3D Printout Models vs. 3D-Rendered Images: Which Is Better for Preoperative Planning? ☆

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INTRODUCTION: Correct interpretation of a patient's anatomy and changes that occurs secondary to a disease process are crucial in the preoperative process to ensure optimal surgical treatment. In this study, we presented 3 different pancreatic cancer cases to surgical residents in the form of 3D-rendered images and 3D-printed models to investigate which modality resulted in the most appropriate preoperative plan.

METHODS: We selected 3 cases that would require significantly different preoperative plans based on key features identifiable in the preoperative computed tomography imaging. 3D volume rendering and 3D printing were performed respectively to create 2 different training ways. A total of 30, year 1 surgical residents were randomly divided into 2 groups. Besides traditional 2D computed tomography images, residents in group A ($n = 15$) reviewed 3D computer models, whereas in group B, residents ($n = 15$) reviewed 3D-printed models. Both groups subsequently completed an examination, designed in-house, to assess the appropriateness of their preoperative plan and provide a numerical score of the quality of the surgical plan.

RESULTS: Residents in group B showed significantly higher quality of the surgical plan scores compared with residents in group A (76.4 ± 10.5 vs. 66.5 ± 11.2, p = 0.018). This difference was due in large part to a significant difference in knowledge of key surgical steps (22.1 ± 2.9 vs. 17.4 ± 4.2, p = 0.004) between each group. All participants reported a high level of satisfaction with the exercise.

CONCLUSION: Results from this study support our hypothesis that 3D-printed models improve the quality of surgical trainee's preoperative plans. (J Surg Ed 73:518-523. © 2016 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

KEY WORDS: rendered image, 3-dimensional printing, preoperative planning, simulation, surgical education

COMPETENCIES: Patient Care, Medical Knowledge, Practice-Based Learning and Improvement, Interpersonal and Communication Skills, Systems-Based Practice

INTRODUCTION

The pancreas is a retroperitoneal organ deep in the abdominal cavity surrounded by several critical structures. The anatomical location of the pancreas and intimate relationship with these delicate structures contribute to complexity of surgery performed in this region of the abdomen.[1] Pancreatic surgery is generally considered as one of the most technically challenging and demanding abdominaloperations.[2,3] A complete understanding of patients' anatomy and their unique disease process is therefore essential for ensuring safe surgical treatment. However, preoperative planning has known to be difficult and even more challenging to trainees and young surgeons.[4]

Preoperative planning for surgical pancreatic resection demands accurate evaluation of the surrounding vascular structures by the aid of computed tomography (CT) or magnetic resonance imaging data. Surgeons review a large number of medical images during this preoperative phase before deciding on a surgical approach. Experienced surgeons are able to use 2-dimensional (2D) CT images to create a 3-dimensional (3D) representation in their minds eye. However, previous studies have demonstrated that novice surgeons or trainees find this particularly challenging.[5]

New advancements in computer technology have permitted the 3D reconstruction of abdominal structures from

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TABLE 1. Features of 3 Pancreatic Cancer Cases

	Tumor Location	3D Models Included	Key Anatomy Features	Surgical Plan
Case 1	Pancreatic head	Pancreas, artery, portal vein	Vascular anatomy tumor location	Duodenopancreatectomy with preserved variant hepatic artery
Case 2	Pancreatic neck	Pancreas, portal vein	Tumor invasion portal vein	Duodenopancreatectomy with portal vein prosthesis
Case 3	Pancreatic tail	Pancreas, spleen, portal vein	Adjacent structure localization	Distal partial pancreatectomy

traditional multidetector CT imaging. 3D-rendered images provide additional information for surgical planning and teaching.[6,7] However, these reconstructed models are still limited to viewing on a computer monitor and provide only additional visual cues. For a novice surgeon with limited experience with spatial perception, accurately evaluating the anatomy from visual cues alone may be cognitively and perceptuallydemanding.[8] Consequently, 3D-rendered images may not provide a significant advantage over traditional visualization methods.

Examples of training aids that incorporate both visual and tactile cues come from simulation where models mimic key portions of relevant anatomy.[9,10] Previously, physical models have been criticized for lacking patient-specific information. Recently, with the development of 3D-printing technology, a physical model can be fabricated from the 3D-rendered image from a real patient data.[8,11] When studying a patient's anatomy using a 3D-printed model, surgeons can use haptic feedback and interact with a model in a real time. As more and more 3D-printed models are employed in health care, we believe that this technology has the potential to improve the quality of preoperative planning.

