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TISSUE REALISTIC ANTHROPOMORPHIC ABDOMINAL PHANTOM FOR RADIOGRAPHY – 3D PRINTING

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INTRODUCTION

Three dimensional (3D) printing is an exciting tool in patient centered precision medicine. Useful applications for 3D printing tools have been developed in medical education and for surgical planning. However, 3D printing is not commonplace in medical imaging (MI) departments. A successful 3D printing program in MI requires the close collaboration of a multi-disciplinary team that includes the radiologist, technologist, medical physicist and the biomedical engineer. This case study successfully demonstrates multi-disciplinary collaboration in designing and constructing an abdominal phantom with realistic radiological and anatomical structural properties utilizing 3D printing methods and appropriate materials.

DESIGN AND CONSTRUCTION

The abdominal phantom design is a combination of purchased components, 3D printed organs and components fabricated by material based-sculpting and modeling. More specifically the outer shell, spine and pelvis purchased, the abdominal organs were 3D printed and the muscle and fat were fabricated.

A) OUTER CASING

A commercially available hollow clear plastic full body mannequin was used as the phantom shell to house all the abdominal organs, shown in Fig-1(a). The mannequin is made from polycarbonate, a transparent, impact resistance, stiff thermoplastic capable of withstanding heating of up to 155 degrees Celsius. An opening was made anteriorly measuring 20 cm x 30 cm to access the inside of the mannequin, as shown in Fig-1(b). The thoracic and femoral portions of the phantom were not used for the x-ray field and filled with high density liquid urethane foam (FlexFoam-iT! ® polyurethane foam manufactured by Smooth-ON Macungie, PA). The phantom shell was then ready to house abdominal organs, bony structures, and muscle and fat components.

Fig-1: On left (a), empty mannequin; and on right (b), thoracic and femoral portions filled with polyurethane foam.

B) 3D PRINTING OF THE ABDOMINAL ORGANS

The process of building the abdominal organs is described in this section.

Step 1: Image Acquisition

Computed tomography (CT) was used to acquire image data due to its high contrast, signal-to-noise ratio and spatial resolution. An anonymized contrast enhanced CT scan of abdominal/pelvis was selected to extract the DICOM imaging data used to create the organs [2].

Step 2: Organ Segmentation

The DICOM data from the contrast enhanced abdomen scan was loaded into Slicer software (v. 4.7.0) and then cropped to just include the organ of interest. To accurately segment each organ, manual tracing was utilized to trace each organ and internal vessels slice by slice (Fig-2a). Only certain tissues were considered to be relevant to form the shape of organ.

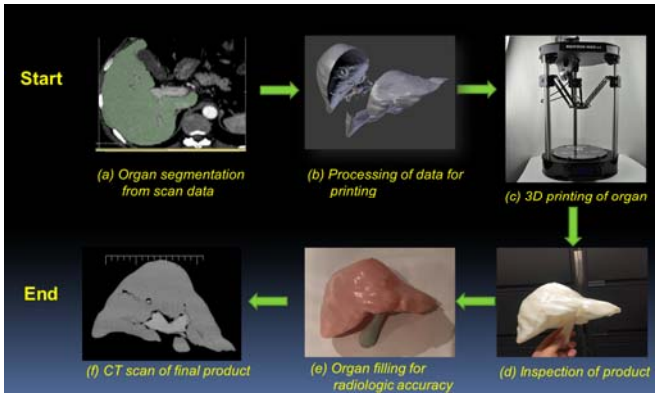

Fig-2: 3D Printing Step by Step Process

Step 3: Image Post Processing:

The 3D DICOM volume data was then converted into Standard Tessellation Language (STL) format. Further the STL files were refined using an open source computer-aided design (CAD) software called Blender (v.2.78) [3]. This process consists of "closing" open gaps, smoothing out surfaces, and adding support structures. Further editing of the mesh was necessary to produce hollow shells. These shells could later be filled with the appropriate material to would the mimic x-ray properties of real organs. Finally the organ was sectioned into smaller portions in order to make printing possible and to fit on the build plate.

Step 2: 3D Printing

The printer used was a Rostock Max V2 printer which utilizes the fused deposition modeling (FDM) technique. It is equipped with a 0.5 mm nozzle, and has a minimum layer height of 0.0125 mm and an X and Y-axis Resolution of 100 microns (0.1 mm). In this work, the layer height was set to 0.2 mm for increased speed of printing, giving it a Z resolution of 0.2 mm (200 microns).

