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Faculty of Medicine
Biomedical Engineering

Master of Science Thesis

3D Liver Reconstruction from Tracked Ultrasound

by

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Abstract

The abstract should provide a concise (300-400 word) summary of the motivation, methodology, main results and conclusions. For example:

Osteoporosis is a disease in which the density and quality of bone are reduced. As the bones become more porous and fragile, the risk of fracture is greatly increased. The loss of bone occurs progressively, often there are no symptoms until the first fracture occurs. Nowadays as many women are dying from osteoporosis as from breast cancer. Moreover it has been estimated that yearly costs arising from osteoporotic fractures alone in Europe worth 30 billion Euros.

Percutaneous vertebroplasty is the injection of bone cement into the vertebral body in order to relieve pain and stabilize fractured and/or osteoporotic vertebrae with immediate improvement of the symptoms. Treatment risks and complications include those related to needle placement, infection, bleeding and cement extravazation. The cement can leak into extraosseous tissues, including the epidural or paravertebral venous system eventually ending in pulmonary embolism and death.

The aim of this project was to develop a computational model to simulate the flow of two immiscible fluids through porous trabecular bone in order to predict the three-dimensional spreading patterns developing from the cement injection and minimize the risk of cement extravazation while maximizing the mechanical effect. The computational model estimates region specific porosity and anisotropic permeability from Hounsfield unit values obtained from patient-specific clinical computer tomography data sets. The creeping flow through the porous matrix is governed by a modified version of Darcy's Law, an empirical relation of the pressure gradient to the flow velocity with consideration of the complex rheological properties of bone cement.

To simulate the immiscible two phase fluid flow, i.e. the displacement of a biofluid by a biomaterial, a fluid interface tracking algorithm with mixed boundary representation has been developed. The nonlinear partial differential equation arising from the problem was numerically implemented into the open-source Finite Element framework *libMesh*. The algorithm design allows the incorporation of the developed methods into a larger simulation of vertebral bone augmentation for pre-surgical planning.

First simulation trials showed close agreement with the findings from relevant literature. The computational model demonstrated efficiency and numerical stability. The future model development may incorporate the morphology of the region specific trabecular bone structure improving the models' accuracy or the prediction of the orientation and alignment of fiber-reinforced bone cements in order to increase fracture-resistance.

Acknowledgements

Here you may include acknowledgements.

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe. Alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche kenntlich gemacht. Mir ist bekannt, dass andernfalls der Senat gemäss dem Gesetz über die Universität zum Entzug des auf Grund dieser Arbeit verliehenen Titels berechtigt ist.

Bern, October 31$^{\text{th}}$ 2018

Luca Sahli

Contents

Chapter 1

Introduction

1.1 Motivation

The goal of computer assisted surgeries is to reduce the time used to do the surgery and to also improve the surgical result for the patient. In the case of surgeries involving liver resections, navigation systems are rarely used because they do not provide enough advantages compared to the additional time needed to set them up. The accuracy of such navigation systems is affected by deformations of the liver during the surgery [10]. Additionally for registration based methods is the registration error and the time used to register the patient's anatomy to the preoperative 3D-model of the liver. Supplementary these preoperative 3D-models are very expensive and time consuming to generate. Therefore we aim to develop a new concept to navigate during liver resections. This concept should not need a preoperative scan and would therefore not need a registration. That way we would avoid the expensive and time consuming preoperative 3D-model.

1.2 The Liver

1.2.1 Liver Anatomy

The human liver overlies the gallbladder, is located in the right upper quadrant of the abdomen and has different functions. It produces biochemicals necessary for digestion, synthesizes proteins and detoxifies various metabolites. A human liver wheighs normally around 1.5 kg, is the heaviest internal organ and the largest gland of the human body. Two large blood vessels are connected to the liver: the portal vein and the hepatic artery. Both of them subdivide into small capillaries called *liver sinusoids* and then lead to the functional units of the liver known as *lobules*. To refer to the different parts of the liver, it is subdivided into eight subsegments. Each segment has its own vascular inflow and outflow.

