

RESEARCH REPORT

3D printing variation: Teaching and assessing hepatobiliary variants in human anatomy

Christian Myles  | Laura Gorman | James F. X. Jones 

Biomedical Section (Anatomy), School of Medicine, University College Dublin, Dublin, Ireland

Correspondence

Christian Myles, Biomedical Section (Anatomy), School of Medicine, University College Dublin, Dublin, Ireland.
Email: christian.myles@ucd.ie

Abstract

Textbook anatomy depiction of the hepatobiliary tree is present in 55%–62% of the population. Misidentification of hepatobiliary variants can lead to bile duct injuries in cholecystectomies. A better understanding of variants has been cited as a key area for improvement in anatomy education. The aim of this study was to compare the effectiveness of 3D printed models with hepatobiliary variants to conventional 2D image-based teaching and assessment. The study invited medical students to participate and were allocated to either a 2D image projection group or a 3D physical model group. Training sessions described arterial (5) and ductal (5) variant anatomy. While the 2D groups were taught with planar projections, the 3D group were taught variant anatomy using only 3D printed models. A multiple choice question form (with nine distractors per question) assessed identification of anatomical parts in both 2D images and tagged printed models for both groups. Thirty-four students participated in the study. The median total correct answer for 2D group was 83% (62%–94%) IQR, and 3D group was 83% (70%–94%) IQR. Both groups showed a significant increase in scores when assessed with 3D model, 2D and 3D groups (** $p=0.008$, 0.003 , respectively), two-tailed Wilcoxon-signed rank test. There was no difference in outcomes following two different methods of instruction (2D vs. 3D). However, both groups performed significantly better when tested on 3D models. This finding suggests that forms of assessment in anatomy may yield superior results when tailored to physical models.

KEYWORDS

3D printing, anatomy education, clinical anatomy, hepatobiliary variation, pedagogical research, surgical training

INTRODUCTION

The importance of learning anatomical variations and specifically hepatobiliary variations

Current methods for educating students and surgeons about anatomical variations include donor dissection, which is widely

recommended for teaching anatomy and variations in medical schools.¹ However, there is emphasis on introducing these variations in clinical phases and postgraduate training.¹ Surgical and radiology trainees primarily learn about variations from experienced clinicians and specialty textbooks.² Many training curricula lack specific classifications for trainees to learn, and some do not assess knowledge of variations at all.² To address these gaps, suggestions

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2025 The Author(s). *Anatomical Sciences Education* published by Wiley Periodicals LLC on behalf of American Association for Anatomy.

include creating a registry of encountered variations¹ and integrating variations earlier in medical education.³ These approaches aim to improve clinical practice outcomes and prevent surgical errors related to anatomical variations.

Learning about the significance of anatomical variants in preclinical years is seen to be beneficial in standardized medical curricula.³ Furthermore, an integrated curriculum linking other disciplines such as pathology to anatomy aids students' understanding of the clinical significance of variation.³ Three-dimensional (3D) printed models or a series of models displaying anatomical variations in other body regions may be beneficial for surgeries prone to iatrogenic complications. These models would serve to highlight potential surgical injuries, in surgeries such as appendectomy, as misidentification of vermiform appendix position can lead to bowel perforation and sepsis.⁴ Problems may arise post splenectomy because 15% of the population have an accessory spleen and thrombocytopenia can result from failure to remove all splenic portions.⁵ In the case of thyroidectomy, damage to recurrent laryngeal nerve(s) can occur after thyroid removal due to misidentification of the nerve's course or branching patterns.⁶ Learning specifically about hepatobiliary variants is important at this stage given higher proportions of the population will display variation compared to other regions of the body.⁷ Anatomical knowledge of this very common surgical site serves as an exemplar of the potential untoward consequences of variation.⁸

Textbook anatomy depiction of the hepatobiliary tree is present in only 55%–62% of the population.⁹ Misidentification of hepatobiliary variants can lead to bile duct injuries during cholecystectomies, and a better understanding of variants has been cited as a key area for improvement in clinical anatomy education.¹⁰ Anatomical variations in the cystic artery and cystic duct are common and can lead to complications during laparoscopic cholecystectomy. Cystic artery anomalies are the most prevalent, occurring in 16.8% of cases, followed by cystic duct variations at 11.4%.¹¹ These variations can increase the risk of intraoperative complications, including hemorrhage and bile leaks.¹¹ Rare variations, such as duplication of the artery to the cystic duct¹² and low medial insertion of the cystic duct,¹³ can be particularly challenging to identify and manage. The artery to the cystic duct, a consistent branch of the cystic artery, is present in 91.47% of cases and can cause troublesome bleeding if not properly identified.¹⁴ Accurate preoperative imaging and careful intraoperative identification of these structures are crucial to prevent vasculobiliary injuries and ensure successful outcomes in laparoscopic cholecystectomy procedures¹⁵ **Figure 1** highlights potential misidentification of hepatobiliary variants.

