Image Processing and Modeling for Active Needle Steering in Liver Surgery

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Abstract

Image-guided intervention and needle steering for radiofrequency ablation (RFA) of the liver is reviewed in this paper. In particular, the concept of active needle is proposed for RFA treatment. Methods and techniques of image processing and modeling are presented for a stereo liver model. The liver model and constituent components extracted from computerized tomography (CT) images can be used to plan the navigation paths of the RFA needle. The system also provides an option for active needles, which are more amenable to those refractory cases of RFA treatment.

1. Introduction

The liver is the largest solid organ in human body. It holds about one pint (13%) of the body's blood supply at any given moment. Till now the liver has been identified with more than 500 physiological functions vital to body health. The widespread involvement in physiological processes makes the liver susceptible to various pathological alterations, some of which may ultimately evolve to liver tumors. In general, liver tumors do not cause severe symptoms in their early stage. However, once the symptoms become noticeable, the treatment will be quite limited. As a matter of fact, the overall 5-year survival rate of liver cancers is less than 10% [1]. The number increases to the range of 30% to 60% if the patients are in their early stage and their pathological liver tumors are surgically removable. In other words, early detection and appropriate treatment are of vital importance for the survival of patients with liver tumors.

There have been various tools and instruments developed for liver tumor detection and diagnosis. In essence, they are based on either laboratory testing (e.g., biopsy and AFP test) or medical imaging. But the latter is of great help to capture the vital information for liver tumor staging. One of the fundamental challenges in liver tumor treatment, regardless of resection or conservative treatments, is how to fully remove those malign carcinomas while avoiding damage to healthy liver parenchyma as well as hepatic vasculature. Conventionally, surgeons follow Couinaud's approach by dividing the liver into eight segments, each of which has its own independent vascular inflow, outflow, and biliary drainage. Resections along such planes diminish the risk of leaving unviable parenchyma or damaging viable ones. However, both liver morphology and vascular distribution are subject to person-to-person variances. The dogmatic Couinaud model is often not an optimal one for liver tumor treatment [2].

It is increasingly popular to plan a liver surgery optimally by integrating computers and imaging systems [3]-[4]. Image-guided intervention has demonstrated its potentials in minimizing surgical invasiveness and other types of risks [5]-[6]. The participation of medical robotics further relieves the workload of clinical surgeons and enhances the quality of surgical treatment [7]. Radiofrequency ablation (RFA) is a widely-employed operation for liver tumor treatment in clinical medicine. It is necessary for those cases not amenable to resection. In RFA a needle is guided to the specific sites and laser, ultrasound or microwave radiation is applied to destroy the tumors. Two challenges persist till now: one is how to accurately position the tumors and set the extent of treatment; another is how to steer the needle. In this paper, the methods and techniques for image processing and modeling will be reviewed and investigated for a surgical planning system. Its ultimate target is to steer an active needle for liver tumor treatment by RFA [8]-[9].

2. Active Needle Steering

One of the common operations in contemporary medicine is piercing and catheterization, where a needle is used to penetrate the soft tissues, for example, blood sampling, percutaneous insertion, tumor biopsy, and so forth. The operations are determined by needle materials, penetration traces and tissue properties. For those superficial penetrations, the operator can steer the needle by means of haptic information. However, once internal targets are involved (e.g., RFA for liver tumor treatment), it is not possible any more for haptic steering. One possible solution is to mimic the haptic effects based on the information obtained from medical imaging. A more conventional way is to utilize a needle with enough rigidity and disregarding the properties of soft tissue. By doing so, the controlling parameters are the pushing force and angle only (Fig. 1a). But we should bear in mind that their interaction is very complicated [10].

The rigid needle is not suitable for all cases. Take RFA for liver tumor treatment as an example. Sometimes the tumors lie between the critical hepatic vessels. It is extremely difficult to find an optimal path by which the rigid needle can reach the tumors without damaging the hepatic vessels. Many investigators propose to solve that problem by flexible needles [11]. Unfortunately, the interaction between physiological tissues and flexible needles is far more challenging than that of rigid needles. Firstly, the needle tip is with a bevel angle instead of an awl shape (Fig. 1b). Thus its track is not a straight line, but often likely a curve [11]. Secondly, the pushing force and angle are not enough to control flexible needles. More controlling parameters are necessary to be introduced, for example, the screwing force [12]. Thirdly, the spatial controllability of flexible needles, in particular for heterogeneous physiological tissues, is not clear yet. Till now published works are merely based on computer simulations of homogeneous materials [8]-[12]. Steering flexible needles are more frequently modeled as an inverse problem. An optimal path is determined for flexible needle progressing, followed by calculating the controlling parameters in accordance with the path, the properties of flexible needles and soft tissues. The finite element method is now considered as the most appropriate solution, and has been widely utilized [8], [10]-[12].

