Pipeline for the evaluation of navigated 3D intraoperative enhanced ultrasound imaging in neurosurgery for brain tumor resection

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Abstract:

We present in this paper a pipeline for the evaluation of navigated 3D intraoperative enhanced ultrasound imaging for brain tumor resection. The method consists essentially in comparing the tumor in the intraoperative ultrasound data with a gold standard, the tumor in T1 MR data. A protocol for the acquisition of data is provided. Tumors in US and MR data are manually and semi-automatically extracted. The segmented tumors are then qualitatively and quantitatively compared. First results on a patient data set highlight differences in terms of tumor size and position. Moreover, we point out the necessity to develop US-specific segmentation methods and to take into account the brain shift motion in the comparison of tumors.

Keywords: intraoperative US imaging, segmentation, neurosurgery

1 Problem

Brain tumor resection is a complex surgery. Surgeon has to navigate through the brain to reach the region of interest, i.e. the tumor, without damaging healthy structures like blood vessels. According to the kind of tumor, brain tumor may look similar at macroscopic level to surrounded tissue, especially edema. Some tumors have well delimitated borders while infiltrated tumors may have very complex shape which makes it difficult to check removal of the entire tumor.
Intraoperative imaging is however nowadays used to control tumor resection once the neurosurgeon expects having removed the tumor. Among the available intraoperative imaging systems, ultrasound (US) technique is developing for neurosurgical applications. Compared to the most common intraoperative CT and MR imaging systems, ultrasound devices are smaller, easier to handle with a bit of experience and cheaper.
The evaluation of 3D intraoperative ultrasound (3D-iUS) imaging in neurosurgery for tumor resection has been so far few explored in the literature ([1], [2]), especially with the use of a contrast agent. Indeed, the injection of an intravascular US contrast agent may allow enhancing the tumor in the image if it contains blood vessels. But general questions remain. Which kinds of brain tumors may be revealed with 3D-iUS imaging? How are tumors represented in 3D-iUS data compared to MR data, considered as the gold standard? Is 3D-iUS imaging suitable to control tumor resection? In this project we aim studying these questions. A previous step consists in comparing the tumor in intraoperative 3D US data acquired before and after resection with pre- and post-operative MR data, which is the subject of this paper. We describe a pipeline for the acquisition, processing and comparison of data, illustrated with an example on a patient data set.

2 Method

The pipeline in figure 1 shows on a patient example the approach to compare a brain tumor represented in 3D-iUS data with a reference, the tumor in preoperative MR data. A similar scheme may be used to control the resection between 3D-iUS data acquired at the end of the intervention and postoperative MR data. The different steps are detailed now.

- Pre- and post-operative MR data acquisition

Enhanced T1 MR data sets of patients are acquired in a time of maximum 48 hours before and after tumor resection intervention.

- 3D intraoperative enhanced ultrasound data acquisition

The intraoperative data acquisition system consists of an ultrasound device (Elegra, Siemens) with a free-hand 2D 2.5 MHz phased array probe including a contrast mode, an optical tracking system (NDI Polaris) and a navigation system (SonoNavigator, Localite). The different steps for obtaining the 3D-iUS data in the operating room are (1) rigid registration of the pre-operative MR volume with the patient, based on anatomical landmarks interactively specified by the surgeon, (2) continuous injection with a low velocity of the intravascular contrast agent (SonoVue, Bracco), (3) scan of the brain tumor for acquiring a set of 2D US data which positions are known in the space thanks to the tracking system, (4) transfer of the 2D US data from the US device toward the navigation system using a video connection, and (5) in the navigation system, reconstruction of the 3D volume, transform into the patient coordinate system and visualization. These acquisition steps are performed on the opened skull, before and after tumor resection.

