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# Towards realistic organ models for 3D printing and visualization

**Abstract:** Three-dimensional visualizations and 3D-printed organs are used increasingly for teaching, surgery planning, patient education, and interventions. Hence, pipelines for the creation of the necessary geometric data from CT or MR images on a per-patient basis are needed. Furthermore, modern 3D printing techniques enable new possibilities for the models with regard to color, softness, and textures. However, to utilize these new features, the respective information has to be derived from the medical images in addition to the geometry of the relevant organ structures. In this work, we propose an automatable pipeline for the creation of realistic, patient-specific 3D-models for visualization and 3D printing in the context of liver surgery and discuss remaining challenges.

**Keywords:** Liver, surgery, 3D-printing, visualization

## 1 Introduction

Medical images resulting from Magnetic Resonance Imaging (MRI) or Computed Tomography (CT) play an important role for clinical diagnosis and therapy decisions. Modern visualization technologies, including virtual and augmented reality as well as recent 3D printing methods, enable new ways of exploring such images in the context of medical training, patient education and surgery planning [1]. Various degrees of details are needed for each application domain. For instance, idealized 3D models are well suited to communicate complex vasculature while highly detailed models including surface textures are needed for education, for example to familiarize with the various stages of a disease such as liver cirrhosis. In addition to shape and color, haptic sensation is an important factor in particular during training. Using modern 3D printing technologies, all these aspects can be transferred into highly realistic organ models, which have the potential to revolutionize operation planning, student education and patient communication.

The processing of the patient data involves multiple interdependent steps forming a dedicated workflow. While such a process chain may be feasible in a manual way for training models, automation of a higher degree is desirable for scenarios that involve patient-specific models.

In this work, we propose an end-to-end pipeline for the generation of highly realistic virtual and physical organ models from standard CT and MRI data, utilizing state of the art techniques as well as novel approaches. The presented pipeline was created in the context of the VIVATOP project [2] and focuses on the creation of models in the scope of liver surgery planning and training, but its principles can be translated to other applications as well.

## 2 Model Creation Pipeline

Our process chain covers the whole process for model creation starting with the image acquisition and finally resulting in final models for 3D-printing and visualization. Figure 1 gives an overview of the whole pipeline, which is described below.

### 2.1 Data Acquisition

CT and/or MR images of patients, in our case provided by the University Clinic for Visceral Surgery at the Pius Hospital Oldenburg, are used as basis for the (patient-specific) organ models for 3D visualization and printing. The CT or MRI data is acquired as a series of contrast-enhanced images following clinical routine protocols for diagnosis and intervention planning either in-house or is imported from external referrers.

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To extract, visualize and print sufficient anatomical details, the image data should fulfil certain requirements. For liver segmentation in MRI, contrast-enhanced T1-weighted sequences in breath-hold technique are typically used. Repeated sequences cover one contrast phase of the liver. Additional diffusion- or T2-weighted sequences facilitate tissue characterization and may be used to add further functional information and potential input for image analysis. A desirable voxel size should be 1 by 1 mm in-plane and 1-3mm slice thickness., preferably for all used modalities.

## 2.2 Image Analysis and Model Creation

CT and MR images are analyzed by radiological experts using a proprietary software application by Fraunhofer MEVIS. The software includes automatic and semi-automatic algorithms for the segmentation of liver, lesions, and hepatic vessels, as well as automatic and interactive approaches for the registration of different contrast agent phases. An overview of the workflow steps and methods is provided in [3], updated image processing approaches can be found for example in [4,5] for registration and in [6,7] for deep-learning-based segmentation of liver and lesions.

Masks of the segmented structures are taken as input for the subsequent mesh generation using the Marching Cubes algorithm [8]. For vascular surfaces a dedicated model-based approach is used based on [9]. For each structure, heuristically defined parameters for remeshing and smoothing are applied, also depending on the need for later deformation to depict the pathological state (see section 2.4). Furthermore, structure-specific colors are applied to enable easy distinction. For 3D prints of the organ without real transparency, a simplified lattice structure is derived by reducing the number of vertices, converting the edges into cylinders and smoothing the union of theses shapes (see fig. 2). To this end, the open source software *Blender* [10] is used. Finally, for cast molds, 3D print data is derived from the negative organ shape (fig. 2).

## 2.3 Tissue characterization

The stiffness (or hardness) of the organ tissue corresponds to certain states of the organ and in particular to potential diseases. Especially for the liver, the stiffness correlates with the fibrosis grade and also tumors show a significant difference in stiffness compared to healthy liver tissue [11]. Since we want to estimate the fibrosis score [12] for realistic textures and haptics, the stiffness is of high importance in our pipeline for operation planning and student training.

