



# Impact of 3D printing technology on the comprehension of surgical liver anatomy

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## Abstract

**Background and aims** Surgical planning in liver resection depends on the precise understanding of the three-dimensional (3D) relation of tumors to the intrahepatic vascular trees. This study aimed to investigate the impact of 3D printing (3DP) technology on the understanding of surgical liver anatomy.

**Methods** We selected four hepatic tumors that were previously resected. For each tumor, a virtual 3D reconstruction (VIR) model was created from multi-detector computed tomography (MDCT) and was prototyped using a 3D printer. Forty-five surgical residents were evenly assigned to each group (3DP, VIR, and MDCT groups). After evaluation of the MDCT scans, VIR model, or 3DP model of each tumor, surgical residents were asked to assign hepatic tumor locations and state surgical resection proposals. The time used to specify the tumor location was recorded. The correct responses and time spent were compared between the three groups.

**Results** The assignment of tumor location improved steadily from MDCT, to VIR, and to 3DP, with a mean score of 34.50, 55.25, and 80.92, respectively. These scores were out of 100 points. The 3DP group had significantly higher scores compared with other groups ( $p < 0.001$ ). Furthermore, 3DP significantly improved the accuracy of surgical resection proposal ( $p < 0.001$ ). The mean accuracy of the surgical resection proposal for 3DP, VIR, and MDCT was 57, 25, and 25%, respectively. The 3DP group took significantly less time, compared with other groups ( $p < 0.005$ ). The mean time spent on assessing the tumor location for 3DP, VIR, and MDCT groups was 93, 223, and 286 s, respectively.

**Conclusions** 3D printing improves the understanding of surgical liver anatomy for surgical residents. The improved comprehension of liver anatomy may facilitate laparoscopy or open liver resection.

**Keywords** Three-dimensional printing · Surgical anatomy · Hepatic tumor · Computed tomography · Virtual 3D reconstruction

## Abbreviations

2D Two-dimensional

3D Three-dimensional

3DP Three-dimensional printing

CT Computed tomography

MDCT Multi-detector computed tomography

VIR Three-dimensional virtual reconstruction

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The liver consists of complex anatomical structures and is divided into eight autonomous segments based on the Couinaud classification [1, 2]. A comprehensive understanding of the spatial relationship of hepatic pathology to the vascular and biliary system is imperative for successful hepatectomy. Traditionally, surgeons rely on multi-detector computed tomography (MDCT) or magnetic resonance imaging to evaluate the spatial relationship of hepatic pathology to the vascular and biliary system. However, these conventional radiological modalities provide only two-dimensional (2D) images of a three-dimensional (3D) organ. To overcome the limitations of 2D imaging, VIR of the liver is generated by means of dedicated software based on a standard medical image dataset [3]. VIR provides surgeons with more in-depth knowledge of the topographic anatomy and more precise localization of liver pathology [3–5]. These digital 3D models represent a valid step forward compared to conventional radiology and are more effective and precise in clarifying surgical liver anatomy [4]. In contrast, VIR is usually viewed through a flat screen and depends on the viewer's mental ability to transfer digital 3D images into virtual 3D structures. Thus, the accuracy of localizing liver pathology could vary among surgeons [4]. Moreover, the sense of touch, which is considered essential for the proper comprehension of any 3D organ, is unavailable in VIR [6].

The spread of 3DP technology in various fields of surgery has considerable potential with respect to producing physical 3D organ models [7–15]. The 3DP liver model based on MDCT images provides a high-fidelity representation of the original liver organ [7, 9, 16–18]. 3DP liver models demonstrate hepatic anatomy and tumors with high accuracy [19]. Preliminary results suggest that 3DP liver models allow surgeons to better evaluate crucial anatomical features such as precise localization of small tumors, which may not be easily accessible with traditional imaging methods [9, 18]. The models can assist with preoperative planning and may be used in the simulation of surgical procedures for the treatment of malignant hepatic tumors [19]. These 3DP liver models might have the potential to overcome the limitations of MDCT and VIR. The models will be of great surgical value as the 3DP model can help to improve the understanding of surgical liver anatomy.

We designed this cross-sectional study to ascertain whether the 3DP liver model could be more informative

than standard MDCT and VIRs with regard to predicting the surgical anatomy of the liver.

