Review

3D haptic modelling for preoperative planning of hepatic resection: A systematic review

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HIGHLIGHTS

- 3D printing allows a fast, accurate and inexpensive production of a 3D liver model.
- A 3D printed model is excellent for education of junior staff as it offers insight to a patient’s unique anatomy.
- 3D printed models could also aid in patient education and facilitate surgery by obtaining informed consent.

ARTICLE INFO

Article history:
Received 19 February 2016
Received in revised form 30 June 2016
Accepted 2 July 2016

Keywords:
3D Printing
General surgery
3D Haptic model
3D Printing liver

ABSTRACT

Introduction and background: Three dimensional (3D) printing has gained popularity in the medical field because of increased research in the field of haptic 3D modeling. We review the role of 3D printing with specific reference to liver directed applications.

Methods: A literature search was performed using the scientific databases Medline and PubMed. We performed this in-line with the PRISMA [20] statement. We only included articles in English, available in full text, published about adults, about liver surgery and published between 2005 and 2015. The 3D model of a patient’s liver venous vasculature and metastasis was prepared from a CT scan using Osirix software (Pixmeo, Gineva, Switzerland) and printed using our 3D printer (MakerBot Replicator Z18, US). To validate the model, measurements from the inferior vena cava (IVC) were compared between the CT scan and the 3D printed model.

Results: A total of six studies were retrieved on 3D printing directly related to a liver application. While stereolithography (STL) remains the gold standard in medical additive manufacturing, Fused Filament Fabrication (FFF), is cheaper and may be more applicable. We found our liver 3D model made by FFF had a 0.1 ± 0.06 mm margin of error (mean ± standard deviation) compared with the CT scans.

Conclusion: 3D printing in general surgery is yet to be thoroughly exploited. The most relevant feature of interest with regard to liver surgery is the ability to view the 3D dimensional relationship of the various hepatic and portal veins with respect to tumor deposits when planning hepatic resection.

Systematic review registration number: researchregistry1348.

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1. Introduction

Three dimensional (3D) printing has gained popularity in medicine since the 1980s. As 3D printers have become more affordable, the real strength of this technique has been recognized; its ability to deliver anatomical models based on the unique characteristics of individual patients. Surgeries in fields as diverse as orthopedics [3,5,6,11], maxilla-facial [1,2,4,8–10] and especially plastic and reconstructive [13–15] have published reports of examples of 3D printing being used in their fields. However, this technology has only slowly been adopted in general surgery.

3D printing should be of great advantage in liver surgery. Functional hepatic anatomy is separated into 8 segments known as Couinaud segments, labeled I to VIII, and defined in part by the course of the hepatic and portal veins [22]. Currently identification of these structures and delineation of hepatic segments relies on pre-operative imaging and intra-operative ultrasound. Resection of these various segments is mainly carried out for malignancies (metastatic and primary lesions) although various benign diseases may also be treated surgically.

The hepatocellular carcinoma (HCC) is the most common primary liver tumor with a prevalence in adults of 4.9 per 100,000 making it the 5th most commonly diagnosed gastrointestinal malignancy in adults [7]. HCC most commonly presents in patients with cirrhosis who have a reduced physiological reserve to withstand major liver resection. This makes preoperative planning critical to minimize removal of liver volume and avoiding post-operative liver failure. More commonly, hepatic resection is performed for colorectal liver metastases (CRLM), that have a cumulative risk of 16% of distance metastasis spreading from the primary tumor within 5 years [17]. In appropriate patients, repeat hepatectomy following recurrence of CRLM may be feasible, and for this population preoperative planning and preservation of hepatic venous structures is of even greater clinical importance. This is also true for living-donor liver transplantation (LDLT) where the venous inflow and outflow to both the recipient and donor component livers must be maintained and therefore characterized with certainty, both pre- and intraoperatively. Currently, preoperative imaging with contrast-enhanced CT or MRI remains the most important planning tool for surgery [25]. Computer based 3D CT scans have been developed for pre-operative planning, however interpretation on a 2D computer screen is inherently limited. We believe a 3D printed model will provide tactile (haptic) feedback to the user and facilitate spatial recognition of important structures.

Here, we report a systematic review of the literature and describe the use of a low cost 3D printer to create a liver model for a patient undergoing liver resection.