In this study, we investigate the pedagogy values of using 3D-printed model in teaching surgical residents' perception of the pancreas and surrounding vasculature anatomy, and effects on improving the quality of their presurgical plan. It is our hypothesis that surgical residents who study patients' anatomy using 3D-printed model would identify more pathophysiological changes and achieve higher test score compared with those viewing the patients' anatomy from the on-screen 3D CT images. This study is the first part of an ongoing research program focused on the training and assessment of surgeons and more specifically, their decision-making skills during pancreatic surgery.

METHODS

Cases

This study was reviewed and received approved from the Ethics Review Board from the Second Affiliated Hospital of Zhejiang University School of Medicine. To evaluate surgeons' preoperative planning, we selected 3 pancreatic cancer cases for which the technical aspects of surgery were varied based on key imaging features demonstrated on CT images of the abdomen. The main features of 3 cases are displayed in Table 1.

Models

CT data files (Digital Imaging and Communications in Medicine, DICOM format) pertaining to the selected cases were obtained from a radiology archive and anonymized to protect patient privacy. Each CT image was processed using Mimics Innovation software (Materialise HQ, Leuven, Belgium). After isolation of the relevant structures in each image set, 3D volume rendering was performed (Fig. 1A, On-screen 3D model). The generated stereolithography files were subsequently used to produce a 3D-printed model using an Objet Connex500TM 3D printer (Stratasys Ltd., Eden Prairie, MN) using Acrylonitrile Butadiene Styrene (ABS) material (Fig. 1B, Printout 3D model). The CT data provided sufficient information to create high-fidelity models. A 3 patient-specific 3D-printed models were created, containing the pancreas and surrounding structures. The models were then used to assist the interpretation of the anatomy and demonstrate key portions of the operation during the knowledge assessment.

Participants

A total of 30, year 1 surgical residents who completed a training course on the surgical management of pancreatic cancer voluntarily participated in this study. After a brief introduction, the participants were randomly divided into 2 study groups. There was no significant difference between the 2 groups in sex, age, or baseline academic score. The study procedure is demonstrated in Figure 2. All participants received instruction on the anatomy and operative procedures used to manage pancreatic cancer. In group A, residents ($n = 15$) each had 15 minutes to review traditional 2D CT (axial cuts) images and the 3D-rendered models of the 3 selected cases on the computer, whereas in group B, residents ($n = 15$) reviewed the 3D-printed models of the pancreas and surrounding vasculature in addition to traditional 2D CT images. After 15 minutes, both groups were

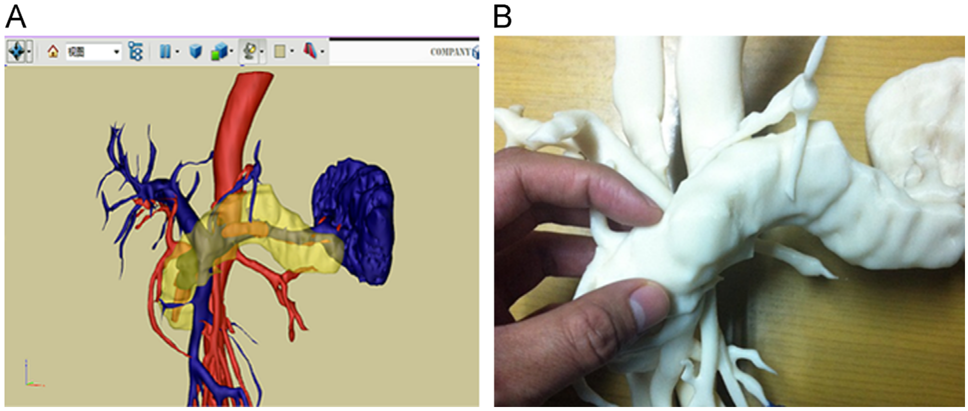

FIGURE 1. (A) 3D-rendered images and (B) 3D printout model.

required to take a test assessing the quality on their preoperative planning.