## Methods

Four hepatic tumors (three cases of hepatoblastoma and one case of focal nodular hyperplasia) that had been surgically resected were selected. These tumors included those situated in only one liver segment and those positioned at the border where the traditional Couinaud classification conflicts with the individual vascular tree-based segment border. Specifically, one tumor was located in segment 5, one in segment 2 and 3, one in the right hemiliver, and one in the right hemiliver and segment 1 (Table 1).

For each patient, a VIR model was created from the original MDCT dataset. Thereafter, a full-size physical liver model was prototyped using a 3D printer. Correspondingly, the dataset of each patient was classified into MDCT, VIRs, and 3DP model groups (Figs. 1, 2, 3). The operating surgeon, radiologists, and technicians worked closely regarding the process of 3D segmentation.

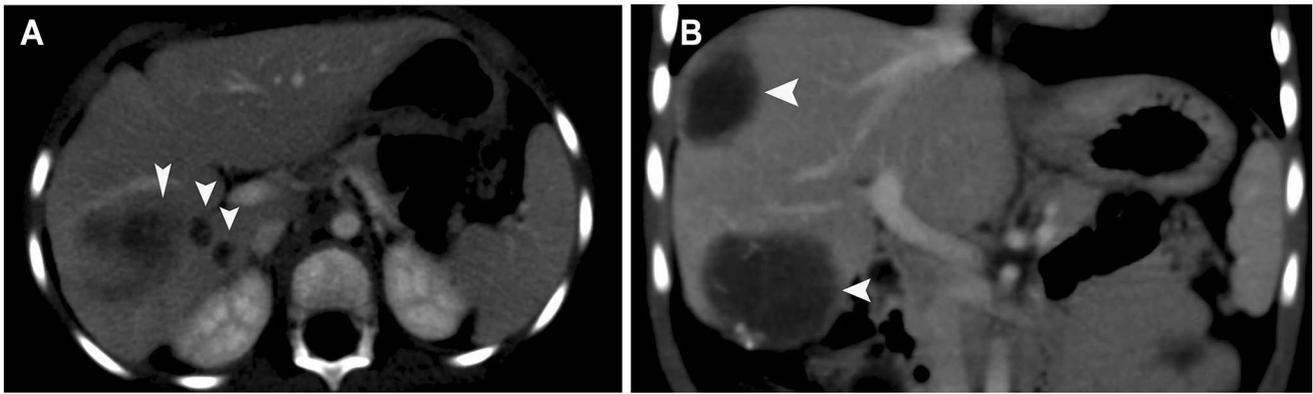
## 3D printing process

Enhanced computed tomography (CT) data were collected with a Philips Brilliance 64-MDCT scanner (Philips, Eindhoven, Netherlands). MDCT images were obtained with multiple phase scanning, with a slice height of 0.625 mm. Ultravist (Iopromide) 370 was the contrast medium. The CT data were imported to the Mimics software program v14.01 (Materialize Corp, Leuven, Belgium) to perform segmentation of the tumor and mass vascular system in the abdomen, and were saved in the “STL” file format. The segmentation was performed both automatically and manually. The STL files were then imported into the PolyJet Studio™ 3D printing software program for preprocessing [20]. Subsequently, the data flow was exported to the Stratasys J750™ 3D printer, which has full-color capability with texture mapping and color gradients. The Transparent VeroClear™ and RGD720 were used to build the model. The 1:1 scale patient-specific 3D model displays the tumor, normal hepatic parenchymal, hepatic vein, and portal vein. The hepatic

