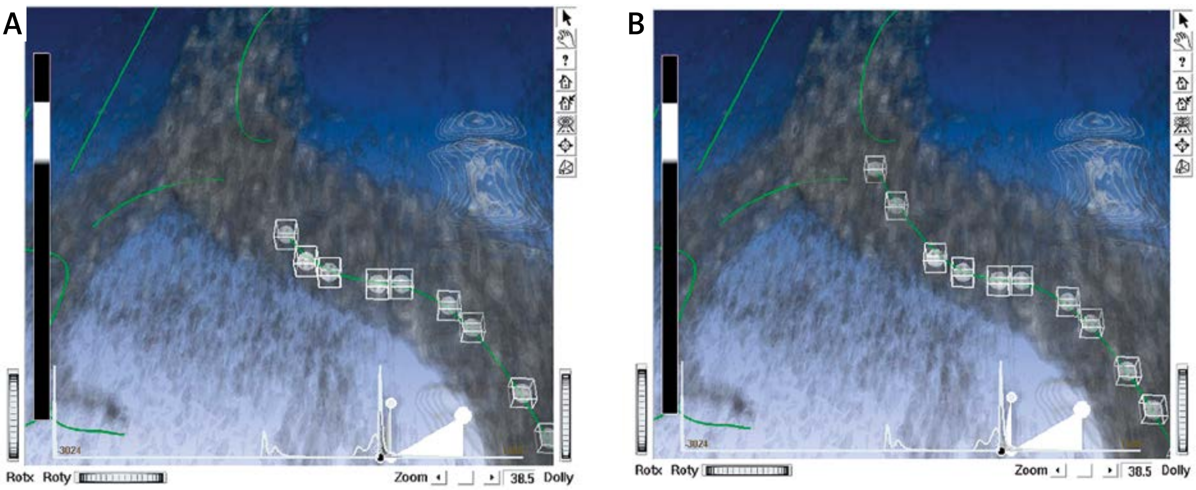

Photo 5. Manual vessel skeleton evaluation: **A** – before correction, **B** – after correction

The proposed method of processing data on the basis of image segmentation creates surface models, vascular structures and lesions. Selected methods of presentation allow one to interact with the presented model for the possible correction of the results.

In the process of computer-aided surgical intervention a pre-operative anatomical model should be registered based on medical diagnosis images of the position of the patient in the operating room. The registration process is to find the correspondence between points in the anatomical model and the corresponding physical positions in the patient. Usually this process can be divided into two steps. The first step implements rigid correspondence, based on the assumption that there is no difference in shape [7]. The permissible operations to fit data include shift, rotation and finding a scale factor. Opposite to the deformable registrations, the initial rigid registration has the advantage that it may find clear correspondence points. It is also worth emphasizing that if the proposed approach does not modify the existing medical procedures, it is easier to implement in clinical practice. The presented approach takes into account the successive stages of processing. To prepare an anatomical model no modification in CT examination is applied, but due to easier registration of an anatomical model during the procedure a few radiological markers can be attached to the patient's abdomen. These markers are highly visible in CT images and can also be found on the abdominal surface. The minimum number of markers is three to allow use of a rigid registration algorithm (e.g. rigid Horn algorithm) [29]. To obtain comparable results markers can be attached to the patient's abdomen in a similar anatomical position. Then, one should also take into account the factors that cause discrepancies between a pre-operative anatomical model and the actual situation in the operating field during intervention, such as breathing movements or displacement and deformation of bodies under the pressure of laparoscopic instruments [7]. The future work will be the evaluation of a rigid registration preoperative CT-based anatomical model and the patient's position during intervention.

Conclusions

The patient's specific anatomical model is useful in the planning phase. Progress in medical image processing, data visualization and inexpensive graphics hardware allows a closer cooperation between the radiologist and the surgeon to choose the data presentation suitable for the surgeon's needs. Selected segmented anatomical structures are presented in color against DICOM layered 3D images presented in a grayscale map. The entry point, the target and the surgical trajectory may be selected, so that critical anatomical structures are not affected. The 3D model used in the planning phase and during the procedure allows a better perception of challenging intervention for a specific patient's anatomy [30].

Acknowledgments

The authors would like to acknowledge the financial support from the Polish National Centre for Research and Development (NCBiR), grant no.

LIDER/03/47/L-1/NCBiR/2010 "Development of planning system and computer aided minimally invasive surgery for hepatic and metastatic liver carcinoma localization, diagnosis and destruction". The author would like to thank the Department of Clinical Radiology of the Silesian Medical University for access to the anonymous abdomen CT data set.

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Received: 16.04.2013, **accepted:** 23.01.2014.