Organ stiffness can be measured in multiple ways, often denoted by the term *elastography* [13]. The most common ways to derive tissue stiffness are Ultrasound elastography or

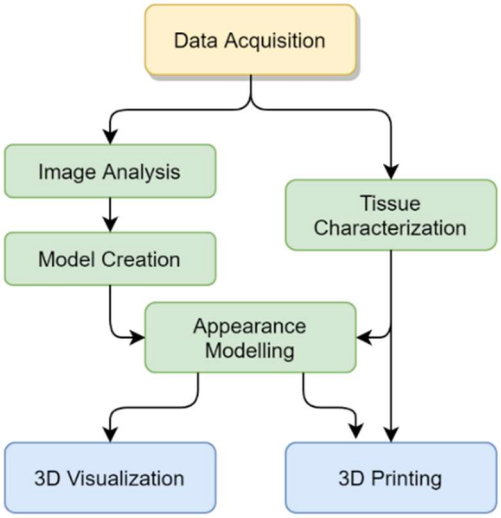


**Figure 1:** Overview of the processing pipeline.

MR elastography techniques. However, elastography is not a standard procedure and quite time-consuming. Furthermore, some studies indicate the possibility of deriving stiffness parameters directly from image data [14]. In our current approach, we investigate perfusion parameters from CT data and their correlation to a measured ground truth stiffness. To this end, we measure the tissue hardness *in vivo* and *ex vivo* with a durometer (cf. fig. 3), an instrument for hardness measurements, that has been adapted for use in a clinical environment by several modifications that made it sterilizable [15]. The hardness is being measured with an adapted measurement method and a liver-specific value range for every liver segment to account for local differences. Perfusion analysis, its correlation to the durometer measurements and the organ state is currently ongoing work and part of a clinical study.

## 2.4 Appearance Modelling

Textures and surface displacement are common techniques to modify the appearance of a surface in computer-generated images and are used here to depict the state of an organ. We choose 2D texture images to apply color to the organ surface. This allows us to import and interpret the textured meshes easily in many target applications. However, in an intermediate step we utilize solid texturing based on a combination of various procedural 3D textures such as fractal Perlin noise and Worley noise [16] to define organic and realistic looking variations of color and displacement on the surface based on the state of the organ. To map these values onto 2D textures, texture coordinates are created. The displacement values are used to deform the vertices of the mesh while the color information is baked into 2D maps using

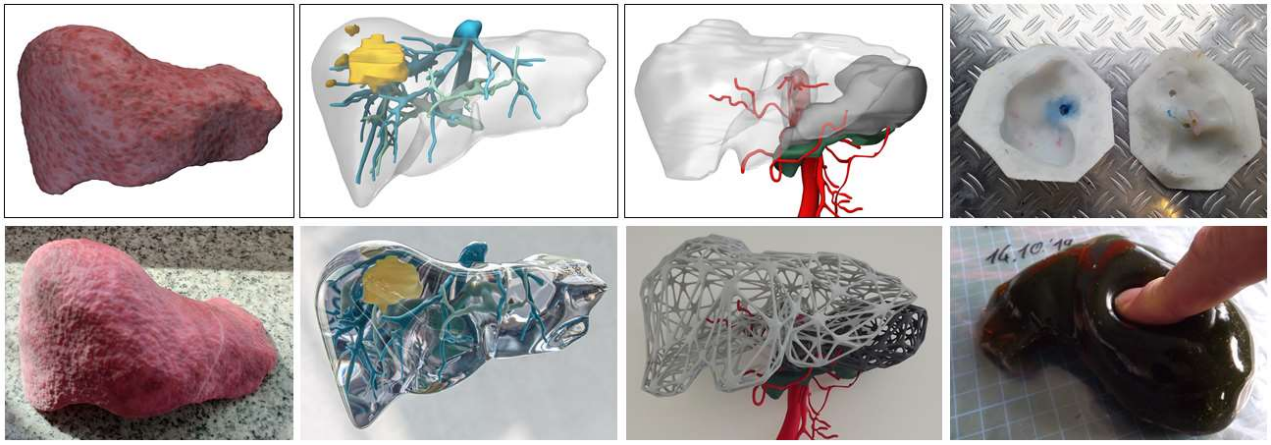

**Figure 2:** Results of the pipeline: 3D-visualization (top) and 3D-print (bottom) for a fibrotic liver (left), a transparent model with a tumor (middle left) and a complex planning model with the neighbored pancreas using simplified mesh representations of the organs (middle right). The rightmost images show a 3D printed negative mold (top) and corresponding cast (bottom) with realistic haptics.

the created texture coordinates as described in [17]. We eliminate the manual work that is typically associated with this common workflow by utilizing *Blender* [10] and its Python API to automatize these tasks completely.

## 2.5 3D Printing

State of the art 3D printing techniques can easily create solid organ models and highly transparent materials are available using the Polyjet printer [18]. However, printing very soft and elastic material as needed for realistic haptics remains a difficult issue.