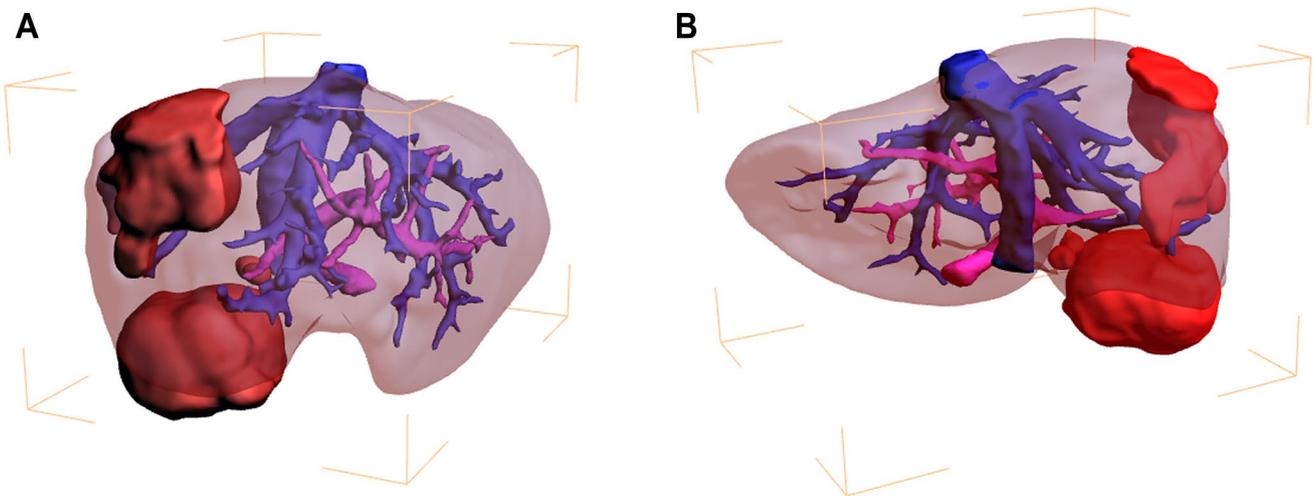
**Table 1** Tumors characteristics and surgical procedures

Case	Diagnosis	Location	Size (cm)	Surgical procedure
1	FNH	Segment 5	7.1×4.5×6.9	Segmentectomy 5
2	HB	Segment 5, 6, 7, 8	6.3×5.1×8.8	Right hepatectomy
3	HB	Segment 2, 3	8.1×5.7×7.5	Bisegmentectomy 2, 3
4	HB	Segment 1, 5, 6, 7, 8	6.4×3.1×3.7	Right hepatectomy

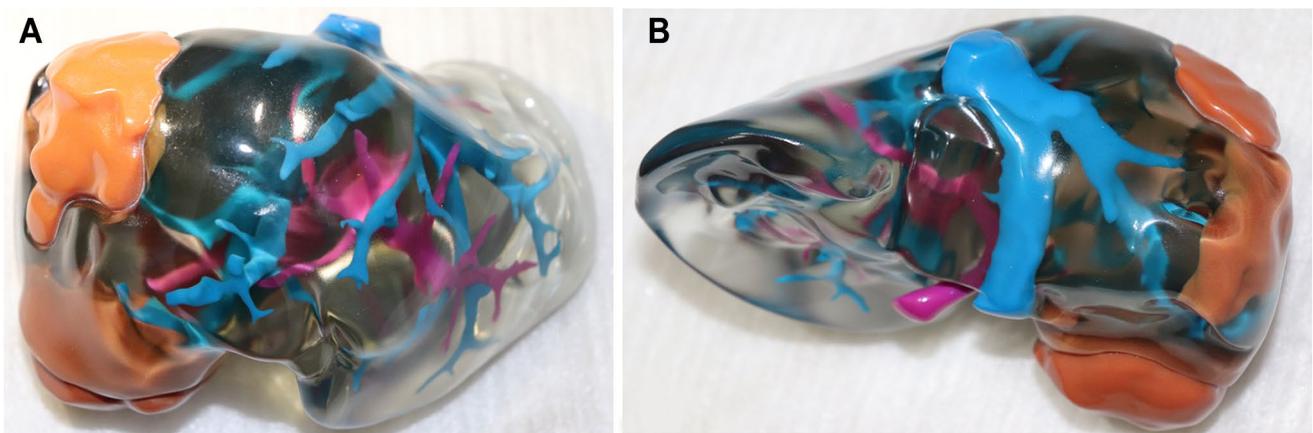
FNH focal nodular hyperplasia, HB hepatoblastoma



**Fig. 1** MDCT images showing multifocal intrahepatic tumors involving both the right liver and caudate lobe (case 4) (**A** axial plane, **B** coronal plane). Arrows indicating tumors. *MDCT* multi-detector computed tomography



**Fig. 2** VR of the patient in Fig. 1 (case 4) (**A** anterior view, **B** posterior view). The red color shows the tumors; blue color shows the inferior vena cava and hepatic veins, and the purple color shows the portal vein. (Color figure online)



**Fig. 3** 3D printed liver model of the patient in Fig. 1 (case 4) (**A** anterior view, **B** posterior view). The red color shows the tumors; blue color shows the inferior vena cava and hepatic veins, and the purple color shows the portal vein. (Color figure online)

artery is not printed. The production of a full-size model costs approximately \$1200.

