Three-Dimensional Liver Surgery Simulation: Computer-Assisted Surgical Planning with Three-Dimensional Simulation Software and Three-Dimensional Printing

著者別名	大城　幸雄, 大河内 信弘
journal or publication title	Tissue engineering. Part A
volume	23
number	11-12
page range	474-480
year	2017-06
権利	(C) Mary Ann Liebert, Inc.
URL	http://hdl.handle.net/2241/00146639

doi: 10.1089/ten.tea.2016.0528

Review article

3D liver surgery simulation: computer-assisted surgical planning with 3D simulation software and 3D printing

Yukio Oshiro and Nobuhiro Ohkohchi

Department of Surgery, Division of Gastroenterological and Hepatobiliary Surgery and Organ Transplantation, Faculty of Medicine, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, 305-8575, Japan

Correspondence: Yukio Oshiro, M.D., Ph.D.; Department of Surgery, Division of Gastroenterological and Hepatobiliary Surgery and Organ Transplantation, Faculty of Medicine, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, 305-8575, Japan.

Email: oshiro@md.tsukuba.ac.jp

Abstract

To perform accurate hepatectomy without injury, it is necessary to understand the anatomical relationship among the branches of Glisson's sheath, hepatic veins, and tumor. In Japan, three-dimensional (3D) preoperative simulation for liver surgery is becoming increasingly common, and liver 3D modeling and 3D hepatectomy simulation by 3D analysis software for liver surgery have been covered by universal healthcare insurance since 2012. Herein, we review the history of virtual hepatectomy using computer-aided surgery (CAS) and our research to date, and we discuss the future prospects of CAS. We have used the SYNAPSE VINCENT medical imaging system (Fujifilm Medical, Tokyo, Japan) for 3D visualization and virtual resection of the liver since 2010. We developed a novel fusion imaging technique combining 3D computed tomography (CT) with magnetic resonance imaging (MRI). The fusion image enables us to easily visualize anatomic relationships among the hepatic arteries, portal veins, bile duct, and tumor in the hepatic hilum. In 2013, we developed an original software, called Liversim, that enables real-time deformation of the liver using physical simulation, and a randomized control trial has recently been conducted to evaluate the use of Liversim and SYNAPSE VINCENT for preoperative simulation and planning. Furthermore, we developed a novel hollow 3D-printed liver model whose surface is covered with frames. This model is useful for safe liver resection, has better visibility, and the production cost is reduced to one-third of a previous model. Preoperative simulation and navigation with CAS in liver resection are expected to help planning and conducting a surgery and surgical education. Thus, a novel CAS system will contribute to not only the performance of reliable hepatectomy but also to surgical education.

Keywords: 3D; computer-aided surgery; simulation; 3D printing

INTRODUCTION

In Japan, image-aided surgery of the liver has been covered by medical insurance since 2011. Since then, hepatic navigation surgery has spread throughout Japan. In addition, many institutes in Japan have adopted the technology of three-dimensional (3D) images reproduced from the computed tomography (CT) of patients undergoing liver resections to share visual information with the surgical team and to evaluate the simulated liver volume for liver resection.[1–7] Recently, 3D image-aided surgery has been applied not only to hepatobiliary surgery but also to pancreatic surgery.[8,9] In addition, a novel preoperative fusion technique using 3D computed tomography combined with 3D magnetic resonance imaging (MRI) for hepatobiliary malignant diseases has been reported.[2] In this paper, we review the history of virtual hepatectomy using computer-aided surgery (CAS) and our research to date, and we discuss the future prospects of CAS.

