Three-Dimensional (3D) Printing: A Novel Tool for Surgical Planning and Intraoperative Guidance

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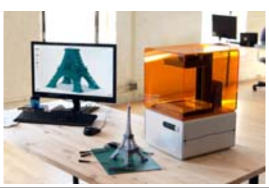
Disclosure

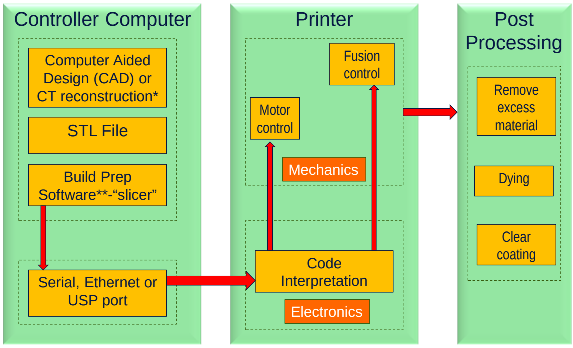
I have no conflict of interest in relation to this presentation

Definition

- 3D printing [also referred to as additive manufacturing (AM) and rapid prototyping (RP)] is a process of making 3D solid objects of virtually any shape from a digital model.



The Process



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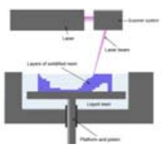
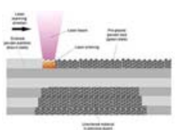
* MEVIS or TeraRecon
** Catalyst (FDM) or Objet Studio (polyjet)

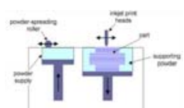
3D Printing Technologies



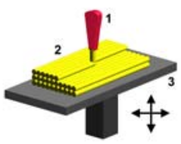
Stereolithography
- Laser cured liquid resin



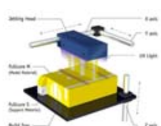
Selective Laser Sintering
- Laser sintered powder (metal, plastic)



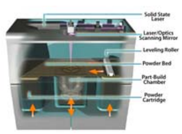
Powder/Inkjet
- Powder glued selectively via liquid binder



Fused Deposition Modeling
- Extruded liquid thermoplastic



Polyjet
- UV light cured liquid resin



Selective Laser Melting
- Laser melted/fused metal powder

3D Printers at CCF

Stratasys Connex 350 ("Polyjet")
- UV cured liquid resin
- 2 materials in same build
- Accuracy: +/- 0.04mm
- Flexible, Clear materials

Stratasys uPrint SE Plus ("FDM")
- ABS Thermoplastic
- Strong parts
- Accuracy: +/- 0.4mm
- Low cost

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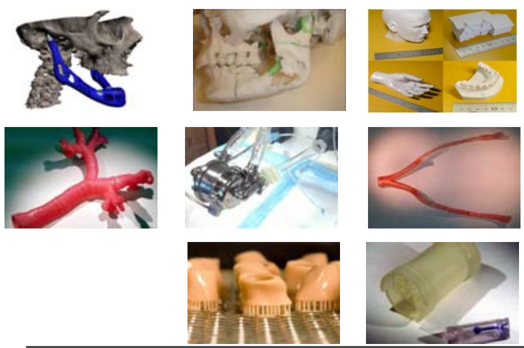
Stratasys Object500

Stratasys Objet500 (“Polyjet”)

- UV cured liquid resin
- Multi-materials in same build
- Multi-color in the same build
- Accuracy: +/- 0.02mm
- Flexible, Clear materials

3D Printing Examples in Medicine



Surgical Planning

- Fact: Great public, governmental and professional interest in improving surgical outcomes
- A wide-range of pre-operative planning techniques have been used to diminish operative time and complications:
  - –Imaging (CT, MRI, angiogram, biliary imaging, etc.)-2D
  - –Computer-assisted 3D imaging-viewed through 2D computer screen
  - –Generic physical models-not patient specific

Limitations in Liver Imaging

- Complex and overlapping vascular and biliary anatomies
- Lack of transparency of liver parenchyma interfering with intra-operative visualization of anatomical structures
- absence of reliable liver surface markers corresponding to hepatic segmentation
- Mobilization of the liver during surgery limits the utility of intraoperative imaging.