Test

A subjective test evaluating the quality of the surgical plan (QSP) was designed to assess (1) the resident's knowledge of patient anatomy and pathophysiological changes; (2) the resident's operative plan including key surgical steps, with a focus on how to maintain a safe approach to the area of interest and protect vital structures along the surgical path; and (3) the resident's preparation for unexpected events that might occur during the course of the operation, which examines whether residents demonstrate an appropriate mindset as a team leader in the operating room. The QSP questions were designed by 3 surgeons with more than10 years of pancreatic surgery experience. The QSP questionnaire is provided in Appendix Table A1. In addition,

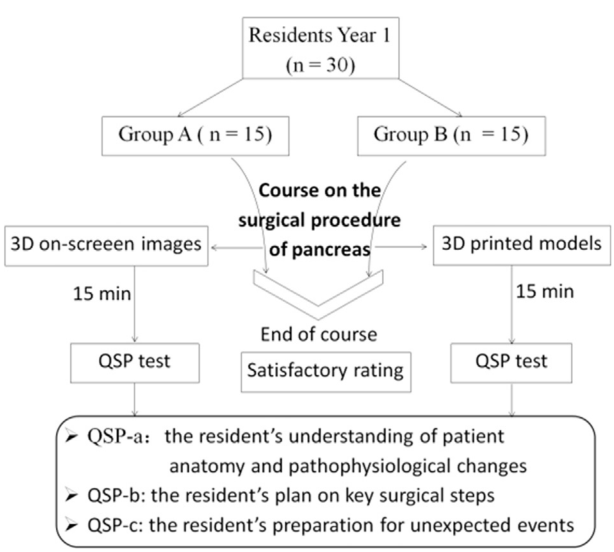

FIGURE 2. Study flowchart.

participants were asked to rate their satisfaction on a 5-point Likert scale regarding the effectiveness of the training course, knowledge acquisition, utility of the 3D models and prints, and overall teaching outcomes. QSP scores and self-reported satisfaction levels were compared between groups A and B using the Student's *t*-test and chi-square test, respectively. Statistical significance was defined as $p < 0.05$.

RESULTS

Residents who were provided with the 3D-printed models (group B) showed significantly higher QSP scores compared with residents who reviewed 3D-rendered models on the computer (group A) (76.4 ± 10.5 vs. 66.5 ± 11.2, $p = 0.018$; Fig. 3). The difference between the 2 groups was strongly affected by differences in the demonstration of knowledge of key surgical steps (22.1 ± 2.9 vs. 17.4 ± 4.2, $p = 0.004$). Consequently, residents who were allowed to inspect the 3D-printed models were able to develop a more accurate surgical plan.

Although there was no statistical difference in self-reported satisfaction level between 2 groups ($p > 0.05$),

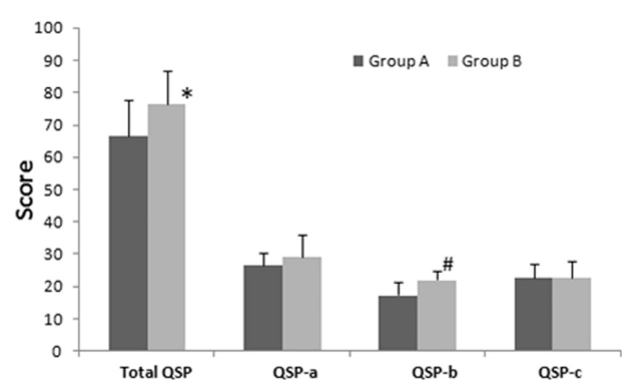

FIGURE 3. Differences of QSP scores between 2 groups. *, # Statistically significant, $p < 0.05$.

TABLE 2. Satisfactory Rate of the Course

	Overall Satisfaction	Knowledge Acquisition	Tool Utility	Learning Outcome
Group A	15/15 (100%)	13/15 (86.7%)	12/15 (80.8%)	14/15 (93.3%)
Group B	15/15 (100%)	14/15 (93.3%)	13/15 (86.7%)	14/15 (93.3%)

all residents reported a high level of satisfaction at the end of course. Specifically, group B reported a higher level of satisfaction in knowledge acquisition than group A (93.3% vs. 86.7%, $p = 0.301$). A total of 86.7% of residents in group B and 80.8% in group A reported that they are adapted to use the new tools. Almost all residents (93.3%, groups A and B) stated that their learning goals were achieved (Table 2). Additional comments indicated that residents felt that the 3D models improved their knowledge of these specific surgical procedures.

