Abstract

Introduction

Liver surgery is widely used as a treatment modality for various liver pathologies. Despite significant improvement in clinical care, operative strategies and technology over the last few decades, liver surgery is still risky and optimal preoperative planning and anatomical assessment are necessary to minimize risks of serious complications. 3D printing technology is rapidly expanding and its applications in medicine are growing, but its applications in liver surgery are still limited. This article describes development of models of hepatic structures specific to a patient diagnosed with an operable hepatic malignancy.

Methods

Anatomy data was segmented and extracted form CT and MRI liver of a single patient with a resectable liver tumour. The digital data of the extracted anatomical surfaces was then edited and smoothed resulting in a set of digital 3D models of the hepatic vein, portal vein with tumour, biliary tree with gallbladder and hepatic artery. These were then 3D printed.

Results

The final models of the liver structures and tumour is provide good anatomical detail and representation of the spatial relationships between the liver tumour and adjacent hepatic structures. It can be easily manipulated and explored from different angles.

Conclusions

A graspable, patient specific, 3D printed models of liver structures could provide an improved understanding of the complex liver anatomy, better navigation in difficult areas and allow surgeons to anticipate anatomical issues that might arrive during the operation. Further research into adequate imaging, liver specific volumetric software, and segmentation algorithms are worth considering to optimize this application.

Introduction

Liver surgery is a mainstay of treatment for a variety of pathologies varying from primary hepatic and metastatic cancer[1] to congenital diseases. The unique regenerative properties of the liver combined with innovative neo-adjuvant strategies, allow successful resection in selected patients with increasingly greater disease burden[2–4]. Although significant improvements in surgical technique, diagnostics, postoperative care, patient choice[5], and surgical training[6], have been made over the last few decades, liver surgery carries considerable mortality and morbidity risks[7,8] due to surgical complications, or cancer recurrence[5,9]. Due to the complex anatomical nature of the liver, adequate preoperative planning is imperative to minimise complication and recurrence rates, whilst preserving liver function[7,10,11].

Current practice relies on contrast CT and magnetic resonance (MRI) imaging techniques to assess tumour extent, spread, and liver arterial supply as well as biliary, portal and hepatic venous drainage[7,12]. Liver volumetry utilises CT scan data to assess the volume of the remnant liver segment(s) and to estimate each patient's liver regeneration potential and has been used for some years to predict the remnant liver volume and assess the need for additional interventions to prevent life threatening liver failure[13].

Current image- based computer technology allows for virtual surgical rehearsal where different resection planes can be evaluated virtually under realistic anatomic conditions[14]. Rapid prototyping, or 3D printing, is rapidly growing with increasing numbers of applications in medicine[15,16]. A recently published study, where several 3D liver models

based on CT scan data of liver transplant recipients and donors, found these replicas to be highly accurate when compared to anatomical specimens during surgery[11,15].

A 3D graspable model of liver structures based on patient's radiological data could aid preoperative planning by providing anatomical detail and insight into the spatial relationship between various structures within the liver. A graspable physical model could further aid the hepatectomy rehearsal process by allowing the surgeon to test the technical aspects of the resection and practice manual skills proficiency in an open or laparoscopic access environment. This article reports our experience with a development of a patient specific liver model for use in surgical planning.

Methods

Data Extraction and Segmentation

Retrospectively collected radiology image data from a patient with an operable malignant hepatic tumour consisted of a standard CT angiogram of abdomen and pelvis and MRI of liver performed using a standard hepatic imaging protocol with gadolinium contrast. The CT slides were 3mm thick and MRI slides were 8.99 mm thick, both yielding anisotropic voxels when viewed as 3D. The data of both scans was stored in Digital Imaging and Communications in Medicine (DICOM) files. Amira 4.5.4. visualisation software (FEI, Hillsboro, USA) was used to view and segment the data. All scans were interrogated in three planes and pixels containing image data for hepatic and portal veins, hepatic artery, biliary structures and tumour were manually selected. (Figure 1). Due to varying image quality between the two radiology modalities used, MRI data was used to segment the biliary tree, portal vein, hepatic veins and tumour, whilst the CT was used to collect data for the hepatic artery. Segmentation was completed with a combination of manual, and "region growing" techniques, where the latter was used for large regions of similar density signal.

