Hepatic Vessel Segmentation for 3D Planning of Liver Surgery:

Experimental Evaluation of a New Fully Automatic Algorithm

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Rationale and Objectives: The aim of this study was to identify the optimal parameter configuration of a new algorithm for fully automatic segmentation of hepatic vessels, evaluating its accuracy in view of its use in a computer system for three-dimensional (3D) planning of liver surgery.

Materials and Methods: A phantom reproduction of a human liver with vessels up to the fourth subsegment order, corresponding to a minimum diameter of 0.2 mm, was realized through stereolithography, exploiting a 3D model derived from a real human computed tomographic data set. Algorithm parameter configuration was experimentally optimized, and the maximum achievable segmentation accuracy was quantified for both single two-dimensional slices and 3D reconstruction of the vessel network, through an analytic comparison of the automatic segmentation performed on contrast-enhanced computed tomographic phantom images with actual model features.

Results: The optimal algorithm configuration resulted in a vessel detection sensitivity of 100% for vessels > 1 mm in diameter, 50% in the range 0.5 to 1 mm, and 14% in the range 0.2 to 0.5 mm. An average area overlap of 94.9% was obtained between automatically and manually segmented vessel sections, with an average difference of 0.06 mm^2. The average values of corresponding false-positive and false-negative ratios were 7.7% and 2.3%, respectively.

Conclusions: A robust and accurate algorithm for automatic extraction of the hepatic vessel tree from contrast-enhanced computed tomographic volume images was proposed and experimentally assessed on a liver model, showing unprecedented sensitivity in vessel delineation. This automatic segmentation algorithm is promising for supporting liver surgery planning and for guiding intraoperative resections.

Key Words: Liver; automatic vessel segmentation; liver surgery; computer-based surgery planning; rapid prototyping.

Recent literature has highlighted the need for methods that allow planning liver operations on the basis of individual patient data (1). The liver has a complex internal anatomy, which in some cases may differ notably from commonly adopted schematic classifications (2–6), thus making liver resection a challenging operation.

Planning systems for liver surgery use specific algorithms to identify relevant anatomic structures within images obtained through computed tomographic (CT) or magnetic resonance imaging. The most crucial step is the segmentation process, consisting of the assignment of image voxels to anatomic structures. In fact, any kind of localized liver treatment requires the same information: fine liver surface segmentation, accurate detection of tumors, and precise vessel topography (7). Automatic liver segmentation is a challenging task, because the liver usually shares image intensity values with other nearby organs (eg, the kidneys), and the boundaries of target structures are generally not sharp (8). As a consequence, several liver segmentation methods have been implemented and validated in recent years, showing numerous possible compromises between segmentation accuracy, computational complexity, and the degree of algorithm automation (9–13).

In particular, a fully automatic method for the rapid segmentation of liver tissue and its internal lesions applied to CT scans was recently introduced by our research group (14). This method, validated on a series of patient data sets presenting different anatomic and pathologic situations, proved to be a robust and efficient tool for performing automatic segmentations of liver tissue and tumors that are very close to the manual contour drawing made by an expert radiologist and considered to be the gold standard.

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The aim of this study was to present and evaluate a new algorithm for automatic segmentation of the hepatic vessel network, with the final goal of integrating our two algorithms in a single software tool for computer-assisted planning of liver surgery.

The accurate segmentation of liver vessels is fundamental for the successful outcome of several therapeutic liver treatments (15). In fact, the availability of robust preoperative planning systems based on precise and automatic identification of the hepatic vessel network would be very helpful for safely removing tumors located near major vessels (16,17). Furthermore, “in situ” ablation techniques (eg, cryoablation, radiofrequency ablation) are becoming increasingly important as alternatives to liver resection (18–21). These techniques also require precise vessel detection for suitable treatment planning and execution, because major hepatic vessels strongly influence the actual cancer cell destruction (22–26). Various approaches to liver vessel segmentation have been recently implemented and tested (1,27,28), but none of these methods has demonstrated the ability to maintain 100% sensitivity in the automatic identification of vessels < 3 mm in diameter and presenting the true morphologic configurations of a human liver.