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Hypothesis

The production of a patient-specific, anatomically accurate physical model of the liver may overcome the limitations of 2D and 3D imaging and accordingly improve surgical outcomes

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3D Printing of Skull in Complex Cranio-maxillofacial Surgery Improved Outcome

- Prospective trial (45 patients) compared operative planning, measurement accuracy and operative time:
  - Standard imaging
  - Standard imaging + 3D printed model
- Patients-specific 3D printed models improved accuracy, lowered operative time and significantly improved understanding of spatial relationship of structures in critical anatomical areas.

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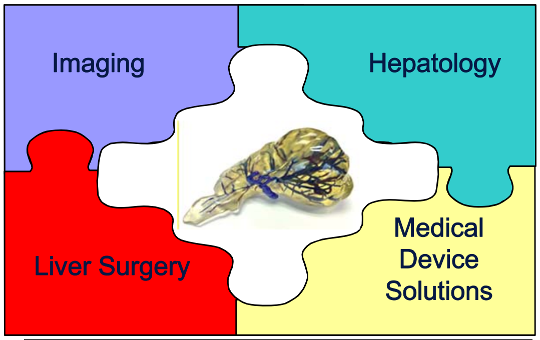
D'Urso PS, et al. J Craniomaxillofac Surg 1999

The Team: A Multidisciplinary Effort



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Objectives

1. Create the first patient-specific three 3D printed liver based on standard 2D imaging (CT and MRI)
2. Validate the accuracy of 3D-printed liver models against native resected liver specimens
3. Assess the utility of individualized 3D printed livers in surgical planning and medical education.

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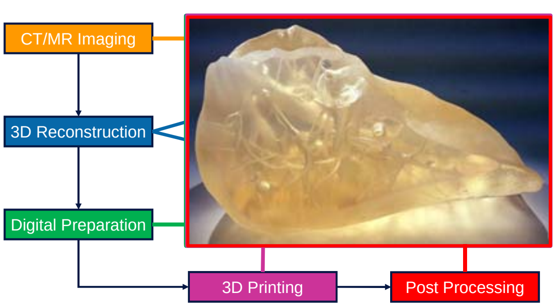
Objective #1: 3D Liver Model Production



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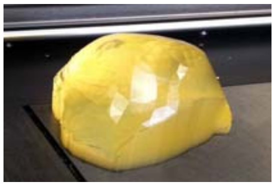
Post Processing



As printed After cleaning

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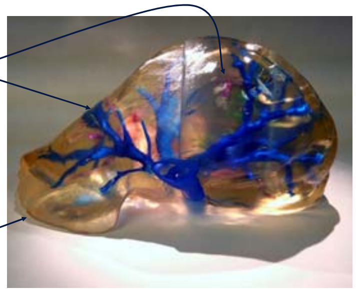
Final Post-Processing

- Dyeing vessels for improved contrast
- Clear-coating for improved transparency



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Objective # 1

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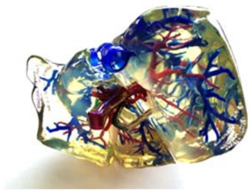
Improved Real-Size Version

- ➢ Dyeing Vasculature & Biliary Tree for Improved Contrast:
  - •Blue: Hepatic Vein
  - •Purple: Portal Vein
  - •Red: Hepatic Artery
  - •Green: Bile Duct
- ➢Clear Coating for Greater Transparency and Better Preservation



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Objective # 2: Accuracy Validation

- 3D-generated models were compared to:
  - ➢Native livers intra-operatively
  - ➢CT sections before surgery
  - ➢Gross pathology slices after surgery
- Measurements
  - –Overall shape, vasculature and biliary anatomy
  - –Linear Measurements
  - –Volumetric measurements

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LDLT, Total Right Lobectomy
Healthy Donor to His Brother with Cryptogenic Cirrhosis