It is noteworthy that the current state-of-the-art solutions for the flexible needles (Fig. 1b) are still oriented to homogeneous tissues. However, such models are obviously not enough to characterize the RFA needles in liver tumor treatment. To reach liver tumors, the RFA needles have to pass through the derma, the fat, the diaphragm, liver parenchyma, and others. With the aforementioned flexible needles, the analytical model becomes too complicated to solve. As a matter of fact, manipulation of needle advancement can be more effectively implemented by a multi-link microcatheter-based needle design with active joint actuators (Fig. 1c). A prototype of a multiple-link catheter using shape memory alloy actuator has been introduced to intra-vascular applications [13]. In essence, such kind of active needles are flexible only at the specific nodes, which are controlled by various actuators precisely. The involved controlling parameters may be more than those of the paradigm in Fig. 1b, but the underlying mechanisms are obviously more amenable to robotic engineers. At the same time, active needles seem more promising for RFA operations, where a needle has to penetrate various tissues with heterogeneous properties [11].

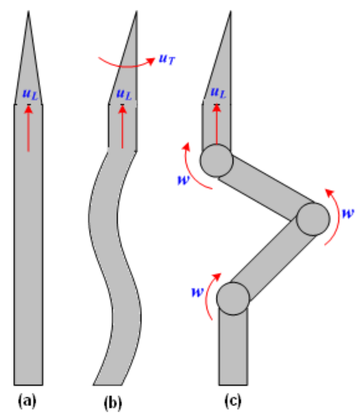


Fig. 1 Different paradigms of needles (a: conventional rigid; b: flexible; c: active)

3. Image Processing and Modeling

No matter which paradigm of RFA needles is adopted, a prerequisite is the optimal path for needle insertion. If the path is a straight line, the rigid needles may be a good candidate. On the contrary, the active needles are more amenable to the curves or the spiral traces. In most surgical planning systems, the optimal paths come into being from the reconstructed models of physiological systems. The modeling is generally built on the series of medical images, including their spatiotemporal resolution and image constituents. The former depends on the performance of imaging modalities, while the latter has to resort to various computing toolboxes. In terms of RFA piercing, the critical factors include the volumes of liver tumors as well as their spatial relations to hepatic vasculature.

We have developed a medical image computing toolbox (MICT). It has an interface to the standard picture archiving and communication systems (PACS) for image acquisition. Various image computing modules are integrated for image processing, segmentation, analysis and visualization. For RFA surgical planning, its functions on hepatic vessel segmentation, liver tumor segmentation and volume modeling are presented here.

For image segmentation, a region growing algorithm is applied to extract hepatic vessels and liver tumors from CT images. The algorithm can be summarized as follows: in the first step, the intensity range for valid seeds and the allowed intensity are predefined for those pixels in the final regions; in the second step, finding the first unvisited seed which is in the allowed intensity range, assigning the next available region number to this seed, and pushing it into a waiting queue; in the third step, popping a pixel from the queue, and then examining all unvisited neighbors. This step is repeated until the queue is empty.