Surface extraction and model processing

Surface extraction of segmented data into digital 3D model was performed automatically using the Amira software. The final digital models consisted of a 3D mesh made up of many thousands of polygons. Automatic smoothing was applied via an algorithm to the digital surface models to reduce the number of polygons, improve the models' appearance and render the surfaces more computationally effective (Figure 2). The model data were exported into a 3D design software- 3ds Max 2014 (Autodesk, San Rafael, USA), where manual editing of polygonal mesh structures to repair all artefacts took place, in order to made the models printable. Once the models were rendered free of errors, the data was converted to data was converted to a .STL – a format compatible with 3D printers.

3D printing

The .STL file of the final digital dataset was delivered electronically to the Laboratory of Rapid Prototyping at the University of Strathclyde, Glasgow, where the 3D printing was carried out using the Object Eden 350V printer (Stratasys, Rehovot, Israel). Two materials were used for manufacture. The models of the biliary tree with gallbladder and the hepatic artery were manufactured using TangoPlus (Stratasys, Rehovot, Israel), and the models representing the hepatic veins, liver tumour and the portal vein were printed using TangoBlack (Stratasys, Rehovot, Israel). Each structure was printed en-bloc, surrounded by a gel-like support structure to protect overhanging parts of the model during the printing process (Figure 3). Once printed, the models underwent post-manufacture processing which included removal of the support structures with pressured water jet, and painting.

Results

The CT and MR image data contributed to the generation of four separate graspable 3D models of anatomical liver structures: portal vein, hepatic veins with tumour, gallbladder with biliary tree, and hepatic artery. Segmentation allowed for surface extraction of all the structures of interest from the CT and MRI scan data. The resulting digital model was then edited to repair the artefacts in the polygonal structures, and render it printable.

The digital model representing the hepatic artery required minimal manual editing, apart from minor smoothing and polygon error repair, whilst the digital models representing the biliary tree with the gallbladder, as well hepatic and portal veins had a significant number of artifacts including gaps in the polygonal wall, and an irregular block-like appearance. Once mesh editing was applied to the extracted surface models, they appeared more realistic and resembled closely anatomical structures in the CT and MRI scans (Figure 4).

The final, edited models were printed as four separate objects: gallbladder and biliary tree, hepatic veins with liver tumour, portal vein, and hepatic artery. All models, except the hepatic artery, were in 1:1 scale; the hepatic artery model was slightly larger. The models were produced using two different materials: gallbladder and biliary tree, and the hepatic artery were printed with a semi-transparent TangoPlus, which gave the models a soft, rubbery, and elastic texture. The models of the hepatic veins with tumour and the portal vein were printed with Tango black, giving the object a more rigid texture. Once painted, the models closely resembled the anatomical structures visible on image data, and could be easily handled and manipulated from all angles (Figure 5).

Discussion

In this paper we describe manufacture of 3D printed models of liver structures based on CT and MRI data of a specific patient diagnosed with an operable liver tumour. The 3-D printed models allow detailed representation of the anatomical structures of the liver vasculature and biliary tree, and their relationship with the liver tumour. The resulting models could complement preoperative planning of hepatic resection by displaying the complex geometry of vascular and biliary, as well as malignant structures of the liver.

The limitations of this study include data errors, which resulted in artefacts and inaccuracies in the digital models, and necessitated the need for digital editing in order to make the final 3D print printable and look more realistic. Data editing can sacrifice anatomical accuracy. Type and quality of radiological data contributed to errors encountered in the digital precursors of the 3D printed models and played a major role in the accuracy and anatomy of the graspable structures. Our data originated from two separate sources: CT angiogram, and MRI liver. Choice of radiological data contributing to the final 3D model depended on how well each hepatic structure was displayed by retrospectively collected scans. The hepatic artery model was based on the CT data, whilst the remaining structures were modelled based on the data of various post gadolinium acquisitions of the MRI liver. The CT images depicted the hepatic artery clearly, because of the arterial contrast, but other liver structures were poorly visualised. The MRI dataset depicted liver structures fairly well but the slices were very thick (8.99mm). Thick slices led to information loss, and less detailed representation when images were rendered in 3D. The models created based on the MRI data required to undergo a significant amount of digital editing to appear more natural. To avoid loss of crucial anatomical details and ensure optimal resolution, obtaining data via scanning modalities optimal to planned 3D printing should be carried out. Multi detector CT