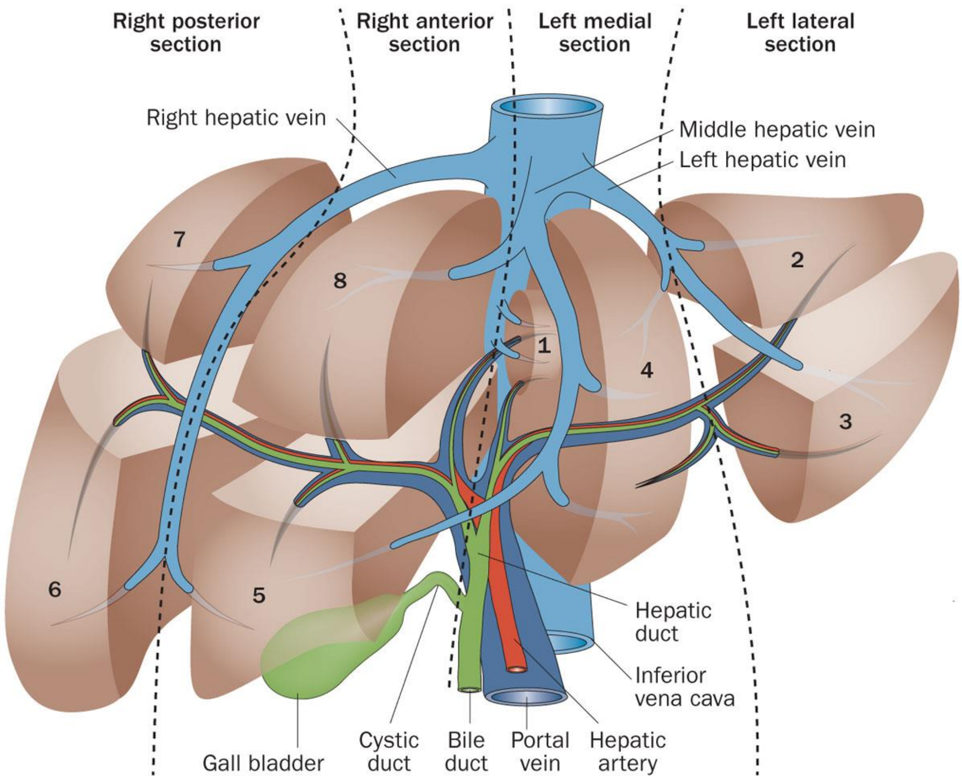

Figure 1.1. The liver and its eight Chouinaud segments. In red is the hepatic artery which transports blood from the heart a into the liver. In dark blue the portal vein, it transports blood from the gut into the liver. All the blood leavs the liver through the hepatic veins to the vena cava [30].

1.2.2 Liver Cancer

Liver cancer is cancer that starts in the liver. If the cancer has spread from elsewhere to the liver, then it is known as liver metastasis. Liver metastasis are about 20 times more common than primary tumors. One of the reasons for that is the rich blood supply of the liver which helps the tumors to grow [26]. Liver cancer patients often have chronic liver diseases such as cirrhosis, problems of alcohol abuse, and viral hepatitis (B or C) [15]. The gold standard to treat liver cancer are surgical resections [20]. The liver tissue can easily regrow, given that after resection there is enough healthy tissue and blood supply preserved. Alternatively to resections one can treat liver tumors by local ablation. Both variants treat the tumors with a safety margin of 10 mm. This safety margin ensures that all tumor cells are destroyed and to prevent further spread of cancer cells [24].

1.3 Liver Resections

Hepatectomy is the surgical resection (removal of all or part) of the liver. Liver resections are considered major surgeries and are done under general anesthesia. Most hepatectomies are done laparoscopicly. However for complicated cases also open surgeries are done [8].

Two resection techniques can be separated. Anatomical or parenchymal-sparing resections. This work will concentrate on the latter technique.

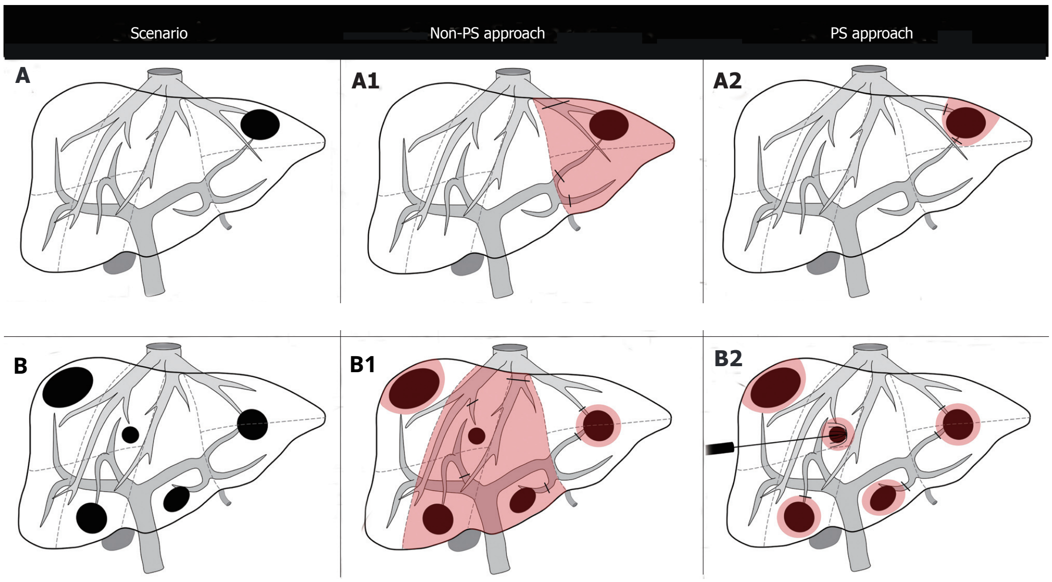

Figure 1.2. Two different approaches to resect liver tumors in two different situations. The *Scenario* column shows the situation of the patient's liver, the *Non-PS approach* column shows how an anatomical resection plan would look like and the *PS approach* column shows how a parenchymal-sparing resection plan would look like [4].