- Tumor extraction in MR and US data

In order to compare the tumors in MR and US data a segmentation step is necessary. Tumor extraction in MR data is semi-automatically performed with the freeware ITK-SNAP [3]. Since tumors look homogeneous in the data, a region-based segmentation method is well appropriate. The MR volume is first preprocessed using thresholding intensity values to provide a region competition feature volume. Starting from a bubble manually positioned at the center of the tumor, a snake algorithm extracts in few seconds the tumor within the previously defined volume. Tuning the curvature force values in the snake equation, it is possible to extract tumors with different shapes. On the other hand, it allows avoiding the snake to overgrow into adjacent anatomical structures to the tumor with similar image intensities.
Common semi-automatic segmentation methods fail to correctly extract tumor in the US data because: (1) tumors look inhomogeneous; (2) the blood vessels which feed the tumor are visible as well because of the contrast agent and their presence may disturb the segmentation process (3) tumor borders are smooth partially due to the 3D reconstruction algorithm. Therefore, manual delineation of tumors realized by a user is here performed. This task is done slice by slice using the ITK-SNAP tool as well. Since the voxel size is $1 \times 1 \times 1$ mm^3, volume of tumor is relatively small and the user needs around 15 minutes to provide the segmented tumor.

- Comparison of tumors

The comparison of tumors is performed through the computation of their size and the examination of their position in the head. Since MR and US data are represented in their own coordinate systems, the extracted tumors have to be transformed into a same reference to be compared, i.e. into the patient coordinate system. Alignment of both volumes with the patient is performed here using the navigation system. Tumors are then compared using the Valmet software [4]. This tool provides different quantitative measures, as well as a visualization tool for a qualitative comparison.

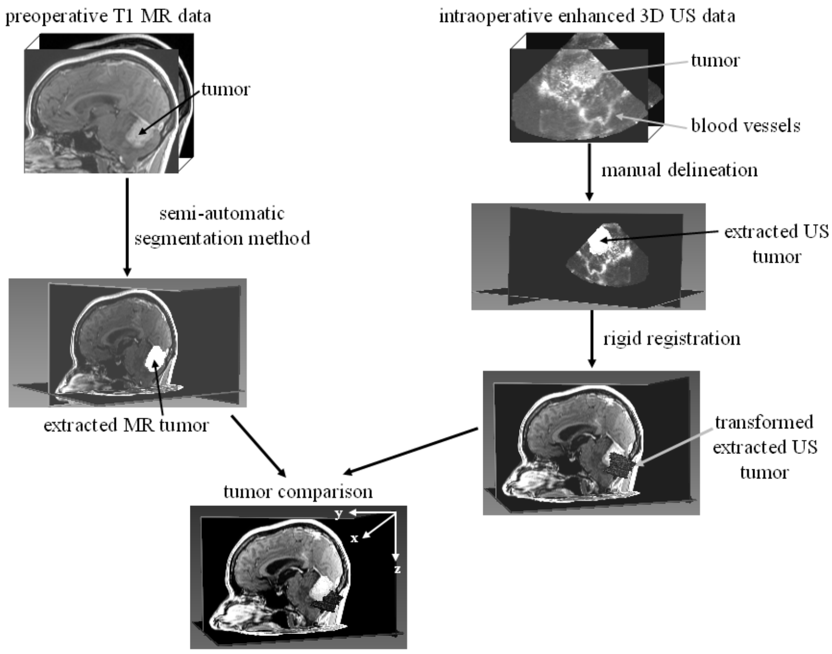

Figure 1. Pipeline for the evaluation of navigated 3D intraoperative enhanced ultrasound imaging, here depicted on preoperative T1 MR and intraoperative 3D US data sets.

3 Results

The proposed pipeline was tested on a patient data set with metastasis. The surgery was performed in the supine position. We dispose for this patient of one preoperative T1 MR data and one enhanced US volume, intraoperatively acquired before tumor resection. Tumors have been segmented as described previously and qualitatively and quantitatively compared using the Valmet software.

- Visualization tool for tumor overlap

Valmet provides curves which represent the number of voxels in the MR and US extracted tumors computed for each volume slice, in the directions x, y and z of volume (see Figure 2). The curves show here that (1) the size of the segmented US tumor is larger than the size of the segmented MR tumor and (2) both segmented tumors are not aligned and the displacement is especially clear along z and y directions, i.e. towards skull opening.