## Study design

This research was designed as a prospective comparative study with three parallel groups. Surgical residents (2–4 years of training) without any notification of the study purpose were invited to participate in this study. Forty-five surgical residents evenly assigned to one of the three groups (MDCT, VIR, and 3DP groups) to evaluate the different presentations of patients' anatomical data. The MDCT images were loaded on the software to provide uniform study conditions, allowing both axial and coronal scans visualization, while the 3D virtual reconstructions were loaded onto the visualization software which enables free rotation and zooming of the virtual model. Regarding the patient-specific 3DP liver models, the surgical residents were allowed to freely handle them.

The residents were asked to state the liver segment where the tumor was located and to make a minimal resection proposal, including the tumor, safety margin (1 cm), and dependent liver tissue. The time (seconds) spent on assigning each tumor location was recorded.

For tumor allocation to the liver segments, 100 points were awarded if all segments in which the tumors resided were correctly identified. If the tumor was located in more than one segment, the 100 achievable points were divided between these segments. Erroneously identified segments were awarded a minus point according to the formula mentioned earlier [4]. The resection proposals were considered correct or incorrect, based on surgical recommendations proposed by the operating surgeon and a senior radiologist. Only those who achieved 100 points in the tumor location assignment and who presented the resection proposal using the Brisbane 2000 Terminology of Liver Resections [21] were considered correct.

This study was approved by the Institutional Review Board of Guangzhou Women and Children's Medical Center (Guangzhou, China). All patient records were anonymized and de-identified prior to analysis.

## Statistical analysis

The statistical analyses were performed with R version 3.3.2 (R Core Team, Vienna, Austria) using freely distributed software packages. Two-tailed  $p$  values of  $<0.05$  were considered statistically significant. The outcomes of the three groups were compared using one-way analysis of variance. Multiple pairwise comparisons of the groups were performed using the Bonferroni method.

## Results

Assignment of tumor location improved steadily from MDCT, to VIR, and to the 3DP model, with a mean score of 34.50, 55.25, and 80.92, respectively (Table 2). These scores were out of 100 points. The 3DP model group achieved significantly higher scores compared to the VIR and MDCT groups ( $p < 0.001$ , Fig. 4). No significant difference was observed between the VIR and MDCT groups.

Furthermore, the 3DP liver model significantly improved the accuracy of surgical resection proposal ( $p < 0.001$ , Fig. 5), compared to VIR and MDCT. The mean accuracy for the 3DP model, VIR, and MDCT groups was 57, 25, and 25%, respectively.

The mean time spent on assigning tumor location for the 3DP model, VIR, and MDCT was 93, 223, and 286 s, respectively. The 3DP model took significantly less time, compared to the two other groups, regarding the assignment of tumor location ( $p < 0.005$ , Fig. 6); no significant difference was observed between the VIR and MDCT groups.

## Discussion

Our study showed that patient-specific 3DP liver models were more informative compared to VIR and MDCT with respect to the understanding of surgical liver anatomy for surgical residents. The 3DP liver model significantly improved the accuracy of hepatic tumor location assignment, taking less time and allowing for better surgical resection planning. Based on our findings, it will be especially important and meaningful to further investigate how 3DP liver models will change intraoperative decision-making and clinical outcomes in the future.