The common variations presented in this study are described in **Figure 2** with statistics to illustrate their presence in the population. Each variation has a corresponding code. The variants used are of cystic duct and cystic artery, as they are the key structures for correct identification and ligation during the operation.

Use of 3D printed models in anatomy education

Over the past 10 years, 3D printed models have become an increasingly utilized resource in anatomy education.^{16,17} Studies have shown that 3D printed models are superior or equally effective in achieving learning outcomes compared to other resources such as donor material, physical models, and 2D image atlases currently used in the anatomy laboratory.^{17–23} In a recent meta-analysis,²⁴ 10 out of 17 studies analyzed compared 3D printed models versus 2D images and found a significant difference in test scores in favor of 3D printed models. The efficacy of 3D printed models have also been reported in terms of student response time,^{25–27} utility,^{28–30} student satisfaction,^{27,28,31–34} and anatomical accuracy.³⁵ For each of these parameters, 3D printed models have been shown to be significantly superior educational tools.

While 10 out of 17 studies cited in Ref. [24] showed that 3D printed models had favorable outcomes compared to control groups using 2D images. The other seven studies compared 3D printed models to a different control group; these included donor materials (four studies), plastic models (two studies), and atlases (one study, which was not included in the 2D image analysis by Ref. [24]). Ye et al.²⁴ report favorable outcomes for 3D printed models in the donor control studies and specific outcomes in terms of usefulness and student satisfaction for 3D printed models over plastic models, while 3D printed models improved the learning curve associated with base of skull anatomy compared to consulting an atlas.

There are few studies that show no effect or inferiority of 3D models compared to control groups. Although a recent paper from Cheung et al., investigating the use of 3D customized 3D printed head and neck models, showed numerically that a 2D image group outperformed a 3D printed model group. The potential reason for this finding was that the 2D image group were less cognitive overloaded compared to interactive modalities, given that the 2D group obtain high scores in recall type questions with respect to other groups with dissections, digital animations and 3D printed models.³⁶

Echoing Ye et al.,²⁴ another meta-analysis focusing on the effectiveness of 3D printed models in anatomy education³⁷ found that 3D printed models have a positive impact on anatomy education for medical students, but interestingly, not for resident physicians. This suggests that the inferiority of 3D models may be audience dependent. The study's findings emphasize the importance of utilizing 3D printed models in the early stages of a medical degree for maximum impact.

Is use of 3D printed models region specific too? Superiority of 3D printed models over controls consisting of plastic models and body donor dissections was not found in two studies of cardiac anatomy and pathology.^{18,27} Both studies cite the limitations of the technology, such as failure to replicate realistic weight, texture, color, and tactile quality of the real anatomy. It is possible that the region itself