(MDCT) enables volumetric liver images to be acquired rapidly in thin, 3mm slices- producing images of good resolution and near-isotropic voxels[17]. Obtaining a thinner slice MRI liver scan is possible but comes at a price of prolonged scanning time. More sophisticated machines such as 3 Tesla MRI provide images with higher quality resolution and thinner slices, but are much more expensive, and not readily available outside major research centres. Alternatively, various liver-specific contrast agents are available for the use with MRI or MDCT[18], exploring their use for maximising imaging quality for the purpose of 3D liver visualisation could provide exciting results. In our case, segmentation was performed partly manually, this proved to be a time consuming and observer-dependent process with a high likelihood of error. Algorithms allowing automatic or semiautomatic segmentation do exist, however, in the radiological data we used, hepatic structures had similar density as non-hepatic tissues, made it difficult to apply those. The volumetric software we used is not liver specific and relies on a "Marching Cubes" algorithm- which has a side effect of creating artefacts and ambiguities in extracted surfaces during 3D volume rendering[19].

Today's market offers a choice of software packages specific for processing liver image data, particularly useful in estimating liver segment volumes. Although none of these software programmes are fully automated, they provide accurate results in delineating surgical planes, predicting graft sizes and outlining anatomical landmarks such as vascular and biliary structures. Improved, novel segmentation algorithms are now available and allow for rapid segmentation of hepatic structures[20]. Finding the optimal liver specific volumetric package and segmentation algorithm could improve the quality and speed of segmentation, whilst minimising observer- dependent errors and data loss.

Our 3D printed model of the hepatic artery is larger than the remaining models. The hepatic artery was modelled on CT angiography data, whist the rest of models were drawn from MRI liver data. The scale discrepancy results from different data sources. To prevent scaling issues from happening in the future all data should be taken from the same source.

Zein et al[11] as well as Sugimoto[15] have successfully produced several 3D printed models of livers specific to patients' anatomy with great detail and accuracy. Our models represent each liver structure separately and are more simple with use of only one type of material per model. Although separate structures are limited in representing anatomical relationship between different hepatic structures, our type of models could be applicable depending on the particular procedure or liver region of interest, minimizing cost of processing, materials and time of production. Our models require a third of time to produce and cost between 500-600 USD and with growing 3D printing technology this will likely become less expensive over the next few years. The simplicity of our model also allows it be applied in smaller and lower fidelity printers making it feasible for use in a small unit as part of a diagnostic/ procedure planning one-stop shop for patients needing liver surgery.

This paper describes manufacturing a patient specific anatomical liver model, identifies limitations that may be encountered and offers solutions to overcoming these limitations. Further research is required to evaluate their usefulness in preoperative planning. Despite the limitations, this study demonstrates the potential of rapid prototyping technology to be applied in liver surgery. Although our models required a degree of data processing and editing to overcome artefacts, the final 3D printed models display structural detail and fidelity. With optimal imaging and improved volumetric software, combined with a widening choice of 3D printers and printing materials we will be able to generate highly accurate and

patient specific models to aid operative decision-making. These models will create opportunities for enhanced surgical anatomy teaching and surgical rehearsal.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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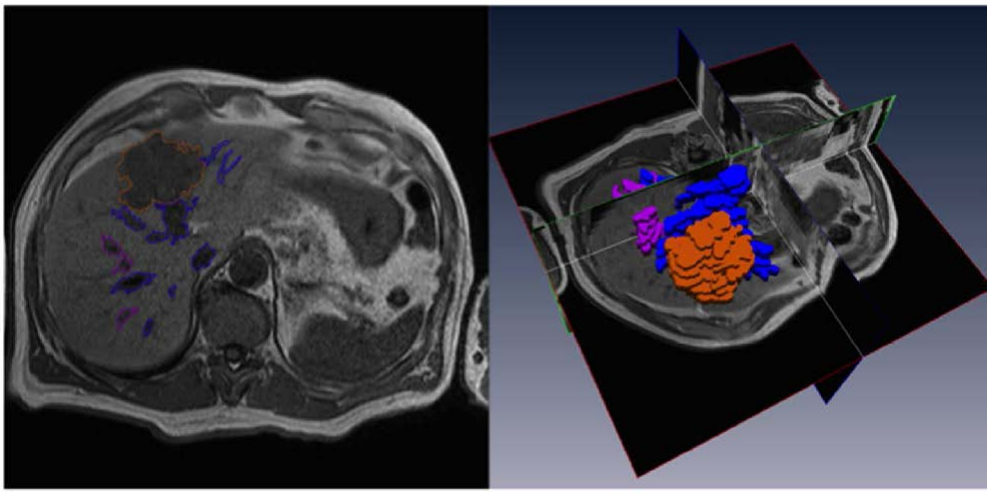