History of 3D liver surgery simulation

During the 2000s, after the introduction of multidetector-row CT and DICOM, several 3D image analytic programs were developed to handle large amounts of imaging data.[1,10-12] In a study in 2000, surgery planning with 3D-reconstructed liver models was performed using a volume rendering method.[10] The authors reported that 3D reconstruction developed the surgeon's ability to recognize the location of a tumor in the liver, regardless of their level of expertise. In 2005, an innovative 3D simulation system was developed, which could calculate the liver volume based on virtual portal perfusion.[1] This study showed precise correlation between the predicted liver resection volume and the actual resection volume. Since 2007, these 3D software systems have been used for surgery for cholangiocarcinoma and liver tumors.[2,3,5] In Japan, operative evaluations for liver surgeries using image-processing software have been covered by universal healthcare insurance since 2012. In 2013, several reports were published regarding surgical simulation with the "SYNAPSE VINCENT" second-generation 3D simulation software (Fujifilm Medical, Tokyo, Japan), remodeled with new algorithms and segmentation functions.[2,6,7] Today, to our knowledge, several softwares are available for 3D liver surgery simulation, such as OVA (Hitachi Medical Corporation, Japan), SYNAPSE VINCENT (Fujifilm Medical, Japan), HepaVision (Mevis, Germany), Ziostation (Ziosoft, Japan), VirtualPlace (AZE, Japan), and VR-Render (IRCAD, France).[13]

Simulation with SYNAPSE VINCENT using CT

SYNAPSE VINCENT is a 3D image-processing software. This software aids in visualizing the complicated vascular structure in the liver and allows the volumetry of the liver and any territory supplied with blood vessels selected by users.[2,7] Until recently, we used SYNAPSE VINCENT for preoperative simulation by 3D-reconstruction of the liver and intrahepatic vessels. We created a tracing of the portal vein or hepatic vein from an independent patient's CT, and the technology of auto-segmentation and manual segmentation was used to complete the 3D-reconstructed liver. Several papers have reported that the simulated liver resection volume significantly correlated with the real liver resection volume.[6,7]Accordingly, virtual liver resection is helpful for the simulating various liver resection procedures. However, to our knowledge, no assessment of the surgical outcomes with simulation using 3D analysis software has been reported to date. Thus, further investigation regarding mortality, morbidity, operative time, blood loss, and survival rate differences of liver resection with and without 3D simulation are needed.[6]

[Case]

This is a case of multiple liver metastases of a rectal neuroendocrine tumor (**Fig. 1**). Initially, the patient was considered inoperable based on the findings of 2D CT; however, 3D simulation helped us re-evaluate the patient's condition as operable. Based on 3D simulation, we planned an extended left lobectomy, partial resection, and radiofrequency ablation of the metastases of the right lobe. An evaluation of the liver volume indicated that the remnant liver volume to total liver volume value was 64.5%. In this surgery, an extended left hepatectomy, partial resection and radiofrequency ablation were performed. After the clipping of the left portal vein, a demarcation line appeared as simulated. Furthermore, several hepatic venous branches draining segments 5 and 8 appeared, consistent with our simulation. After the root of the middle hepatic vein (MHV) with the left hepatic vein was cut, left hepatic lobectomy with MHV was performed without exposing the tumors. A superficial tumor located in segment 7 was partially resected. Other tumors were treated with radiofrequency ablation.

Simulation with SYNAPSE VINCENT using CT-MRI fusion

In 2013, we developed a novel fusion imaging technique combining 3D-CT with MRI.[2,14] This software displays the spatial relationship among the hepatic arteries, portal vein, and bile duct in the hepatic hilum without performing 3D-CT cholangiography or drip infusion.[1,15,16] Moreover, the anatomical images can be shared among the surgical staff preoperatively. Miyamoto et al.[8] reported that integrated CT and MRI images are useful for recognizing anatomical anomalies, such an accessory bile duct from the caudate lobe to the common bile duct. Although this new method was of significant value for surgical planning for biliary cancer, these studies involved only a few patients; accordingly, the method should be confirmed with larger populations.[2,9,14]

[Case]

The case in Fig. 2 is a hilar cholangiocarcinoma, Bismuth type 3B. The tumor was located in the left hepatic bile duct, and dilatation of the left intrahepatic duct was found. Because CT is not appropriate for observations of the bile duct, the 3D CT images included no bile duct images (**Fig. 2A**). However, using this fusion method, the CT-MRCP combined image demonstrated the anatomical relationships between the portal veins, hepatic arteries, bile duct, pancreas, and liver (**Fig. 2B**). We were also able to simulate the limits of ductal resection without difficulty. According to this 3D simulation before surgery, we performed left hepatic lobectomy and extrahepatic bile duct resection.