DISCUSSION

Preoperative planning is very important for the safe performance of pancreatic resection. However, in a recent survey of approximately 5000 general surgery residents in the United States, only one-third of trainees reported they were being taught preoperative planning as part of their training.[12] The study presented here aimed to address the needs of surgical residents in surgical training by providing innovative technology to improve their preoperative planning skills.

3D printing is an innovative technology in simulation-based surgical education. For the first time, 3D-printed models enable rapid generation of patient-specific models for use in training. With further development of the technology and reduction in cost,[13] 3D-printed models have been increasingly used in surgical planning, skill training, and presurgery rehearsal.[8,11,14] By generating a physical model from 3D-rendered anatomy, our 3D-printed models give surgeons the opportunity to touch and manipulate the pancreas and explore its relationship with surrounding structures before an operation. Results from this study support our hypothesis that the quality of a preoperative plan is improved when residents had the opportunity to inspect the 3D-printed model.

The mechanism behind the superiority of using 3D-printed model has yet to be determined. However, we posit that at least 2 factors are at play. First, on-screen viewing of medical imaging only presents information to a surgeons' visual system, whereas the printed models enable them to immediately touch on the model and perceive in the shape and texture. This novel approach allows surgeons to use their hands and eyes together to enhance their mental model of a particular patient's anatomy. As surgeons need to develop sophisticated skills for sensing and manipulating their physical environments in the operative field,[15] this eye-hand coordination better mimics the key interactions encountered in the operating room.

Secondly, a surgeon's performance of pancreatic surgery is dependent on the understanding of individual, patient-specific variants of complex anatomical structures. Traditionally, physical simulation or animal models could not present patient-specific information that makes it difficult to provide an accurate teaching model.[16] The advent of 3D printing has enabled the economical generation of patient-specific models which has improved the quality of education provided by the simulated environment.[17] Moreover, 3D printing with a variety of materials has aided this teaching process considerably, given that the printer allows for the texture of the models to be tailored to specific educational needs. We believe that trainees prefer 3D-printed models over 3D-rendered images because of the higher fidelity of the printed materials.

Our last comment is on the use of 3D-printed models for presurgery rehearsal. The eventual goal would be to create a physical model that accurately represents tissue behavior of an internal organ. This would permit novice or inexperienced surgeons to practice a procedure in a safe environment outside of the operating room.[18] In addition to creating more effective teaching tools, this innovation has been driven by the desire to improve the quality of patient care safety.[19] In our recent project collaborating with the Surgical Simulation Research Lab at the University of Alberta, we have successfully created a hybrid simulation model by superimposed 3D structure on liver onto a pig liver, which allowed for performing liver resection or suturing around the liver lesion.

CONCLUSION

Results from this study support our hypothesis that the quality of preoperative planning for novice surgeons is improved with the integration of 3D-printed models. As 3D-printed technology is further integrated into surgical training and planning, we anticipate that patient-specific modeling and simulation would provide a useful tool for skill improvement outside the operating room and perhaps even improve patient safety in the operating room.

AUTHOR CONTRIBUTIONS

Concept and design: Y.L. Wu, and B. Zheng.

TABLE A1. The Quality of the Surgical Plan Questionnaire

Q1: Imaging findings of pancreas and adjacent organs?	QSP-a
Q2: Location and imaging findings of lesions?	QSP-a
Q3: Indirect findings resulted from invasion of tumors?	QSP-a
Q4: Anatomy marker to identify 4 parts of duodenum?	QSP-a
Q5: Whatever variants in Celiac trunk and mesentery artery system?	QSP-a
Q6: Location and shape of uncinate process of pancreas?	QSP-b
Q7: Anatomy character of portal vein system? Its relation with tumor?	QSP-b
Q8: What are important structures behind the duodenum related to tumor and surgery?	QSP-b
Q9: Which named vessels would be ligated during pancreatic surgery	QSP-b
Q10: Resection extension and sequence of adjacent organs (stomach, bile duct, jujenum, and pancreas)	QSP-b
Q11: What necessary anastomosis of digestive tracts? What sutures and instruments required?	QSP-c
Q12: Approaches of portal vein reconstruction?	QSP-c
Q13: Dilation of gall bladder and bile ducts? Effects on surgery procedure?	QSP-c
Q14: Whether to identify the pancreatic duct? Dilation or narrow? Effects on surgery procedure?	QSP-c
Q15: How to deal with gross intraoperative bleeding as assistants?	QSP-c

Data collection, analysis, and interpretation: Y.X. Zheng, J.G. Zhao, and D.F. Yu.