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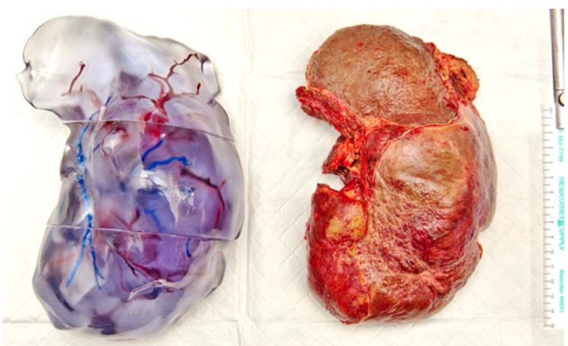
Zein NN, Hanouneh IA, Bishop PD, et al. Three-dimensional print of a liver for preoperative planning in living donor liver transplantation. Liver Transpl 2013;19:1304-10.

PSC-Cirrhosis



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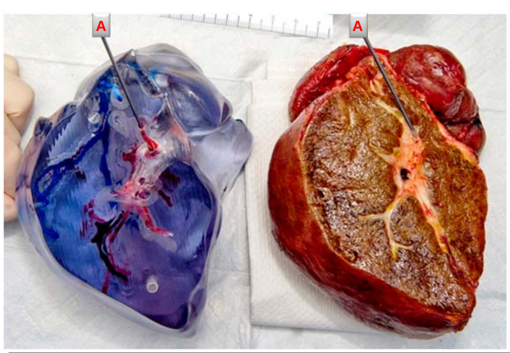
Pathology Validation

PSC-Cirrhosis



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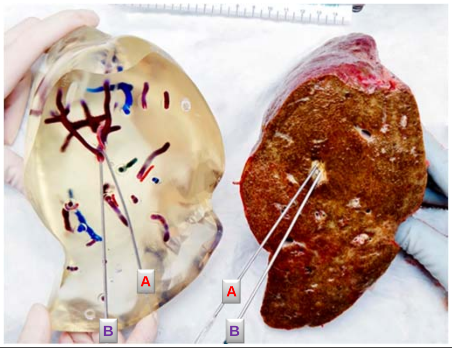
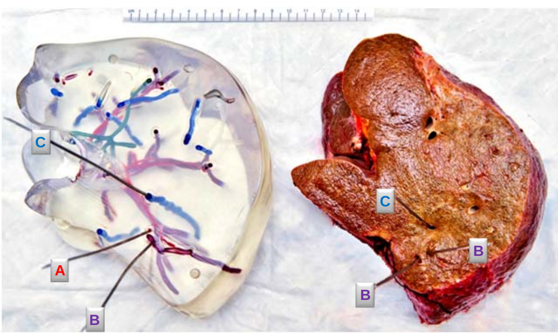
A= Hepatic Artery **Pathology Validation**

PSC-Cirrhosis

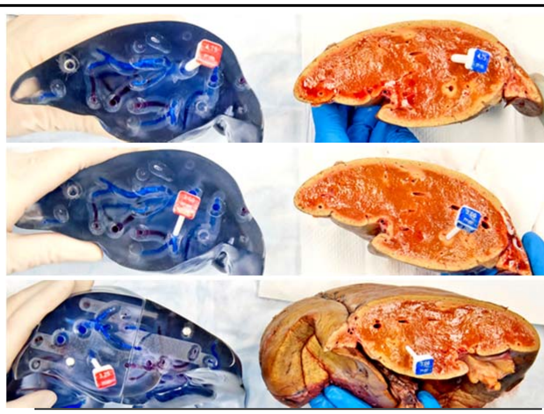


Cleveland Clinic A= Hepatic Artery; B= Portal Vein

PSC-Cirrhosis



Cleveland Clinic A= Hepatic Artery; B= Portal Vein; C=Hepatic Vein



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LIVER TRANSPLANTATION 00:00-00, 2013

ORIGINAL ARTICLE

Three-Dimensional Print of a Liver for Preoperative Planning in Living Donor Liver Transplantation

Nizar N. Zein,[1] Ibrahim A. Hanouneh,[1] Paul D. Bishop,[2] Maggie Samaan,[1] Bijan Eghtesad,[3] Cristiano Quintini,[3] Charles Miller,[3] Lisa Yerian,[4] and Ryan Klatte[5]
[1]Department of Gastroenterology and Hepatology, Digestive Disease Institute, [2]Department of Vascular Surgery, Heart and Vascular Institute, [3]Department of Hepato-Pancreato-Biliary and Transplant Surgery, Digestive Disease Institute, [4]Department of Anatomic Pathology, Pathology and Laboratory Medicine Institute, and [5]Medical Device Solutions, Lerner Research Institute, Cleveland Clinic, Cleveland, OH