Original software "Liversim"

Recently, several conventional 3D software applications have been in use in many hospitals and institutes in Japan. However, there are several problems with these applications. The 3D liver model is fixed and rigid, whereas the actual liver is non-rigid and becomes transformed during hepatectomy; furthermore, resection is not observable with rigid models. Accordingly, we developed a novel 3D virtual simulation system that represents the real-time deformation of the liver using a physical simulation.[17] First, an automatic tetrahedralization is applied to a polygonal mesh that represents the 3D geometry of the liver. A physical simulation based on the finite element method (FEM) is then applied to the tetra mesh.[18] The method of deformation is as follows: the surface of the liver and the operating point are connected, and then the operating point is pulled. In addition to this base simulation, we developed algorithms for two types of incision functions as follows: (1) cutting of the tetrahedral meshes is used for liver parenchyma resection; (2) cutting of the polygonal meshes is used for hepatic and portal veins cutting. These algorithms are implemented using the Sofa framework[19]. When we resect the 3D liver model, we place a simulated cutting line on the 3D liver in the display. The liver parenchyma is then resected at the set depth value. Pulling outward strings, which users have fixed on the liver surface of both sides of the incision line can open the cut surface of the liver model. On the cut surface, we can observe and cut the exposed blood vessels. Therefore, this novel software allowed us to perform real-time transformation and virtual hepatectomy prior to the real surgery.

Little difference in terms of the appearance of the resection process between the virtual hepatectomy with the Liversim and the real operation was found. Therefore, Liversim enabled noting the emergence of blood vessels (e.g., branches of the portal vein or hepatic vein) on the incision line of the liver before surgery. Regarding perioperative outcomes, there were no significant differences in operation time, bleeding amount, and number of hospitalization days between the Liversim and SYNAPSE VINCENT groups retrospectively.[17] That is, Liversim was as clinically effective as SYNAPSE VINCENT. To prospectively confirm the utility of Liversim, a randomized controlled trial comparing Liversim and SYNAPSE VINCENT is ongoing.

[Case]

This case is an extended posterior sectionectomy. The tumor was located at segment 7 according to Liversim (**Fig. 3**). On the resection line, we observed the hepatic vein branches that drain segments 5 and 8 in both Liversim and the actual surgery. Each branch was cut separately, and the anterior portal branch could then be observed. Furthermore, we observed the right hepatic vein on the cut surface, consistent with the simulation by Liversim (**Fig. 3**). The right hepatic vein was clamped and cut without exposing the tumor. Finally, the liver was resected.

A randomized controlled trial comparing Liversim and SYNAPSE VINCENT is ongoing, and we are currently expanding Liversim to pancreatic surgery. We can simulate pancreatoduodenectomy and distal pancreatectomy as well as the location of the main pancreatic duct before surgery. This technique will be very useful for safe pancreatic surgery.[9]

Features of each 3D liver surgery simulation

The above liver surgery simulation software programs and methods have their own advantages. SYNAPSE VINCENT has been widely used for preoperative 3D liver surgical simulation in Japan since 2012, when Japanese universal healthcare insurance began to cover 3D liver surgery simulation using 3D analyzing software for liver surgery SYNAPSE VINCENT was developed using topologic knowledge aimed at easy handling and timesaving for 3D reconstruction. Accordingly, compared with the other conventional software, only approximately half of the working time is needed to perform the 3D simulation.[7]

The integrated CT and MRI images helped us easily perform the preoperative surgical simulation for biliary surgery.[2,9,14] Because it is difficult to depict the bile duct, several institutions have developed 3D-CT cholangiography or drip infusion 3D-CT for use with patients with biliary cancer. However, there are reports of several problems with these radiological examinations, including side effects such as cholangitis or anaphylactic shock due to the infusion of the contrast material into the vein or bile duct.[2]This technology enabled us to assess the anatomical relationship among the bile duct, hepatic arteries, and portal vein without 3D CT- cholangiography or drip infusion 3D-CT.

Although the 3D-reconstructed liver using SYNAPSE VINCENT is fixed and rigid, Liversim can visualize real-time transformation of the 3D-reconstructed liver. Therefore, we can see the process of the surgical procedures before the actual surgery. In other words, we can preoperatively perform several rehearsals of the real liver resection.[17] Until now, no software that enables the visualization of the surgical process has been available.