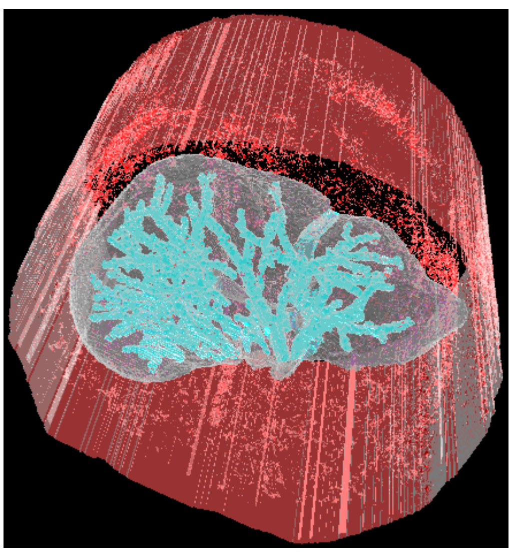
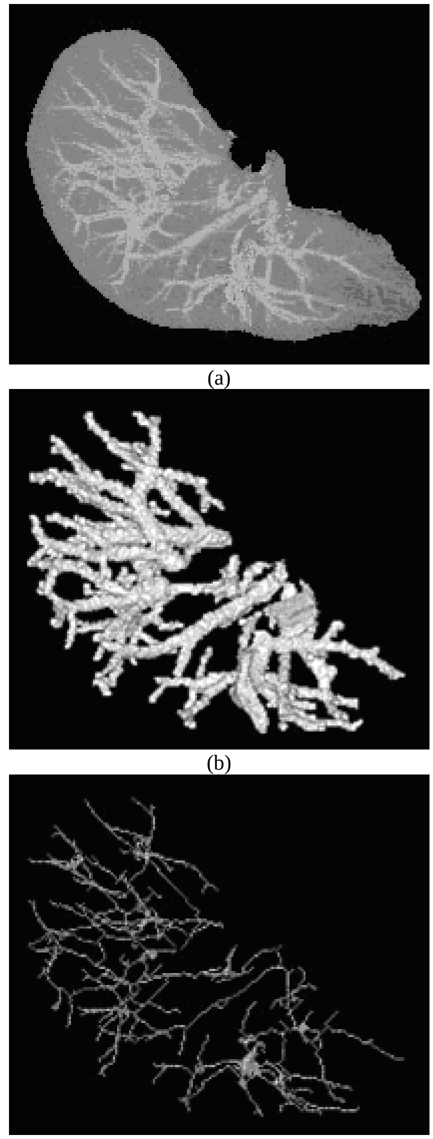


Fig. 2 3D liver volume rendering with vessels

There are different strategies for 3D segmentation of hepatic vessels and liver tumors. Segmenting hepatic vessels is based on a direct 3D version of seeded region growing algorithm (Fig. 3a-b). However, a hierarchical framework is adopted for liver tumor segmentation. In the first step, the candidate liver tumors are identified as mentioned above. Then, the centers of gravity of those liver tumors are calculated. They serve as the seeds for the region growing algorithm in the nearby CT slides. This step is repeated over the entire CT slides.



(a)

(b)

(c)

Fig. 3 Hepatic vessel modeling (a: the maximum-intensity projection images for all slides; b: the raw regions of interest; c: the skeleton of the vessel tree)

Visual effects contribute much to the realism of perception. In terms of volume rendering and image visualization, we extract polygonal surfaces from the segmented data (e.g., the liver, hepatic vessels and liver tumors) as stereolithography (STL), which is a list of the triangular facets that describe a computer generated solid model. However, the complicated and unstructured properties of those STL facets may introduce difficulties on generating computationally efficient visualization. Therefore, we perform some geometric mesh simplification approaches on the generated facets such as decimation, progressive mesh or some smoothing procedures. After obtaining the refined meshes, we render them in a virtual environment using the visualization toolkit (VTK). By carefully setting the transparent properties of the abdomen and liver surfaces, users are able to discern the internal structures such as vessels and tumors (Fig. 2). Accordingly, they may also observe and validate the steering scheme of active needles.

For the hepatic vessel modeling and visualization, we hypothesize that a hepatic vessel could be represented by one or more finite element beam elements. Such an element has a circular cross section and could be visualized as a generalized cylinder. An efficient 3D thinning algorithm [14] is applied to all regions obtained after the segmenting step to extract their skeletons (Fig. 3c). The number of voxels in each skeleton is reduced in a post-processing step leading to a unit-width curve. After that, each branch in the vessel trees is approximated by a cubic B-spline. Finally, a set of control points forming the splines and the branching structure of the trees is used in modeling the hepatic vasculature. The use of control points in this process is computationally faster compared to conventional methods and hence more suitable for augmented reality applications.

4. Conclusion

RFA is an important procedure for liver tumor treatment. It involves needle penetration and the application of controlled electromagnetic effects. The optimal or feasible path to the tumor of the needle is sometimes not a straight line but a curve. The optimal one can be very complex. It is necessary to introduce the concept of active needle into the procedure. The design and the steering of active or flexible needles are a forefront topic in medical robotics.

In this paper, we have presented a system for constructing liver organ, liver tumor and hepatic vasculature models from the series of CT images to determine the optimal paths for RFA needle insertion. Instead of conventional rigid needles, our system provides an option for active needles, which is more amenable to those refractory cases of RFA treatment. In the future, we will couple the image models with our computerized RFA platform for liver tumor treatment. Various paradigms of rigid, flexible and active needles could be investigated and validated.

Acknowledgements

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