Careful consideration was given to ensure that the final model will match the clinical interpretation of the radiological images. 3D printed abdominal organs were produced as shells with empty internal structures. ABS plastic was the selected 3D printing material for the organ shells because it appears similar to fat in a CT scan image. The shell of the liver, kidneys, spleen and the large and small colon were 3D printed with thicknesses of 1 - 1.75 mm. Major internal structures (vessels, including parts of inferior vena cava) within the liver and the kidneys were preserved while constructing the 3D model using software, prior to printing, as an example printed kidney cross section is shown in Fig-3

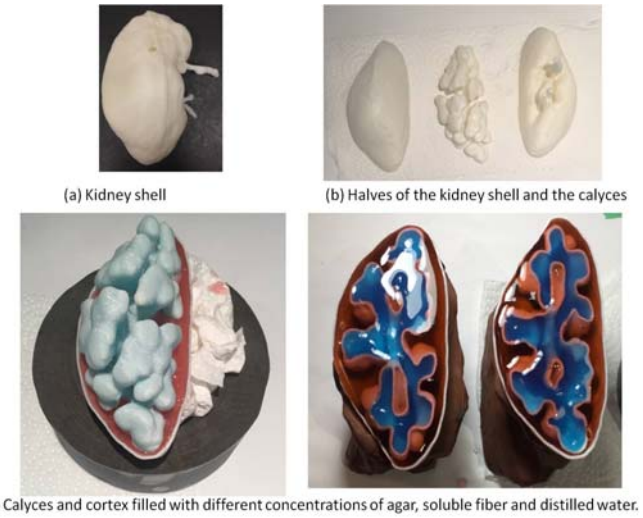

Fig-3: The insides of the printed kidney

The internal spaces of the organs were kept completely empty to be filled with matching attenuating compound. The internal structures were filled with an experimentally determined solidified solution of distilled water, agar, soluble fiber and water soluble iodine to enhance and characterize the radiological densities of each organ and its internal structures. Composition and attenuation in Hansfield Units (HU) is for the materials used are given in Table-1. The shells were then closed with water tight seals.

Table 1*: Comparison of the obtained and target CT attenuation for the organs in HU*

Organ	Obtained Contrast	Composition
Kidney (R + L)	Outer Cortex 40 HU Inner Calyces 20 HU	Outer Cortex 300 mL distilled water 2.5% agar 12% soluble fiber Inner Calyces 350 mL distilled water 2.5% agar 6% soluble fiber
Pancreas	30 HU	Flexible Urethane Rubber (Smooth-ON, Clear FlexTM 50 Series)
Spleen	20 HU	350 mL distilled water 2.5% agar 6% fiber
Liver	40 HU	1.6L of agar solution 1.5 L distilled water 2.5 % agar 3.5% soluble fiber 0.3 % aqueous iodine
Liver vasculature	90 HU	10 mL of iodine contrast 60 mL of distilled water 10 mL of iodine contrast in 1000 mL water = 90 HU's
Fatty Tissue	-100 HU	Modeling Beeswax (mixture of beeswax, olive oil and lanolin cream)

Step 3: Fabrication of the Organs
The construction filling of liver shell with agar mixture is shown in Fig-4.

Fig-4: Filling of liver shell; food coloring helped illustrate level of the liquid to fill entire organ. The opening was sealed with plastic glue to contain agar mixture.

The large and small intestine were filled with mixture of agar and fibers. Small pocket of air were introduced to mimic real organs. Fig-5 shows the printed model.

Fig-5: illustrated 3D printed model of the large and small intestine.

Step 4: Adding the Bones
The right and left hemi pelvic bones were purchased from 3B Scientific, these were artificial bones called ORTHO bones, demonstrating radiopaque properties. Inside the phantom, the two hemi pelvic bones were joined together to make a full pelvic bone. In addition, a complete synthetic lumbar spine with radiopaque properties was purchased from the Sawbones Company (Vashon Island, WA). The lumbar spine was joined with the pelvic bone (see Fig-6).

Fig-6: shows lumbar spine and the pelvic bone.

Step 6: Fabricating the Fatty Tissue & Muscle
To mimic fatty tissue surrounding the abdominal organs, modeling beeswax was used. Modeling beeswax is beeswax with a mixture of olive oil and Vaseline (or lanolin) cream, this mixture provides a soft dough textured substance which can be used for

surrounding the organs. Lightly heating liquefies it and it solidifies at room temperature. The liquefied molding beeswax can be poured around the organs in a container and will solidify and hold its structure, allowing us to create an abdominal phantom with fatty tissue and organs. The modeling beeswax is also approximately -100 HU's when scanned using CT. This is similar the HU values of the abdominal tissues.