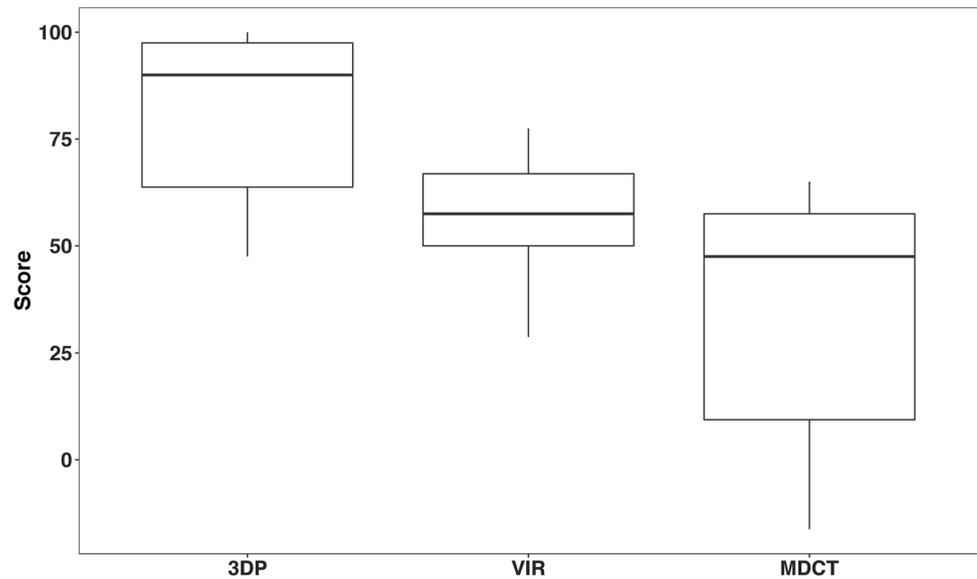
The 3DP liver model achieved a more precise assignment of the diseased liver segment compared to VIR and MDCT. Previous studies suggest that the 3DP model may be more informative for locating complicated and small hepatic tumors [9, 18, 22, 23]. Additionally, 3DP of other organs has yielded similar results regarding the

**Table 2** Tumor assignment, surgical resection proposal, and time for each group

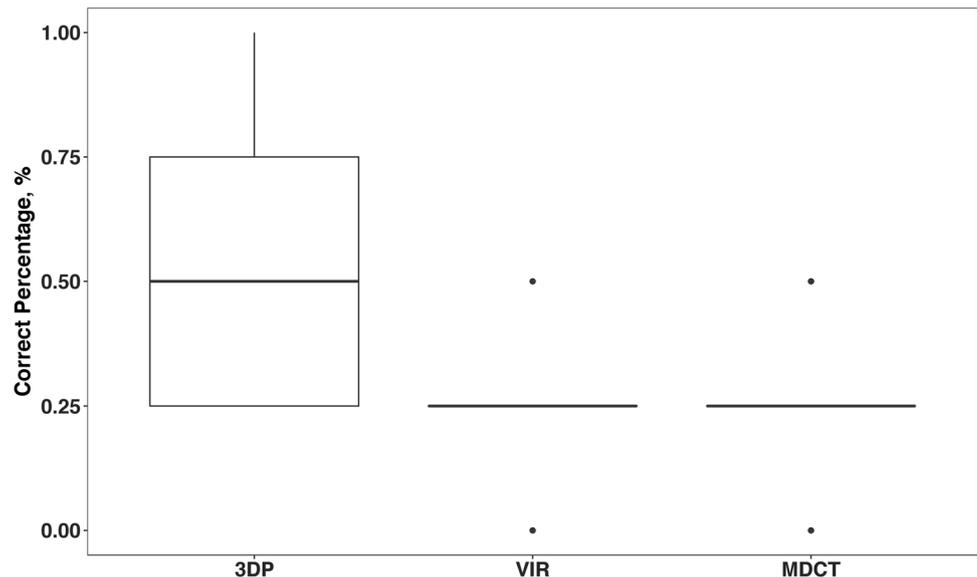
Characteristics	3DP ( $n=15$ )	VIR ( $n=15$ )	MDCT ( $n=15$ )
Score (mean $\pm$ SD)	80.92 $\pm$ 19.34	55.25 $\pm$ 14.26	34.50 $\pm$ 29.11
Proposal (mean $\pm$ SD)	0.57 $\pm$ 0.31	0.25 $\pm$ 0.16	0.25 $\pm$ 0.16
Time (mean $\pm$ SD)	93.42 $\pm$ 65.72	223.12 $\pm$ 137.20	286.10 $\pm$ 108.33

3DP 3D printed model, VIR virtual 3D reconstruction, MDCT multiple detector computed tomography