The growing demand for liver transplantation and the concomitant scarcity of cadaveric livers have increased the need for living donor liver transplantation (LDLT). Ensuring the safety of donors and recipients is critical. The preoperative identification of the vascular and biliary tract anatomy with 3-dimensional (3D) printing may allow better preoperative surgical planning, avert unnecessary surgery in patients with potentially unsuitable anatomy, and thereby decrease the complications of liver transplant surgery. We developed a protocol and successfully 3D-printed synthetic livers (along with their complex networks of vascular and biliary structures) replicating the native livers of 6 patients: 3 living donors and 3 respective recipients who underwent LDLT. To our knowledge, these are the first complete 3D-printed livers. Using standardized preoperative, intraoperative, and postoperative assessments, we demonstrated identical anatomical and geometrical landmarks in the 3D-printed models and native livers. *Liver Transpl 000:000-000, 2013*. © 2013 AASLD.

Received July 22, 2013; accepted July 26, 2013.

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Objective # 3

APPLYING 3D LIVER MODELS TO CLINICAL PRACTICE

- Living Donor Liver Transplantation
- Hepatic Tumor Resection
- Medical Education

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LDLT

- Case #1: Middle hepatic vein curved and too close to resection plane in the donor.
- Case # 2: Rejected donor based on length of R hepatic artery (too short for anastomosis

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Resection for HCC

- Hepatic resection is considered the most curative approach for hepatic tumors.
- Characterization of intrahepatic anatomy, lesions size, number, location and proximity to vascular and biliary structures is critical to achieve cure.
- Traditional imaging modalities, including 2D CT & MRI, provide limited information on the tumor's extent and its relationship with surrounding vessels for complex hepatic resection planning.

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Difficult to Resect Liver Tumors

- Defined as:
  - ➢Extended right/left hepatectomies
  - ➢Central resections
  - ➢Polysegmentectiomies
  - ➢Large atypical resections
- We evaluated the asset of 3D-printed liver models for surgical preplanning and intraoperative guidance.

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AIMS

- Compare 2D imaging (CT or MRI) to 3D printed liver models for preoperative surgical planning and intraoperative guidance:
- Determination of resectability
- Changes in operative strategy

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Patients & Methods

- Prospective study (Jan-Aug 2014) of 6 patients with liver tumors, who underwent high-risk procedures for complex liver tumors.
- 3 patients with central intrahepatic cholangiocarcinoma, 1 patient with Klatskin tumor, and 2 patients with metastatic colon cancer into the liver.
- Median lesion size 7.1 cm.

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Results: Pre-Op

- In 3 of the 6 cases, the pre-operative plan was modified after review of anatomical spatial relationship of tumor to nearby structures in the 3D model compared to initial plan based on standard imaging alone.
- Changes included:
  – resection modification,
  – extension and intrahepatic vascular reconstruction.

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AASLD Abstract

Results: Intra-Op

- Surgeons reported greater confidence with use of 3D model for identification of intra and extrahepatic structure, segmentation and tumor specific extent.
- Surgeons agreed that 3D model offered a realistic representation that allowed interactive manipulation simulating intraoperative mobilization.

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AASLD Abstract

A Case: 56 year old Female

- 4/2013: Developed **pruritis** of extremities and torso.
- 6/2013: Lab work → **Transaminitis and elevated liver tests**
  Abd MRI → L lobe hepatic mass (9 cm), likely malignant. The mass abutting the IVC and hepatic veins with encasement of L and middle hepatic veins. Market L sided biliary dilation
- 7/3/13: **CT Guided Biopsy**: poorly differentiated adenocarcinoma consistent with **primary cholangiocarcinoma**.