Manuscript preparation: Y.X. Zheng and B. Zheng.

APPENDIX A

See Table A1 for The Quality of the Surgical Plan Questionnaire.

REFERENCES

1. Whipple AO. The rationale of radical surgery for cancer of the pancreas and ampullary region. *Ann Surg*. 1941;114(4):612-615.
2. Mohammed S, Fisher WE. Quality metrics in pancreatic surgery. *Surg Clin North Am*. 2013;93(3):693-709.
3. Sadideen H, Alvand A, Saadeddin M, Kneebone R. Surgical experts: born or made? *Int J Surg*. 2013;11(9):773-778.
4. Spottiswoode BS, van den Heever DJ, Chang Y, et al. Preoperative three-dimensional model creation of magnetic resonance brain images as a tool to assist neurosurgical planning. *Stereotact Funct Neurosurg*. 2013;91(3):162-169.
5. Bogdanova R, Boulanger P, Zheng B. Three-dimensional eye tracking in a surgical scenario. *Surg Innov*. 2015;22(5):522-527.
6. Brennan DD, Zamboni G, Sosna J, et al. Virtual Whipple: preoperative surgical planning with volume-rendered MDCT images to identify arterial variants relevant to the Whipple procedure. *Am J Roentgenol*. 2007;188(5):W451-W455.
7. Haigron P, Luo L, Coatrieux JL. Issues in image-guided therapy. *IEEE Eng Med Biol Mag*. 2009;28(4):96-98.
8. Rengier F, Mehndiratta A, von Tengg-Kobligk H, et al. 3D printing based on imaging data: review of medical applications. *Int J Comput Assist Radiol Surg*. 2010;5(4):335-341.
9. Helling TS, Khandelwal A. The challenges of resident training in complex hepatic, pancreatic, and biliary procedures. *J Gastrointest Surg*. 2008;12(1):153-158.
10. Fonseca AL, Evans LV, Gusberg RJ. Open surgical simulation in residency training: a review of its status and a case for its incorporation. *J Surg Educ*. 2013;70(1):129-137.
11. Michalski MH, Ross JS. The shape of things to come: 3D printing in medicine. *J Am Med Assoc*. 2014;312(21):2213-2214.
12. Snyder RA, Tarpley MJ, Tarpley JL, Davidson M, Brophy C, Dattilo JB. Teaching in the operating room: results of a national survey. *J Surg Educ*. 2012;69(5):643-649.
13. He Y, Xue GH, Fu JZ. Fabrication of low cost soft tissue prostheses with the desktop 3D printer. *Sci Rep*. 2014;4:6973.
14. Memon MA, Brigden D, Subramanya MS, Memon B. Assessing the surgeon's technical skills: analysis of the available tools. *Acad Med*. 2010;85(5):869-880.
15. Rentsch S, Rand MK. Eye-hand coordination during visuomotor adaptation with different rotation angles. *PLoS One*. 2014;9(10):e109819.
16. Kneebone RL. Practice, rehearsal, and performance: an approach for simulation-based surgical and procedure training. *J Am Med Assoc*. 2009;302(12):1336-1338.

17. Qayumi K, Pachev G, Zheng B, et al. Status of simulation in health care education: an international survey. *Adv Med Educ Pract*. 2014;5:457-467.

18. Giovinco NA, Dunn SP, Dowling L, et al. A novel combination of printed 3-dimensional anatomic templates and computer-assisted surgical simulation for virtual preoperative planning in Charcot foot reconstruction. *J Foot Ankle Surg*. 2012;51(3):387-393.

19. Weber R, Aretz HT. Climbing the ladder from novice to expert plastic surgeon. *Plast Reconstr Surg*. 2012;130(1):241-247.