The psoas muscles were mimicked with a clear, flexible urethane liquid rubber called ClearFlexTM 50 from Smooth-ON (Macungie, PA). This type of liquid rubber requires the mixing of two component parts at room temperature onto the desired surface and has a curing time of approximately 24 hours. The same material was also used to mimic bilateral multifidus muscle and the erector spine muscles of the lumbar region.

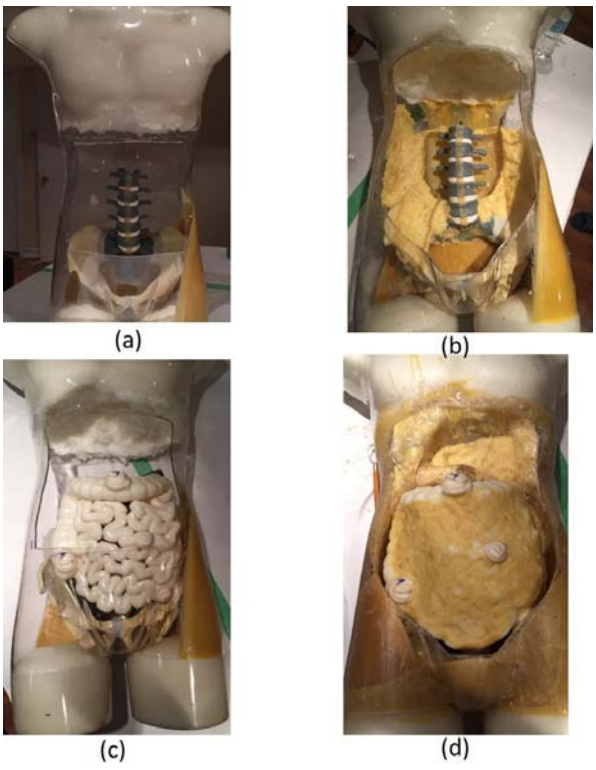

Fig-6: Stages in completing the phantom
(a) Shell, bony structures and muscle.
(b) Insertion of abdominal muscles
(c) Insertion of Insertion of internal organs
(d) small and large intestine and completion with muscle and fat layers

RESULTS / DISCUSSION

The resulting phantom demonstrated a qualitative and quantitative structural match in terms of accuracy in tissue CT attenuation (HU values) [4]. The HU values for the organs were: Liver: 38+15, Spleen: 26+12, Kidney cortex: 52.5 + 11, Kidneys calyces: 35+10, pancreas: 54.5+13, muscle: 54.5+13, pelvis: 575+22.

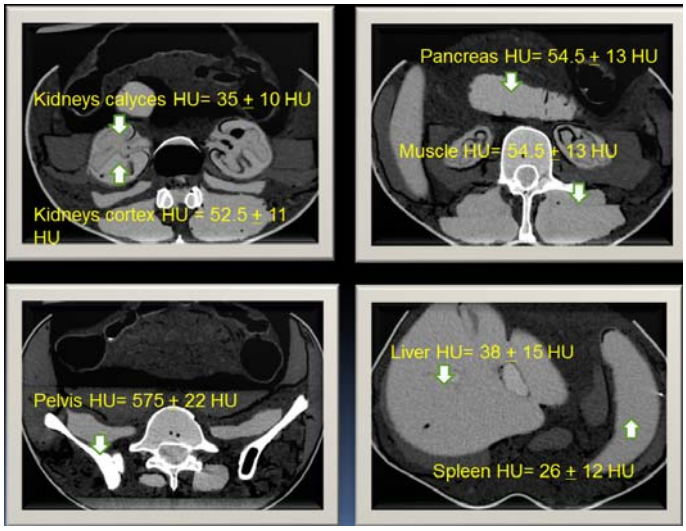

Fig-7: Qualitative structural match and quantitative match of radiological properties

CONCLUSION

Case study demonstrated successful completion of a complex 3D printing of abdominal phantom with tissue specific radiological properties and with anatomical details. The open abdomen phantom concept allow user to remove and replace the organs or place foreign bodies inside the abdominal cavity to simulate an operating room scenario.

References:

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[4 CT Hounsfield Numbers of Soft Tissues on Unenhanced Abdominal CT Scans: Variability Between Two Different Manufacturers' MDCT Scanners. Lamba R, McGahan JP, Corwin MT, et al. AJR American journal of roentgenology.2014;203(5):1013-1020. doi:10.2214/AJR.12.10037.