3D-printed liver model

There have been several reports of the use of the 3D-printed models for living-donor liver transplantation, hepatectomy, cardiovascular surgery, and maxillofacial surgery.[20-23] Three-dimensional printing is more useful for understanding spatial relations than 3D models in a 2D display. However, because of the transparent loading material, the conventional 3D-printed model costs approximately $2,000, which is cost-prohibitive (**Fig. 4A**). Moreover, intrahepatic vessels are difficult to observe because of distortion due to light refraction. Therefore, we have developed a novel 3D-printed frame model (**Fig. 4B**).[23] Our novel 3D print is produced at a 50% scale and does not use transparent loading material. In addition, the liver surface is covered with several frames along its shape. The user can recognize the external forms by the frames and can see directly inside the structure. Accordingly, our model is less expensive and allows superior visualization. The total cost of the model is US $600, which includes not only materials but also labor, among other costs. The cost of only the materials is less than US $150. The frame along the liver surface is helpful for recognizing the spatial relationship between the tumor, blood vessels, and liver.[23] As indicated in a previous report, a 3D-printed liver model was useful for liver resection for a small tumor that was invisible by intraoperative ultrasonography.[22]

[Case]

This is a case of anatomical resection of segment 5 (**Fig. 5**). The white lines indicate simulated resection lines from different angles. We planned to resect the liver along the simulated line (**Fig. 5A**). In the actual operation, as we simulated beforehand, we cut and ligated several Glisson's sheaths of segment 5 and the hepatic vein. We extended the resection line along the right anterior Glisson's sheath. We carefully cut the Glisson's sheath branches of segment 5 to avoid injuring the posterior Glisson's sheath (**Fig. 5B**). Finally, the anatomical resection of segment 5 was completed without exposing the tumor.

Future prospects

As reviewed above, a computer-aided hepatobiliary-pancreatic surgical system has been successfully developed. The next step in CAS would be the application of virtual liver resection to a real-time surgery, similar to a car navigation system. To date, intraoperative ultrasound (IOUS) has been used during hepatectomy as real-time navigation. However, IOUS is not real-time navigation in the true sense. Real-time navigation, such as car navigation, means that a surgical field is visually mapped. Recently, several cases have been reported in which navigation systems with IOUS were used for open liver surgery.[13,24-30] In addition, several investigators have reported the development of surgical navigation systems for laparoscopic surgery.[31-42] Papers have described surgical navigation with an optically tracked mobile C-arm,[39] intraoperative ultrasound,[40] registration of surface patches reconstructed from a stereo laparoscope,[41] and the Polaris Spectra optical tracking system.[31,42] These articles demonstrate the prospective usefulness of surgical navigation in laparoscopic surgery.[42] For a system that presents a virtual laparoscopic view synchronized with the laparoscope view during surgery, patient-to-image registration is crucial for adjusting the coordination system between the CT image and the body. Thus, it is necessary to display the deformity of the organs and indicate accurate positional information. Although registration accuracy in surgical navigation is difficult to accomplish in general, future work includes the reduction of registration error. A more authentic surgical navigation system is expected to be developed in the future. Researchers in this field are currently working toward overcoming the above obstacles.

Conclusions

In conclusion, a novel CAS system continue to contribute to performing accurate hepatectomy and educating surgical residents and medical students.

ACKNOWLEDGMENTS

The authors thank all the members of the 3D-CG virtual operation unit of the University of Tsukuba for their kind support.