2. Materials and methods

2.1. Systematic literature review

The PRISMA [20] statement was used to guide the systematic literature review. A checklist is available and attached. Ovid Medline (2006–present) and pubmed (2006–present) databases were searched using the following terms and keywords alone or in combination: 3D printing, liver, Upper GI, general surgery. Inclusion criteria for studies to be included: published in English, available full text, about adults, about liver surgery and published between 2005 and 2015. Two independent reviewers decided the criterion in a standardized manner. Any disagreements were solved with consensus (Please refer to appendix for search strategy). Ultimately, six studies were found to be directly related to liver surgery and 3D printing that satisfies the inclusion criteria. The date last searched was on the 14th of June 2016. The data were extracted based on the Cochrane effective practice and organization of care, data collection form. Main information that was extracted involved what type of liver model was made, what type of 3D printer used and how it affected peri-operative outcome. In order to access risk of bias, we looked at variability of outcome in the studies as well as analyzed whether there were any possible external funding.

2.2. Printed 3D model

We used a 3D printer to create a model of a liver’s venous vasculature and metastases for a patient undergoing liver resection to test the feasibility of using a low cost 3D printer for pre-operative planning. The conversion of 2D scan into 3D printing instructions are described in detail elsewhere [14]. Briefly, a 70-year-old man presented with liver metastases from a colorectal primary in Couinaud segments 4a and 4b, segment 6 and outer segment 7. Thin, axial view slices (<1 mm) of his pre-operative CT scan were examined using Osirix software (Version 4.1, Pixmeo, Geneva, Switzerland). The Region of Interest (ROI) function was used to map the hepatic and portal veins and map the metastases. The ROI areas were projected as 3D structures to produce a surface area mesh and instruction for the 3D printer. The resultant model was then printed using a 3D printer (MakerBot Replicator Z18, US) with polylactic acid (PLA) filament. The print time was 32 h and materials cost AUD
$30. The end product was manually cleaned of all possible supporting plastic columns (needed for printing process) with forceps and sand paper.

2.3. Validation

The models were then validated by comparing the diameters of the inferior vena cava from the CT scan and comparing with those from the 3D printed model at 3 separate points (Fig. 2a, b, c, d). As the data were normally distributed, the measurements were compared with a paired t-test.

3. Results

Only six articles [16,18,19,21,24,26] reported the use of 3D printing to produce anatomical liver models for liver surgery. Ovid Medline and Pubmed databases provided a total of 110 articles. After removing duplicates only 107 remains. Of these, after reading the abstract we excluded 91 papers as they were not related to the liver and 3D printing. 16 studies were examined further. However ten of the articles did not meet the earlier specified inclusion criteria. Three articles were excluded as they were done in a paediatric population, two articles were not performed for hepatobiliary surgery and four articles did not have full text available. No unpublished relevant data was obtained.

Zein et al. [26] showed that it was possible to 3D print an accurate model of a whole liver. They found their model vascular structure was accurate to ±1.3 mm and the whole liver ±4 mm compared to the patient’s actual liver. The second article by Igami et al. [18] described small liver tumours that were undetectable with conventional intra-operative ultrasound could be located using a 3D printed model. Following chemotherapy and the resultant shrinkage of the liver tumour, there is difficulty in tumour detection using intra-operative ultrasound. Therefore a pre-chemotherapy 3D printed model could guide surgeons towards the margins of these small liver tumours. Quintini et al. [16] discussed the potential of using a 3D printer to prevent complications in Living Donor 3D transplantations such as “large for size syndrome”. They also discussed the potential for 3D printers to be used in hepatobiliary anatomy as an educational tool, where 3D models would provide visual stimulation and tactile feedback during pre-operative planning. Another paper by Nan Xiang [21] discussed the benefits of 3D printing in variable portal vein anatomy. By having a 3D model, they discovered a congenital absence of the segment IV of the portal vein which was close to the tumour. This resulted in a decision to perform a narrow margin hepatectomy to avoid necrosis of segment IV and led to a good postoperative margin outcome. Watson’s study [24] showed it was possible to reproduce liver vasculature using a low cost approach. The review article of Ikegami et al. [19] highlighted the application of 3D printing in medicine and the many potential benefits of 3D printing in hepatic resections. The focus of this article was on the benefit of overcoming “large-for-size syndrome” during living donor liver transplantation. As this is still a relatively new area of research, there could be observation bias. Researchers are keen that this particular technology could be a breakthrough and may tend to over-estimate the benefits it could provide.

3.1. Printed model

The model took 32 h to print (Fig. 1). Note that the metastases (Fig. 1a, b and 1c) are held up with remaining vertical supporting
structures. The metastases are labeled according to the Couinaud segments as metastasis (mets) 4a/4b, 6 and 7 respectively. Fig. 1c shows a magnified view of the metastasis in segment 6. Fig. 3.