1.3.1 Parenchymal-sparing liver surgeries

[4]

1.4 Objectives

Laparoscopic anatomical hepatectomy (LAH)

Chapter 2

State of the art

2.1 Intraoperative ultrasound

Ultrasound imaging works by the *pulse-echo* principle. A short ultrasound-pulse is emitted from a transducer. Then the soundwaves get transmitted and reflected differently by different tissues. The reflected soundwaves travel back into the transducer and get converted into an electrical signal. After post-processing these signals become ultrasound images. Basically the ultrasound measures the mechanical properties of the tissue. The tissues have different acoustic impedance, which is the product of tissue density and ultrasound speed in travelling through the tissue. The resolution of the ultrasound images depends on the frequency of the ultrasound waves. High frequencies lead to high resolutions but low depth into the tissue because the absorption of the sound energy increases with frequency too. Therefore the useability to see deep structures is limited [32]. In liver surgeries the ultrasound is used for intraoperative planning and navigation inside the liver. Figure 2.1 shows an example of an ultrasound image of the liver and its corresponding position in the 3D liver model. The surgeon can find the tumors inside the liver by using the ultrasound. Registration methods based on 3D ultrasound reconstructed liver vessels also exist but are not used in practice a lot yet [19]. Therefore ultrasound is an important and established instrument in liver surgeries.

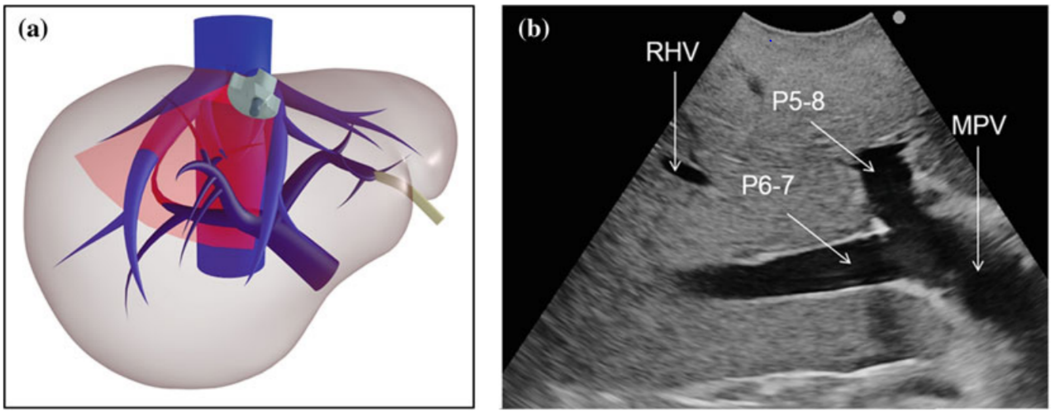

Figure 2.1. Left (a) ultrasound image plane in the liver. Right (b) intraoperative ultrasound image. One can see the right hepatic vein (RHV), the portal branch to segments 5 and 8 (P5-8) and the portal branch to segments 6 and 7 (P6-7) [32]

2.2 Navigation for liver resections

The actual intervention in computer assisted surgeries (CAS) is defined as surgical navigation. For navigated surgeries special instruments are used. These instruments are tracked by the naviagation system. The orientation and position of the instruments in relation to the patient's anatomy is visualized on a monitor in the operating room. The surgeon can then see what he does on the monitor and uses the system to navigate the location and position of its instruments. This is specialy then useful when the tip of the instrument is not actually visible for the suergeon. In liver surgeries, the navigation is mostly done by first registering the patient to a pre-operative 3D computer tomography (CT) scan of the liver during the surgery. All surgical instruments have trackable markers attached to them and a tracking camera sees these markers and can differentiate the different instruments from their attached markers. The achieved navigation accuracy with such a system was 4.5 mm $\pm$3.6 mm averaged over nine surgeries [29]. Current research tries to compensate for deformations of the liver after the CT scan to the actual shape of the liver [10] [11].

2.2.1 Creation of preoperative 3D-models

[27] time consuming and method to create 3d-model from CT

2.2.2 Registration methods

Different registration methods exist. Discrete landmarks, surface scans and volumetric sonography scans are just a few of the approaches that can be used to achieve precise alignment of the preoperative image data with the surgical site [6].