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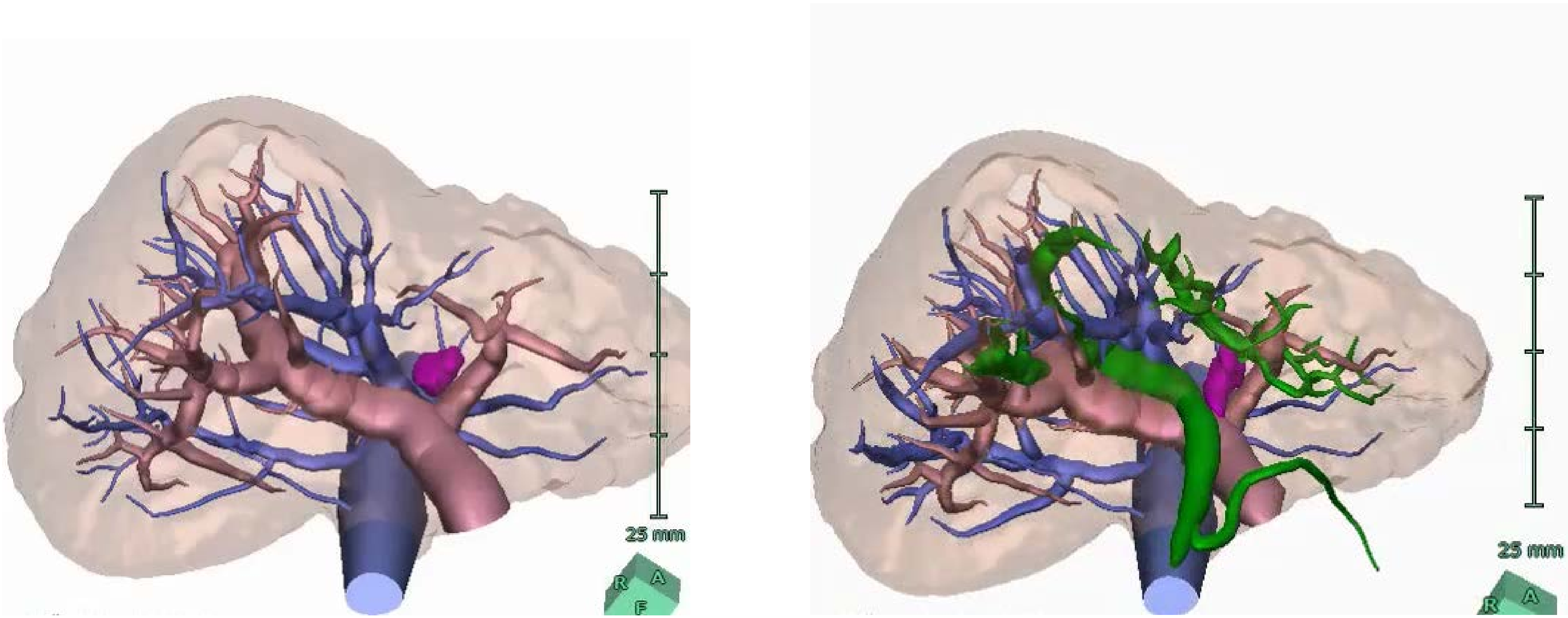
シミュレーション画像
Thickness :1.25 mm
120.0 kV
250 mA(800 msec)
肝臓の断面積: 76 cm²
全肝体積: 1172 ml
肝臓: 416 ml
下大静脈
門脈
静脈
腫瘍
左葉切除術後残肝: 756 ml (64.5 %)