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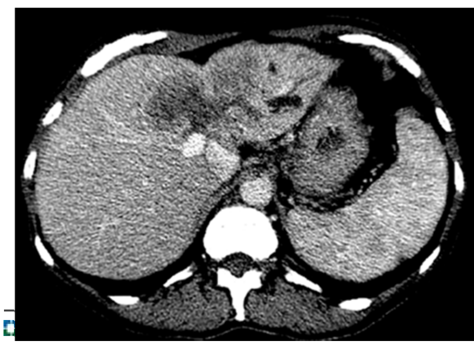
CT diagnostic Pre-chemotherapy



Outside Institution

- Based on all testes, patient was evaluated at Rosewell Park, and tumor was determined unresectable.

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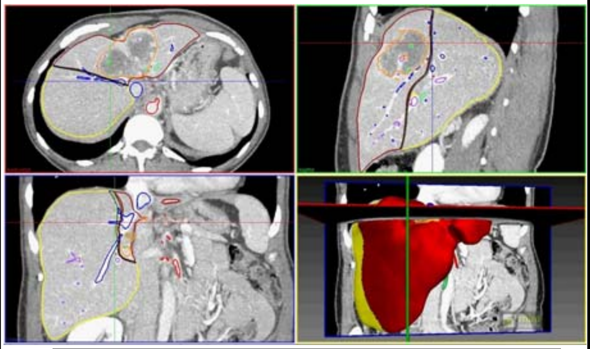
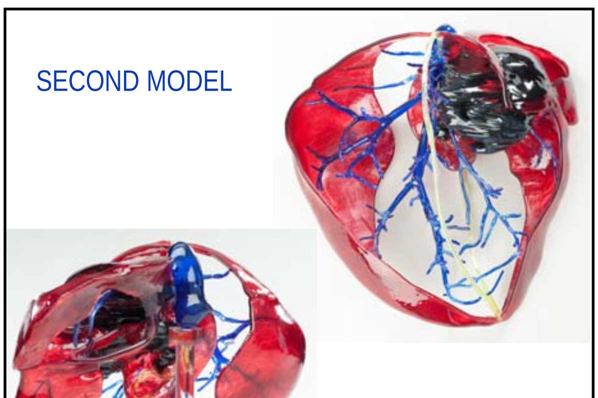
CCF: 3D Liver Model



FIRST MODEL

SECOND MODEL



The Plan

- Total hepatectomy:
  - Ex-vivo left trisegmentectomy and reconstruction of the RHV and IVC using cryopreserved femoral vein graft
  - Intraoperative radiation therapy to the HA nodal region
  - Auto implantation of the right lobe remnant of the liver
  - Roux-en-Y hepaticojejunostomy.

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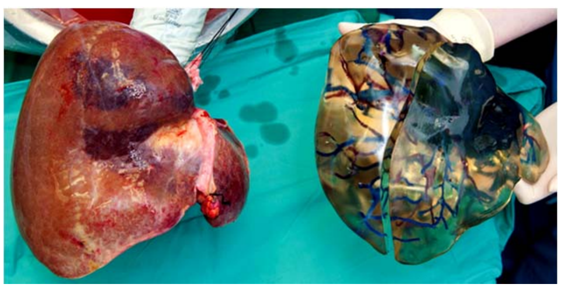

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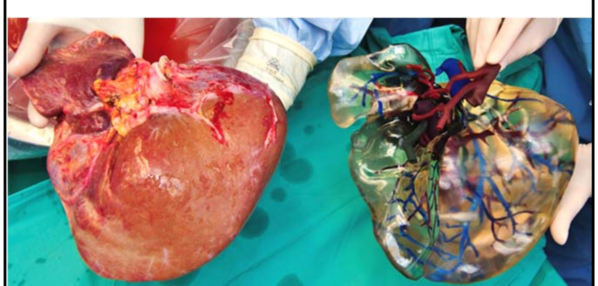

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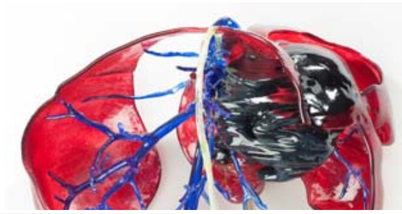