**Fig. 4** Box plot of the three model types regarding the accuracy of tumor assignment. *3DP* 3D printed model, *VIR* VIR, *MDCT* multi-detector computed tomography



**Fig. 5** Box plot of the three model types regarding the accuracy of the surgical resection proposal. *3DP* 3D printed model, *VIR* VIR, *MDCT* multi-detector computed tomography

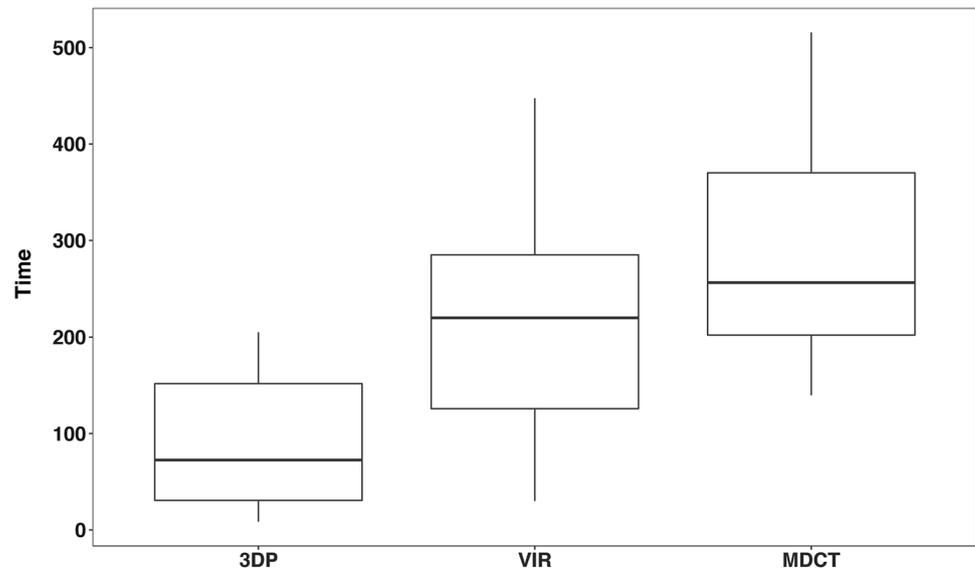


clarification of the specific anatomy of solid organs [14, 24]. These consistent results show that the 3DP model is useful for clarifying complicated surgical anatomy, and our results suggest that the 3DP liver model could be a useful tool to aid surgical residents to understand the surgical anatomy of diseased livers. 3D printing has unique advantages over VIR and MDCT. The spatial structural relationship of the liver is straightforward in the patient-specific 3DP model. Moreover, with the 3DP model, surgeons have the ability to examine and touch the region of interest, which is considered important for understanding the target anatomy [6, 25]. 3DP is expected to have a broad influence on different fields of surgery and should be pivotal for training future generations of surgeons and other care providers [24].

Unexpectedly, no significant difference was found between VIR and MDCT regarding the accuracy of tumor location assignment, although better scores for VIR were observed. In contrast, a previous study including different levels of surgeons showed that VIR resulted in a significantly increased precision of tumor localization compared to MDCT [4]. The inclusion of only surgical residents and a small study sample in our series may account for the difference in results between that study and ours. Furthermore, this inconsistency may also reflect the variability of VIR, which depends on the viewer's mental ability to transfer digital 3D images into virtual 3D structures.

The surgical resection proposals were more accurate in the 3DP liver model group. Regarding the resection proposals, only residents who achieved a correct assignment of all

**Fig. 6** Box plot of the three models regarding the average time spent on tumor location assignment. *3DP* 3D-printed model, *VIR* VIR, *MDCT* multi-detector computed tomography



diseased hepatic segments, with correct surgical statements using the classic method, were considered to have presented correct surgical resection proposals. Reasonably, better tumor assignment should result in more accurate surgical resection planning. However, a resident's understanding of the Brisbane 2000 liver resection terminology could also have influenced the resection proposals, which might explain why VIR did not show any superiority to MDCT. The physical 3D representation of the target anatomical area appears to provide support for surgeons in preoperative planning [7]. Handling these models with both inflow and outflow structured printed provide a mental reconstruction of the anatomy that makes not only the comprehension but also the memorization of essential details easier [6]. Furthermore, 3DP can also be sterilized and brought into the operating theater to assist real-time surgery [9]. Additionally, these 3D models can be especially useful in minimally invasive surgery [22].