A B

Fig.1



A

B

Fig.2

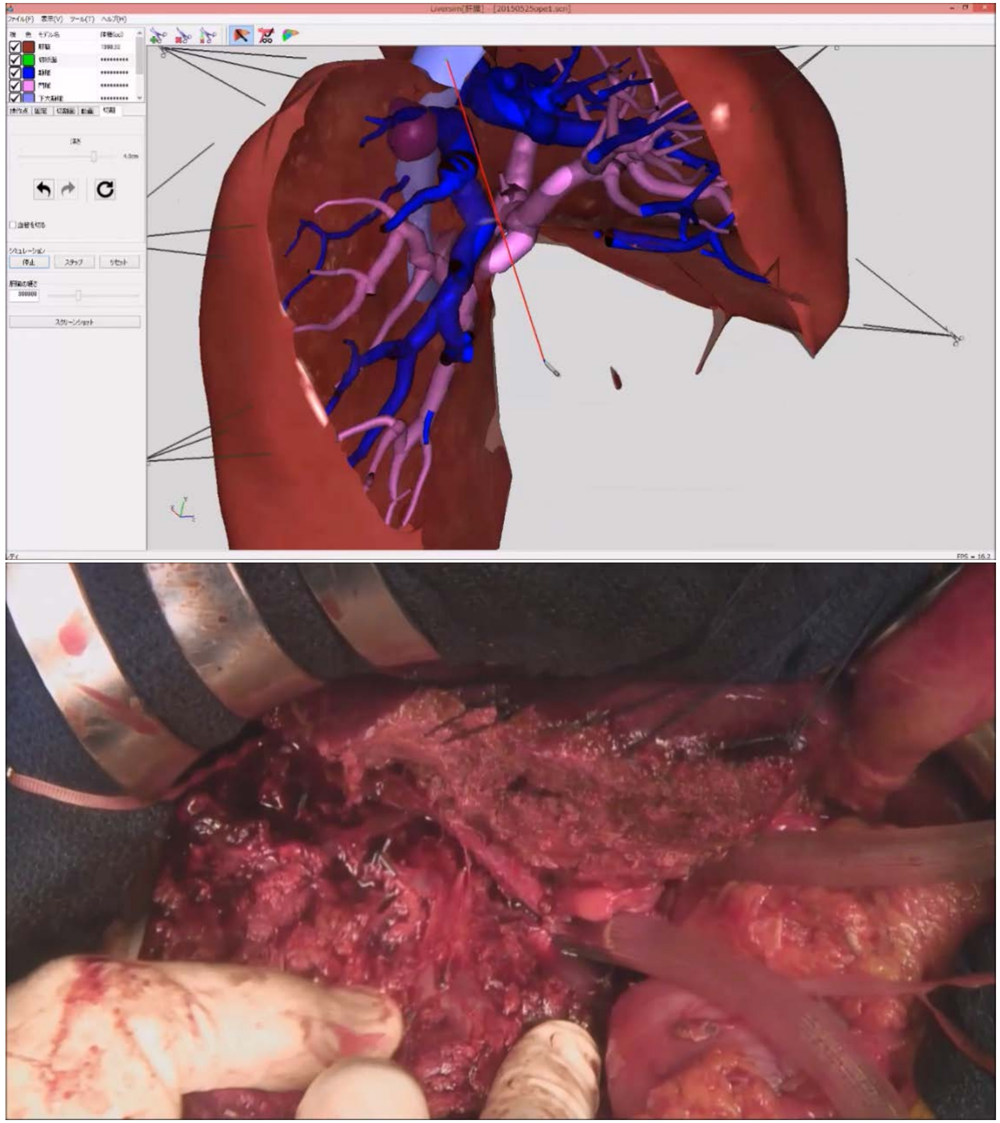
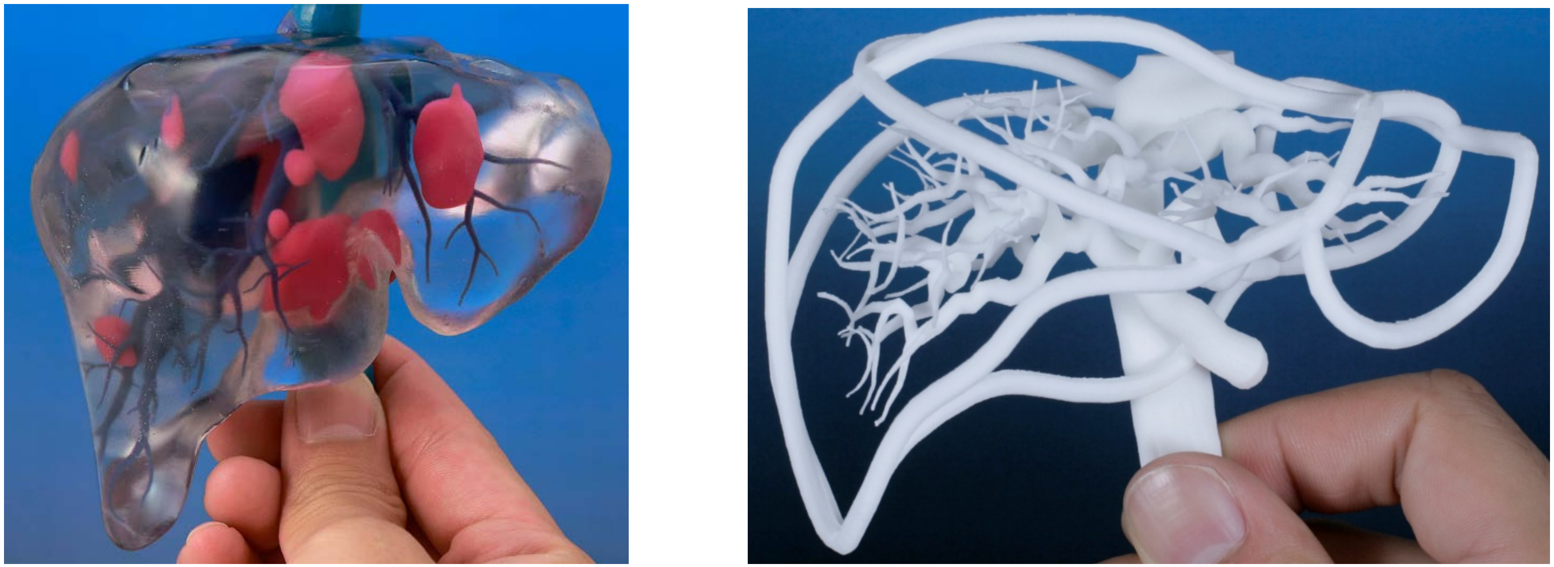