To overcome these limitations, we developed a new vessel segmentation algorithm, specifically optimized to provide fully automatic and more sensitive identification of liver vessels on contrast-enhanced CT (CECT) images.

The effectiveness of our vessel segmentation approach was assessed on a CECT data set obtained from a liver phantom produced through stereolithography (STL), a rapid prototyping technique that allows the accurate fabrication of three-dimensional (3D) complex shapes starting from a 3D computer-aided design (CAD) model (29–33). In our case, the CAD model was derived from a real CECT acquisition of a human liver, so the resulting phantom (made of polymeric resin) had a “natural” and precisely known geometry, accurately reproducing the vessel network of a human liver along with the shape and volume of the surrounding parenchyma.

The automatic vessel segmentation performed by our algorithm on CECT images of the phantom was analytically compared to the measured features of the corresponding model to quantify the actual sensitivity and accuracy of our method for both single two-dimensional (2D) slices and 3D reconstruction of the hepatic vessel network.

MATERIALS AND METHODS

Liver Phantom Production Processes and Measurements

The liver phantom used in this study was fabricated through STL, an additive rapid prototyping technique that creates the desired object by exploiting the photopolymerization of a low-viscosity liquid resin and bonding the object sections, layer by layer. Using this fabrication methodology, complex shapes can be obtained on the basis of a direct link with a 3D CAD drawing of the object, leading to tailor-made or single functional parts that are efficiently and accurately realized (29–33).

The following sections are devoted to the description of liver CAD model preparation, features of the STL apparatus, and fabrication processes of the liver phantom, including specific measurements performed to take into account the accuracy of actual STL realization.

Liver CAD Model. A CECT liver data set acquired during a human subject scansion was used to produce the CAD model that was subsequently passed to the STL apparatus for phantom production.

The data set used was actually chosen from those collected for a previous research study (14) developed for a different purpose. The aforementioned study fully respected national privacy laws and had been also approved by the ethics committee. Adopted CT protocols followed the routine clinical protocols used in the involved hospitals for imaging the abdomen with portal vein phase of contrast enhancement.

In particular, the specific image data set used was acquired on a LightSpeed Pro 16 CT scanner (GE Medical Systems, Milwaukee, WI) located at the Interventional Center of the Rikshospitalet University Hospital (Oslo, Norway). Scanning acquisition parameters were as follows: voltage, 120 kV; x-ray tube current, 425 mA; exposure time, 707 ms; and slice thickness, 2.5 mm. A bolus of 150 mL of a nonionic contrast agent (Visipaque 320; Nycomed, Zurich, Switzerland) was administered intravenously.

Obtained CECT scan data were analyzed and processed through our previous algorithm (14), to automatically segment the liver volume, and through a semiautomatic tool for vessel segmentation, with the aim of obtaining a preliminary visualization of hepatic vessels. This segmentation procedure was then checked and manually refined by an expert operator, particularly ensuring the accurate segmentation of all liver vessels visible on the CECT images. The final result of the manual segmentation was stored as a sequence of Digital Imaging and Communications in Medicine images through MATLAB (The MathWorks, Natick, MA) and then converted into a single STL file using a public-domain image processing program (ITK-SNAP version 1.8; University of North Carolina at Chapel Hill, Chapel Hill, NC). This STL file represented the liver CAD model necessary for STL phantom production.

STL Apparatus. The STL apparatus (SLA 250; 3D Systems Inc, Rock Hill, SC) used for phantom production was composed of the following parts (see also Fig 1) and was used for our purposes according to the reported configuration:

- a He-Cd laser (Omnichrome series 3056; Omnichrome Laser and Electro-Optic Systems, Chino, CA) with a specific power of 17 mW/mm^2, emitting at a wavelength of 325 nm, with a beam diameter of 0.2 mm;
- a hardware and software scanning system that drives the laser beam on the surface of the liquid resin vat;