The transformation of information was quicker in the 3DP group than in the VIR and MDCT groups. The benefit of quicker information transformation in 3DP of other solid organs has also been reported [14]. The speed of visual information transfer that the sense of touch offers through the handling of a physical object, which is missing when the same images (either 2D or 3D) are displayed on a screen, is evidently prominent [26]. 3DP technology has notably advanced in the past few decades and has been used in the fields of preoperative surgical planning [17, 27, 28].

The current study has some limitations. First, this study enrolled only surgical residents who may be considered less experienced in the clinical setting. The study may only reflect the usefulness of 3DP in helping less experienced surgeons to understand the surgical anatomy of the liver. Clarifying the impact of 3DP with regard to surgeons with different levels of experience, and especially its impact on

surgical outcome, is critical. Thus, it will be important to investigate whether a better understanding of the surgical liver anatomy will lead to better complete resection rates and decreased surgical complications.

Furthermore, as an emerging technology, 3DP has its own limitations. Producing a 3D model is costly and time-consuming, which is the main drawback limiting the widespread use of 3DP technology [19, 27]. Fortunately, there are currently tests being done on low-cost solutions [22, 29]. As 3DP technology evolves and costs continue to fall, patient-specific 3DP may become common for both clinical and educational purposes.

## Conclusion

The 3DP liver model helped to improve the understanding of hepatic surgical anatomy by surgical residents. With the 3DP model, accurate tumor localization and better surgical planning can be achieved quickly. The improved comprehension of liver anatomy may facilitate laparoscopy or open liver resection. Further study including surgeons with different levels of experience and a larger study population may be needed to accurately clarify the impact of 3DP in the clinical setting and if the 3D model leads to better clinical outcomes in hepatic resections.

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## Compliance with ethical standards

**Disclosure** Tianyou Yang, Shuwen Lin, Qigen Xie, Wenwei Ouyang, Tianbao Tan, Jiahao Li, Zhiyuan Chen, Jiliang Yang, Huiying Wu, Jing

Pan, Chao Hu, and Yan Zou have no conflicts of interest or financial ties to disclose.