Hence, in order to replicate the stiffness and elasticity of organ tissue, we experimented with collagen-based casting techniques using various concentrations and mixtures. Based on an evaluation of the different mixtures and materials by experienced physicians and comparisons to *in vivo* and *ex vivo* tissue with a durometer, we were able to generate organ models with realistic haptics (cf. fig. 2). In the context of the liver, this enables us to replicate healthy tissue as well as pathologies, like different grades of fibrosis/cirrhosis.

## 2.6 Visualization

Without further processing, the 3D models can be used in almost any 3D visualization environment. Besides classical desktop-based applications, virtual and augmented reality settings, for example implemented in the Unity or Unreal engine, might utilize the textured or untextured models in various scenarios [19].

# 3 Results

We implemented large parts of the proposed pipeline for the creation of liver models. Data acquisition, image processing, and model creation are already established methods and also part of commercial products. The tissue characterization is still work in progress. The automatic appearance modelling process has been implemented with a focus on liver fibrosis and cirrhosis to cover a large range of liver disease stages. For a specific histologic score of fibrosis (Metavir, F0-F4 [12]), it displaces a given liver surface mesh and creates a corresponding texture and the required texture coordinates. For the exchange of the 3D models the standard formats Wavefront OBJ and VRML97 are used.

Figure 2 depicts some of the models created using the proposed pipeline: Two models aiming at education (fibrotic liver and a transparent model illustrating the vascular topology), a patient-specific planning model as well as a 3D cast with realistic softness for training.

We evaluated the use of 3D printed organ models for interaction in VR for the planning and training of surgeries in a focus group, consisting of five surgeons from the Pius Hospital [1]. The surgeons rated the overall approach as highly useful and highlighted the advantage of easier grasping the spatial relations, which has great potential to improve the surgery planning. The 3D-printed models were accepted very quickly and the surgeons saw a huge benefit in the soft models with embedded stiffer tumor structures, in particular for medical education and training.

# 4 Discussion and Conclusion

We proposed an end-to-end pipeline for the generation of highly realistic virtual and physical organ models from standard CT and MRI data, using novel approaches for 3D printing and tissue characterization among others.

While printing transparent models can be realized using state of the art printing techniques and materials, soft tissue is still difficult to replicate. Depending on the pathology, a realistic representation of stiffness or softness can only be reached by using casting technologies. This is in particular important for the case of healthy and slightly fibrotic liver tissue, which is very soft. Cirrhotic tissue on the other hand is relatively stiff and might be printed directly. For preoperative planning models this is less of a problem, as the correct understanding of the three-dimensional anatomical relations of the pathology are in focus and realistic hardness is not mandatory. However, for use as surgical training models, realistic stiffness is by far more important. In addition, the desire to use the training phantoms with modern imaging modalities like CT and MRI and to cut them with high-frequency scalpels for surgical training presents additional challenges. Both functionalities depend on the specific humidity of the material and cannot be represented by common 3D-printing polymer materials. This led to the application of collagen-based casting techniques to manufacture those phantoms.

Transparent printing allows to explore the vascular anatomy in relation to the liver capsule, but e.g. in the context of education, it is currently not ideally suited for patient-specific planning due to relatively high manufacturing costs and distortions due to refraction. Here, alternative ways of depicting the capsule are currently being investigated. For the creation of patient-specific training phantoms that include the individual, complex arterial vessel systems, the combination of casting with 3D-printing technologies is very promising.

Regarding the tissue characterization, first results of the per-segment correlation analysis seem promising, yet we have to investigate this subject further with more samples. A substantial challenge are the multiple factors that are relevant for liver stiffness (systolic blood pressure, amount of drunken liquid, etc.). Therefore, we also collect further patient and more general health-related data, e.g. blood pressure, age, weight, heart rate, and disease-related blood parameters and embed them into the correlation analysis. Nevertheless, it is still debatable if the tissue stiffness can be directly derived from the image data, which renders this issue as a major topic for future work.

Currently, the 3D models are exchanged using standard 3D formats. In the future, we plan to investigate DICOM embedded 3D formats, which would facilitate easier integration into clinical environments. DICOM tags could also be used to transport additional information, such as the organ stiffness.


**Figure 3:** Ex vivo stiffness measurement of a resected liver part with tumors (brighter yellow parts) using the modified durometer.

While there are currently still some manual steps involved, the pipeline is potentially automatable with limitations being segmentation and tissue characterization. These steps provide critical information, e.g. tumor volume and disease state, that should be reviewed by clinical experts, at least when used for individual therapy planning. Further automation of the pipeline is therefore desirable also with regard to bringing the final pipeline to a repetitive and certifiable level for all different applications. This will be part of our future work.

### Author Statement

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