Figure 1. Segmentation in Amira software. a Highlighted pixels representing hepatic structures axial plane. b 3- planar view of segmented surfaces
Figure 1
254x190mm (72 x 72 DPI)

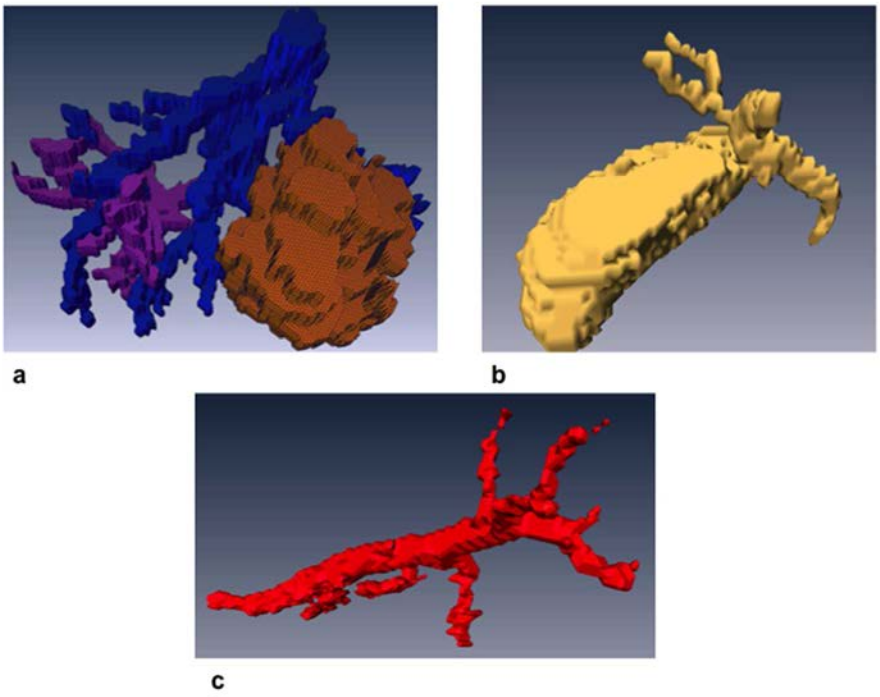

Fig 2. Extracted surfaces of liver structures.
a Hepatic veins, portal vein and liver tumour. b Gallbladder and biliary tree. c Hepatic artery

Figure 2
254x190mm (72 x 72 DPI)

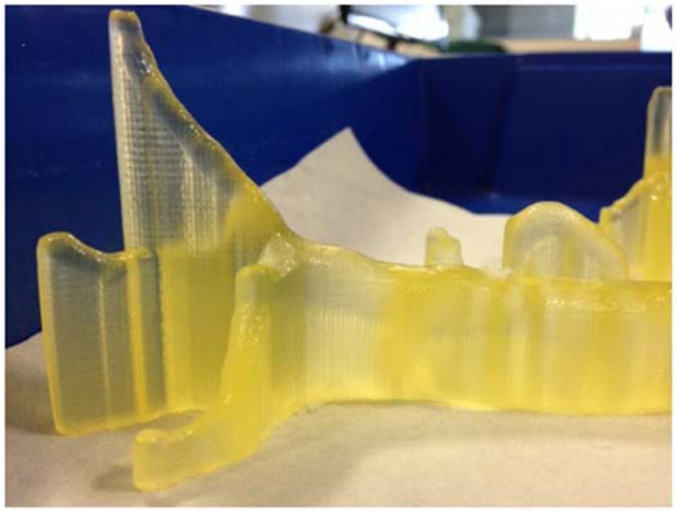

Figure 3. Model with surrounding support structure

Figure 3
338x190mm (54 x 54 DPI)