## References

- Couinaud C (1992) The anatomy of the liver. *Annali italiani di chirurgia* 63:693–697
- Bismuth H (1982) Surgical anatomy and anatomical surgery of the liver. *World J Surg* 6:3–9
- Marescaux J, Clement JM, Tasseti V, Koehl C, Cotin S, Russier Y et al (1998) Virtual reality applied to hepatic surgery simulation: the next revolution. *Ann Surg* 228:627–634
- Lamade W, Glombitza G, Fischer L, Chiu P, Cardenas CE, Meinzer HP et al (2000) The impact of 3-dimensional reconstructions on operation planning in liver surgery. *Arch Surg* 135:1256–1261
- van Leeuwen MS, Noordzij J, Hennipman A, Feldberg MA (1995) Planning of liver surgery using three-dimensional imaging techniques. *Eur J Cancer* 31:1212–1215
- Matsumoto JS, Morris JM, Foley TA, Williamson EE, Leng S, McGee KP et al (2015) Three-dimensional Physical modeling: applications and experience at Mayo clinic. *Radiographics* 35:1989–2006
- Zein NN, Hanouneh IA, Bishop PD, Samaan M, Egtesad B, Quintini C et al (2013) Three-dimensional print of a liver for preoperative planning in living donor liver transplantation. *Liver Transpl* 19:1304–1310
- Costello JP, Olivieri LJ, Krieger A, Thabit O, Marshall MB, Yoo SJ et al (2014) Utilizing three-dimensional printing technology to assess the feasibility of high-fidelity synthetic ventricular septal defect models for simulation in medical education. *World J Pediatr Congenit Heart Surg* 5:421–426
- Igami T, Nakamura Y, Hirose T, Ebata T, Yokoyama Y, Sugawara G et al (2014) Application of a three-dimensional print of a liver in hepatectomy for small tumors invisible by intraoperative ultrasonography: preliminary experience. *World J Surg* 38:3163–3166
- Dickinson KJ, Matsumoto J, Cassivi SD, Reinersman JM, Fletcher JG, Morris J et al (2015) Individualizing management of complex esophageal pathology using three-dimensional printed models. *Ann Thorac Surg* 100:692–697
- Kusaka M, Sugimoto M, Fukami N, Sasaki H, Takenaka M, Anraku T et al (2015) Initial experience with a tailor-made simulation and navigation program using a 3-D printer model of kidney transplantation surgery. *Transpl Proc* 47:596–599
- Liew Y, Beveridge E, Demetriades AK, Hughes MA (2015) 3D printing of patient-specific anatomy: a tool to improve patient consent and enhance imaging interpretation by trainees. *Br J Neurosurg* 29:712–714
- Mitsouras D, Liacouras P, Imanzadeh A, Giannopoulos AA, Cai TR, Kumamaru KK et al (2015) Medical 3D printing for the radiologist. *Radiographics* 35:1966–1989
- Marconi S, Pugliese L, Botti M, Peri A, Cavazzi E, Latteri S et al (2017) Value of 3D printing for the comprehension of surgical anatomy. *Surg Endosc* 31:4102–4110
- Witowski JS, Coles-Black J, Zuzak TZ, Pedziwiatr M, Chuen J, Major P et al (2017) 3D printing in liver surgery: a systematic review. *Telemed J E Health* 23:943–947
- Madurska MJ, Poyade M, Eason D, Rea P, Watson AJ (2017) Development of a patient-specific 3D-printed liver model for preoperative planning. *Surg Innov* 24:145–150
- Soon DSC, Chae MP, Pilgrim CHC, Rozen WM, Spychal RT, Hunter-Smith DJ (2016) 3D haptic modelling for preoperative planning of hepatic resection: a systematic review. *Ann Med Surg* 10:1–7
- Souzaki R, Kinoshita Y, Ieiri S, Hayashida M, Koga Y, Shirabe K et al (2015) Three-dimensional liver model based on preoperative CT images as a tool to assist in surgical planning for hepatoblastoma in a child. *Pediatr Surg Int* 31:593–596
- Perica ER, Sun Z (2018) A systematic review of three-dimensional printing in liver disease. *J Digit Imaging* <https://doi.org/10.1007/s10278-018-0067-x>
- Yang T, Tan T, Yang J, Pan J, Hu C, Li J et al (2018) The impact of using three-dimensional printed liver models for patient education. *J Int Med Res* 46:1570–1578
- Strasberg SM, for the International Hepato-Pancreato-Biliary Association Terminology Committee Survey (2000) The Brisbane 2000 Terminology of Liver Anatomy and Resections. *HPB* 2:333–339
- Witowski JS, Pedziwiatr M, Major P, Budzynski A (2017) Cost-effective, personalized, 3D-printed liver model for preoperative planning before laparoscopic liver hemihepatectomy for colorectal cancer metastases. *Int J Comput Assist Radiol Surg* 12:2047–2054
- Igami T, Nakamura Y, Oda M, Tanaka H, Nojiri M, Ebata T et al (2017) Application of three-dimensional print in minor hepatectomy following liver partition between anterior and posterior sectors. *ANZ J Surg*. <https://doi.org/10.1111/ans.14331>
- Giannopoulos AA, Mitsouras D, Yoo S-J, Liu PP, Chatzizisis Y, Rybicki FJ (2016) Applications of 3D printing in cardiovascular diseases. *Nat Rev Cardiol* 13:701–718
- Lee N (2016) The lancet technology: 3D printing for instruments, models and organs? *Lancet* 388(10052):1368. [https://doi.org/10.1016/S0140-6736\(16\)31735-4](https://doi.org/10.1016/S0140-6736(16)31735-4)
- Kappers AM (2011) Human perception of shape from touch. *Philos Trans R Soc Lond B* 366:3106–3114
- Shafiee A, Atala A (2016) Printing Technologies for Medical Applications. *Trends Mol Med* 22:254–265
- Burdall OC, Makin E, Davenport M, Ade-Ajayi N (2016) 3D printing to simulate laparoscopic choledochal surgery. *J Pediatr Surg* 51:828–831
- Watson RA (2014) A low-cost surgical application of additive fabrication. *J Surg Educ* 71:14–17