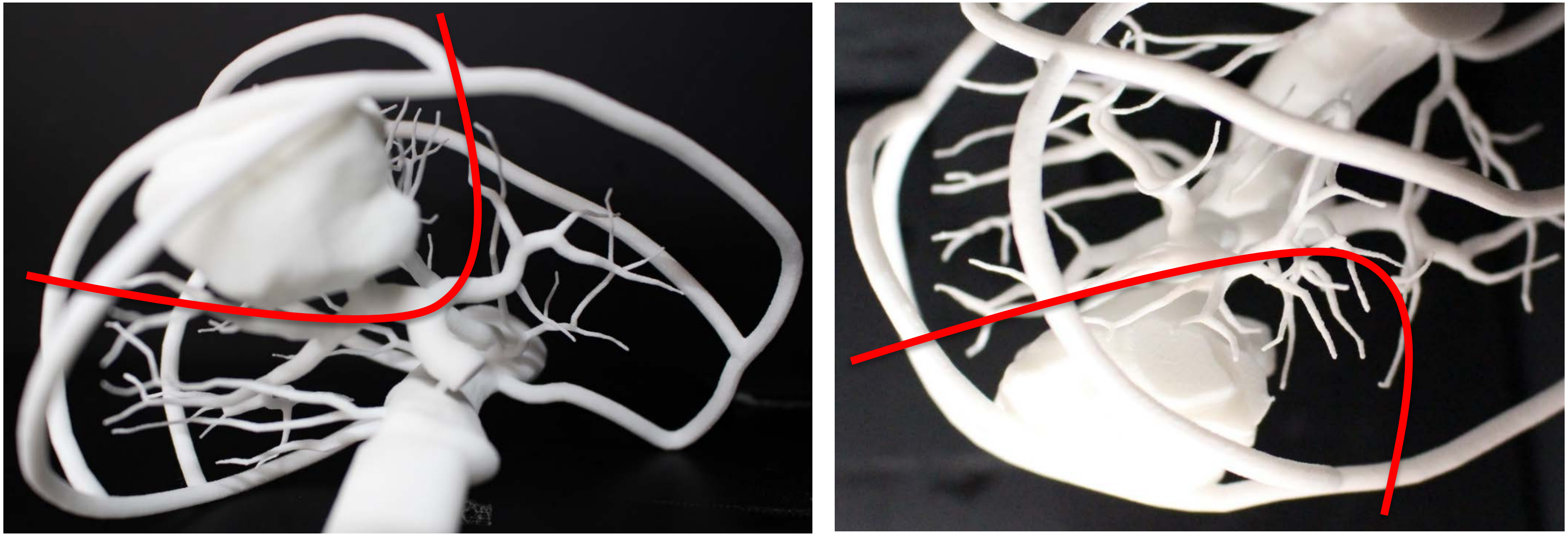


Fig.3



A B

Fig.4



A B

Fig.5