Measurements were taken from three points 1 cm apart, beginning from the junction of the hepatic vein and inferior vena cava. This can be appreciated from Fig. 2a, where color-coded lines show where the measurements are taken from. Green, orange and blue measurements drawn on Fig. 2b, c and 2d show the position of the axial measurements taken from the CT scan respectively. Comparison of diameters measured from the CT and 3D model at the corresponding points had on average an accuracy margin of 0.1 ± 0.06 mm (mean ± standard deviation) which was statistically significantly different from the scan measurements by a paired t-test, P < 0.05).

3.2. Clinical use

The model was available in the operating theatre on the day of surgery. A left lateral hepatectomy, right sided localized wedge resection and radio frequency ablation of segment 6 was performed. The patient was shown the model pre and post operatively with simple explanation and reported that the model has helped his understanding of the surgery that was performed. Theatre nursing staff reported that the model assisted their understanding
of the intended operation, as did the surgical fellow and registrar. The training surgeons felt the model helped in their understanding of the complex operative anatomy of the liver and also in what to expect intraoperatively as the hepatic parenchyma was divided in terms of encountering structures in 3 dimensions and real time. The consultant surgeon reported that the resolution of vessels and their relationship to the metastases was inadequate to plan surgery upon, but agreed that the model had educational and training advantages for junior staff.

4. Discussion

3D printing in liver surgery is a promising new tool for surgical planning. Our review identified six studies directly related to liver 3D imaging. In these studies, cost and time were the major limiting factors in producing a reliable model. We have shown the technique is feasible and with improvements in accuracy, models may aid preoperative planning for liver resections. This not only aids the operating surgeon, but also aids all theatre staff involved in the operating theatre.

Hepatic resections are challenging operations because of the complex nature of hepatic and venous anatomy within the liver. Preoperatively, CT scans and/or MRI’s are obtained from all patients to document tumor distribution, estimate future liver remnant volume and to identify tumor-vessel relationships in order to anticipate intraoperative vascular anatomy [25]. An early step in most hepatic resections is the identification of important vascular structures and tumor deposits using intraoperative ultrasound. With 3D printed haptic models, the surgeon has an additional aid to more accurately visualize individual livers. A 3D model could also potentially facilitate interaction between patients and doctors; operative anatomy could be explained more easily with the model, thus aiding the consent process [12].

In our hospital, we were able to print a structure of a hepatic and portal vein in relation to metastasis using a commercially available 3D printer costing AUD $10,000 that was already available in the hospital. Ultimately, the cost of printing the structure was $30 for the cost of the plastic used for the model. We have also validated our model by comparing the 3D printed model to the CT scan.

Comparing our study with the studies already available in the literature, our study mainly demonstrated that production of a relatively in-expensive yet accurate 3D model is possible. The
model was also well received by various members of healthcare staff and patient. Therefore, it would be a good opportunity to investigate this further in future studies to look at the benefits of patient and workplace education by using 3D printed models. The other present reviews mainly discuss the peri-operative benefits for the surgeon. We were also able to drastically reduce cost compared to the other studies. The 3D printer our institution used in our study is almost 30 times less in cost compared to the 3D printers used by other studies. However, a limitation of our current model includes not having a liver capsule, which could confuse the anatomical orientation of the model and an aspect that could be improved. Another limitation of our study is that we only managed to produce a 3D model in a single patient. In the future, we plan to expand the scope of this research by increasing the number of patients using this form of technology and also involvement of other surgical specialties.

5. Conclusion

In summary, 3D printing in liver surgery is a promising new tool for surgical planning. Our review identified six studies directly related to liver 3D imaging. However, in these studies, cost and time were the major limiting factors in producing a reliable model. We have shown the technique is feasible and applicable to liver resection in principle and with improvements in fidelity of modeling may aid preoperative planning for liver resections.

Acknowledgments

We would like to thank Peninsula Health for their on-going support. We would also like to extend our special thanks towards Dr. Vicky Tobin for her contribution with advice and manuscript preparation.

Appendix

Search Strategy for PubMed:

01 3D printing
02 Upper GI
03 General Surgery
04 Liver
05 1, 2, 3 and 4
06 1, 2 and 3
07 1 and 2
08 1 and 3
09 1 and 4

From 32 studies, we excluded 22 unrelated studies, two in a child, one without full text and another was written in Chinese.

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