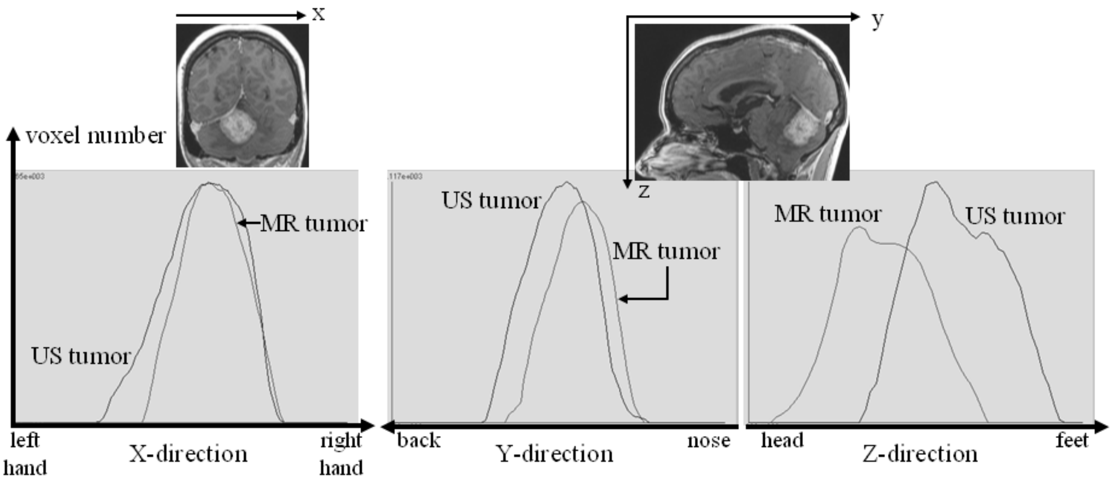

Figure 2. These curves are provided by the Valmet freeware and represent the number of voxels in the tumors, extracted for MR and US data, and computed for each volume slice in the directions x, y and z. The curves highlight here the misalignment of tumors due to the brain shift.

- Quantitative comparison measures

Three kind of geometrical features computed by Valmet are reported here: the tumor size in milliliter, an overlap ration and distance between object surfaces. The overlap ratio indicates how well the segmented tumors are aligned. A score of 1 indicates a total overlap although a score of 0 means that the volume intersection is empty. The Hausdorff distance represents the maximum distance between the surfaces of the segmented tumors. In general, it is an index measuring the similarity between two geometrical shapes. The average distance between surfaces is provided as well. Distances are given in mm.

MR tumor size (ml)	US tumor size (ml)	overlap ratio	Hausdorff distance (mm)	average distance (mm)
12.0	16.4	0.31	19.4	9.3

These values highlight differences between the both extracted tumors. They have different sizes and different shapes (large value of the Hausdorff distance). The low overlap ratio and large values of distances between surfaces is an indicator of the misalignment.

In conclusion, the comparison of the segmented tumors extracted in 3D-US and T1 MR data using the Valmet software indicates an overestimation of the tumor size in the US data and a misalignement of both tumors of less than one cm in the skull opening direction.

4 Discussion

We presented in this paper a pipeline for the comparison of tumors acquired with navigated 3D intraoperative enhanced US imaging with pre- and post-operative MR data. First results on a patient data set showed differences in tumor size and position. Several factors explain the differences:

- Inaccuracy in the manual delineation of the US data provided by a user, which remains a difficult task because of the presence of noise in the data;
- Error in the rigid registration given by the navigation software which may lead to the misalignment of the US data with the MR data;
- Brain shift which occurs when opening the head and may be responsible of large tumor displacement.

Based on the first results obtained here, future work will focus on the improvement of our pipeline, i.e.:

- Development of a semi-automatic segmentation method, specific to US data, for the extraction of tumor to obtain a segmentation result less user-dependent;
- Evaluation of the segmentation methods on a physical phantom;
- Development of a tool for the quantitative comparison of tumors, which takes into account the brain shift motion;
- Application of the pipeline for the study of different kinds of tumors.

5 Reference

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