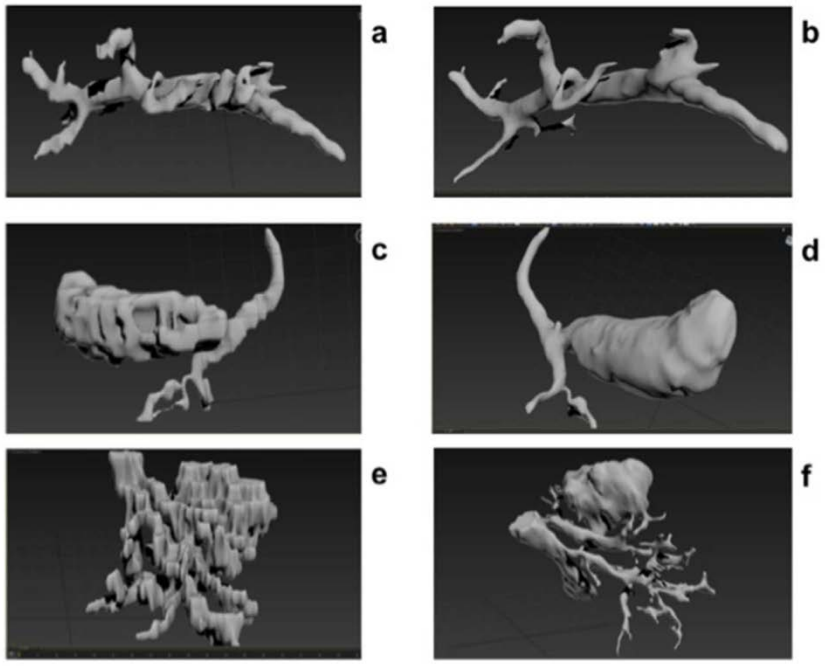

Fig 4. Mesh editing.
Hepatic artery: before a, after b; Gallbladder with biliary tree: before c, after d; Hepatic veins, portal vein and tumour: before e, after f

Figure 4
254x190mm (72 x 72 DPI)

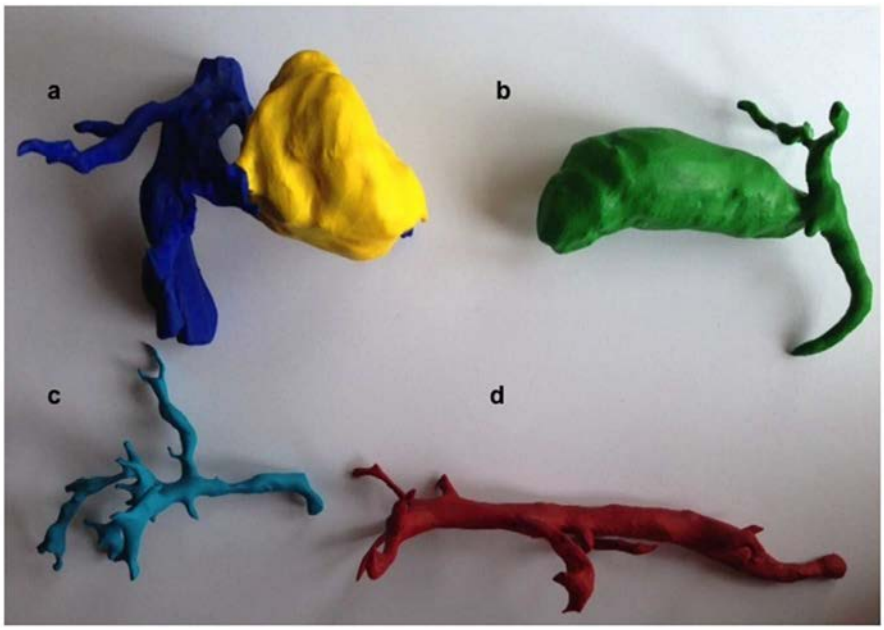

Fig 5.
3D printed models of hepatic structures
a Portal veins with hepatic tumour; b Gallbladder with biliary tree;
c Portal vein and it's branches; d Hepatic artery

Figure 5
254x190mm (72 x 72 DPI)