2.2.3 Tracking modalities

To track surgical instruments and patient's anatomy (define the position and orientation in real time) during naviagated surgery a tracking system is needed. Tracking can be done by different technologies. The most used tracking modality is optical tracking.

Optical tracking

Optical tracking is the most used tracking modality in naviagated liver surgeries. Passive markers (spherical, retro-reflective that reflect infrared light) or active markers (infrared-emitting markers that are activated by an electrical signal) [33] are attached to the objects that need to be tracked. A tracking camera is then emitting infrared light by illuminators on the position sensor (only for passive markers). The position sensor determines the position and orientation of the tracked instruments based on the information it receives from those markers [1].

2.3 Surface reconstruction of unorganized points

A surface reconstruction's goal is to create a surface from sampling points. Two main steps need to be processed. First, collecting the sample points. Second, apply a reconstruction algorithm to the sampled points.

2.3.1 Data acquisition

There exist different methods of collecting surface points [14][21][12][9][13]. Optical (non-contact scan) scans are the most popular ones. Specialy laser based scanners can scan very fast and with a precision in the order of micrometers. Also contact scans exist [28]. Contact scans can also be very precise (in the order of micrometers). Only a few articles were published in the field of liver surface scanning [25] [31]. They used stereo laparoscopic cameras to sample the surface. The resulting sampling points lie on or near an unknown surface. A reconstruction algorithm has now to reconstruct the surface from these points.

2.3.2 Reconstruction algorithms

Again, a lot of reconstruction algorithms exist [23], but not all of them are made to reconstruct from unorganized points. This means that the point orders, orientations, connections and the topological type of the surface is not known a priori. Therefore it is necessary that the algorithm does not assume any structure on the data points [17] [34]. The orientations, connections and the topological type must be inferred from the points. This is a major difficulty of the general surface reconstruction problem [16]. In the past few decades, many algorithms that can solve this problem have been published. Nevertheless it is still a challanging task that is part of current research [22]. The available reconstrction types can be classified into two groups: implicit volume-based and explicit mesh-based reconstructions.

Explicit mesh-based reconstrction

Explicit mesh-based reconstrction methods form a triangular mesh directly from the unorganized points. These mesh-based reconstructions are precise but they have problems with noise, complex shapes and especially holes in data.

Implicit volume-based reconstrction

Implicit volume-based reconstruction techniques construct an implicit volume-function from the input points. From the iso-surface of the volume-function a restored surface can then be optained. For these methods it is not a problem if the surface topology is complex. But most of these methods suffer from oversmoothing the data and the need of accurate directions of normal vectors in addition to the unorganized points.

[18] oriented point set hornung2006robust [17] non uniformly sampled point clouds without normal information [34] NN to reconstruct from unorganized points

Chapter 3

Problem Statement

Chapter 4

Concept

4.1 System

4.2 Functionalities

4.2.1 Surface Reconstruction

4.2.2 Tumor Segmentation

(Automatic 3D)

4.2.3 Resection Planning

4.3 Workflow

4.3.1 Resection planning for non-anatomical ...

Chapter 5

Implementation

This chapter

5.1 Surface Reconstruction

5.1.1 Surface contact detection

5.1.2 Outlier removal

5.1.3 Reconstruction Parameters

grid search

5.2 Tumor Segmentation

graph cuts initialization method

5.3 Resection Planning

5.3.1 Cone fitting around tumor

5.4 Visualization for navigation

5.4.1 Ultrasound overlay

5.4.2 3D model

5.5 UI Concept

Chapter 6

Experiments

6.1 Surface Accuracy on a technical phantom

work presented in this section was presented at CURAC, Luca

6.1.1 Methodology

6.1.2 Results

6.1.3 Discussion

6.2 Surface reconstruction on retrospective data

6.2.1 Methodology

Retrospective data from Banz et. al

6.2.2 Results

6.2.3 Discussion

6.3 Usability Test

3 surgeons questionnaire surface accuracy (using surface registration)

6.3.1 Methodology

6.3.2 Results

6.3.3 Discussion

Chapter 7

Discussion and Conclusions

7.1 Discussion

Interpret your results in the context of past and current studies and literature on the same topic. Attempt to explain inconsistencies or contrasting opinion. Highlight the novelty of your work. Objectively discuss the limitations.

7.2 Conclusions

Formulate clear conclusions which are supported by your research results.

Chapter 8

Outlook

Provide a vision of possible future work to continue and extend your thesis research.

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etc.

Appendices

Appendix A

Vector and Tensor Mathematics

A.1 Introduction

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A.2 Variable Types

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Appendix B

Another Appendix

B.1 Section 1

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B.2 Section 2

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