Title
Deformable resection process map for estimating local appearance of vascular structures in cutting procedures

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Abstract

Purpose:
Virtual planning using preoperative CT/MR images allows quantitative, strategic planning of patient-specific cutting procedures for tumor resection. The planned cutting path and virtual organ images are used as intraoperative cutting guides [1]. During surgery, however, the limited visible parts of the vascular structures (e.g. optically visible or measured from imaging devices such as ultrasound), are commonly used for intraoperative decision making rather than the preoperative plans. One reason to abandon the virtual plan is that the shape of the virtual organs often differs from the deformed states of real organs. A deformed shape may be due to altered physical condition (e.g. air/blood pressure), push/pull manipulation or cuts made during a surgical procedure. The clinical requirements for estimating the visual appearance of such local features are increasing in order to perform evidence-based cutting and reduce surgical risks. Although efforts have been made to provide multilateral anatomical information for navigating cutting procedures [1,2], the local appearance of vascular structures in the intraparative deformed state has been omitted in planning/navigation software due to the difficulty of modeling the effects of soft tissue cuts.

In this presentation, we introduce the deformable Resection Process Map (RPM) for estimating local appearance of vascular structures after cuts as a novel guide for soft tissue tumor resection procedures. The deformable RPM is a geometrical estimator that provides a time-varying local map based on the deformed geometry of the organs (See Fig 1). Unlike static virtual-reality-based training simulators for cutting/ablation procedures, we designed a set of algorithms to provide a semi-automatic software framework tuned for planning/navigation. The RPM can be directly generated from patient-specific medical images using volumetric resampling techniques.

Methods:
To achieve semi-automatic generation of the RPM from medical images, we have newly designed an objective function $f(I, p_k)$ that computes the smooth cutting path $S$ from the segmented organ image $I$ and a set of cutting points $p_k$. First, as a background process, the three-dimensional organ region is sparsely sampled and a proxy geometry bounded by the reference cutting path $S_0$ and...
enclosing the sampled points is generated. The proxy geometry can be described using a tetrahedral mesh. When some cutting points $p_k$ are given on the vascular structures or the organ surface, the vertices of the proxy geometry are relocated using a quadratic minimization function, which is designed to preserve the local shape consistency of the given points $p_k$ and the reference cutting path $S_0$. The cutting points can be manually supplied by the user or extracted from the boundary of segmented blood vessel regions. The estimated cutting path $S$ is locally fit to the cutting points in least squares manner. The curved shape of $S$ can be more complex as the indicated cutting points increase. Next, the discontinuous deformation around the cutting path is computed for the proxy mesh and rendered using the tetrahedral volume rendering algorithm [3]. The vascular structures in the deformed body are linearly interpolated and visualized volumetrically in the proxy geometry.

This approach estimates the cutting path using the given cutting points as geometrical constraints and produces the time-varying local map of vascular structures by progressive deformable representation. We note that the geometry update is performed by the objective function $f$ without relying on vertex addition or mesh subdivision. This scheme enables fast and real-time computation while handling the time-varying geometry of the cutting path. This concept addresses technical issues discussed in [2] and formulates the RPM as a generalized computation framework that can be applied to non-anatomical cutting paths by improving volumetric resampling techniques [4].

Results:

We have applied the software framework to 21 CT datasets for hepatectomy and generated the RPMs in a variety of the deformed states. When some cutting points are indicated on the organ surface or vessels, the RPM is updated and the virtual organ is deformed by applying external force to the cut surfaces. **Fig 1** demonstrates a time-series representation of the resection process map generated from a single CT image set. As the procedure progresses, an updated local appearance is rendered of anatomical structures such as a tumor, hepatic vein, and portal vein in the deformed organ, and a cross sectional image of vascular structures already split by cutting. We have also confirmed that real-time updating of the cutting path and rendering of the deformed organ at greater than 20 frames/s was possible on general-purpose computers with graphic processing units (CPU: 3.5GHz, Memory: 8GB, GPU: NVIDIA GeForce 780).

Conclusions:

We have introduced the deformable resection process mapping as a time-varying geometric guide for cutting procedures. The algorithmic design for semi-automatic generation from medical images was described. Because user input of some cutting points is the only requirement for generating the RPM, the developed software will be directly available for clinical use in previewing surgical procedures and intraoperative workflow management without time-consuming setup or additional
work loads. Quantitative evaluation of the generated cut surface geometry and clinical validation are our future work.

![Fig 1. The deformable resection process map as a guide for soft tissue tumor resection procedures.](image)

**Reference**