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

Controller Computer
- Computer Aided Design (CAD) or CT reconstruction*
- STL File
- Build Prep Software** ("slicer")
- Serial, Ethernet or USB port

Printer
- Fusion control
- Electronics
- Code Interpretation

Post Processing
- Remove excess material
- Dying
- Clear coating

* 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)
- PowderJet
  - 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
Stratasys Object500

Stratasys Object500 ("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.

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.

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.

The Team: A Multidisciplinary Effort

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.

Objective #1: 3D Liver Model Production
Post Processing

As printed | After cleaning

Final Post-Processing

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

Objective # 1
**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

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


PSC-Cirrhosis
Pathology Validation

PSC-Cirrhosis
A= Hepatic Artery Pathology Validation
PSC-Cirrhosis

Measurement Pins, Pathology Validation

A= Hepatic Artery; B= Portal Vein; C=Hepatic Vein
Objective # 3

APPLYING 3D LIVER MODELS TO CLINICAL PRACTICE

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

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)
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.

Difficult to Resect Liver Tumors

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

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
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.

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.

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.
A Case: 56 year old Female

- 4/2013: Developed pruritis of extremities and torso.
- 6/2013: Lab work → Transaminits 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.

CT diagnostic Pre-chemotherapy

Outside Institution

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

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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Innovations in Medical Education: Case Western Reserve University

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