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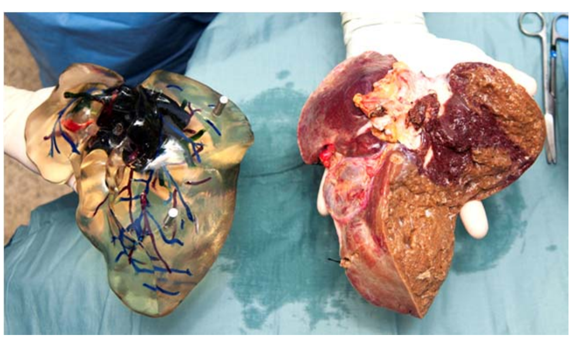
Resected Specimen with Tumor



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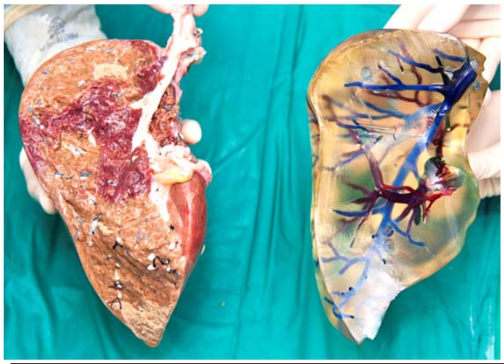
Remnant Liver with Venous Reconstruction



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Exploring

Teaching

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Radiology Teaching

- Interpretation of CT/MRI requires 3D visualization skills of the complex spatial relationships between structures.
- Classic medical education relies on cadaveric dissection and 2D visual representations.
- Detrimental increase in cognitive load and less retention in students with limited innate spatial visualization abilities.
- Existing physical anatomical models are limited by their inability to completely replicate reality.

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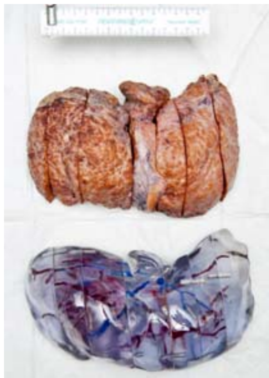
Preece, D., *et al. (2013). ""Let's get physical": advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy." Anat Sci Educ* ***6(4): 216-24.***

Teaching Case

- Cryptogenic Cirrhosis
- Pathology Validation
- CT Interpretation
- Anatomy Identification
- 7 Slices/ 7 Blocks
- 100% scale
- 3D-model/ Explanted-pathology/ CT-with outline/ CT-without outline



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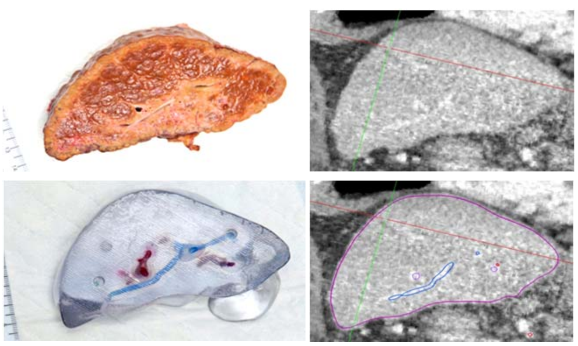

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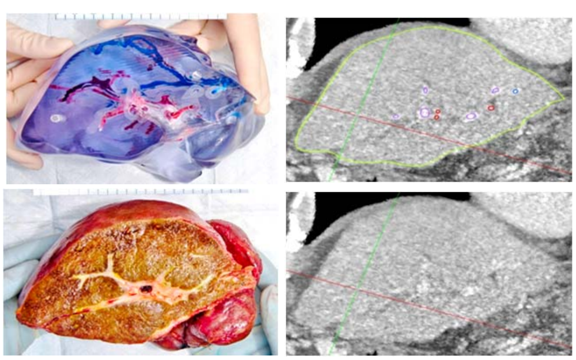

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Innovations in Medical Education: Case Western Reserve University

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Bio-3D Printing?

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Conclusions

- Transparent 3D-printed models used for surgery granted:
  - Easier segmentation
  - Better comprehension of spatial relationships
  - Higher confidence levels among surgical staff
- 3D-printed models may provide a novel educational tool

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Every life deserves world class care.