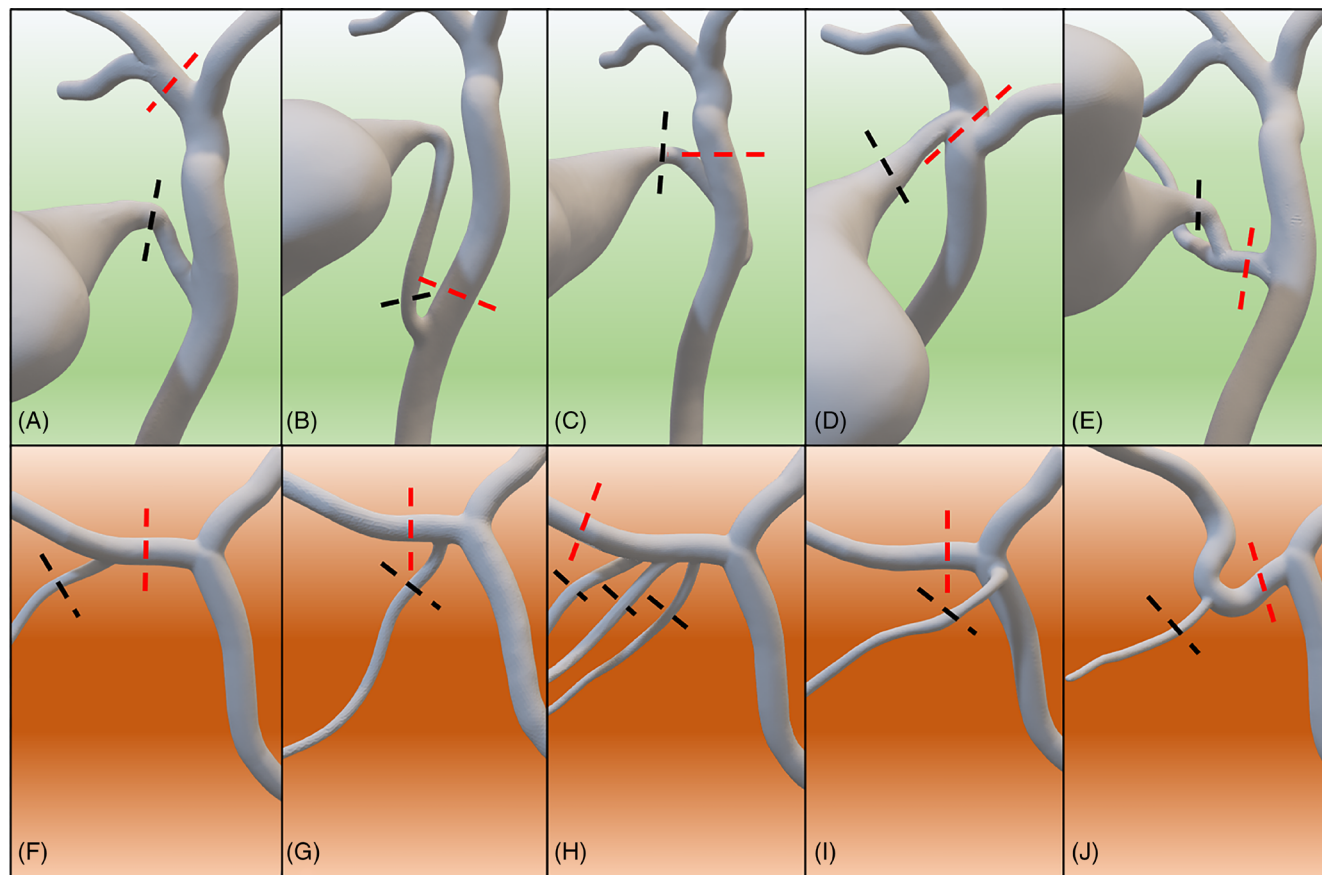


FIGURE 1 Diagrammatic presentation highlighting potential misidentification of hepatobiliary variants. (A) Angular insertion of cystic duct to common hepatic duct (75%); (B) cystic duct parallel to common hepatic duct (20%); (C) posterior spiral insertion of cystic duct to common hepatic duct (5%); (D) cystic duct enters right hepatic duct (0.6%–2.3%); (E) anomalous right sectional duct (0.5%–1.3%); (F) The cystic artery passing anterior to the common hepatic/bile duct (17.9%); (G) a short (<1 cm) cystic artery (9.5%); (H) multiple cystic arteries (8.9%); (I) the cystic artery located inferior to the cystic duct (4.9%); (J) Moynihan's hump (1.3% to 13%). Black dashed lines represent structures to be incised (A–E) cystic duct and (F–J) cystic artery. Red dashed lines represent the incision of misidentified hepatobiliary anatomy (A, D) right hepatic duct (B, C) common hepatic duct, (E) anomalous right sectional duct and (F–J) right hepatic artery.

was not complicated enough to see a significant difference, and perhaps, regions exhibiting greater frequency of variant anatomy would be impacted more by 3D printing variation.

Studies that have shown superiority of 3D printed models compared to other educational resources did not include anatomical variation in their design. Interestingly, little has been done regarding 3D printing anatomical variation for anatomy education, Bonfiglio and Richter study found no impact on knowledge assessment of 3D printed variations of internal iliac artery compared to plastic models and cadavers for allied health graduates.³⁸

What is 3D printing and why create a digital model archive?

3D printing is an additive manufacturing technology invented more than 40 years ago³⁹ as a strategy to rapidly prototype digital designs for testing and refinement of products in a low-cost setting. 3D printing technologies, specifically fused deposition manufacturing (FDM), can produce a 3D object by sequentially depositing thermoplastic

polymers in layers along the z-axis. FDM utilizes an increasingly varied type of thermoplastic polymer. The most commonly used filament is polylactic acid (PLA) which, although easy to print, produces a hard, brittle model. Alternatives such as thermoplastic polyurethane (TPU) filament have a flexible quality, which makes models more robust, and printed structures can be manipulated with TPU of varying Shore hardness. Advances in the range of materials that can be printed have allowed the authors to produce realistic, anatomically, and dimensionally accurate models.

Within an educational institution, a single trimester's cohort of body donors is unlikely to supply the complete spectrum of hepatobiliary variants. A superior strategy may be to create physical models via 3D printing and archive digital models of human anatomical variations and then manufacture these on demand.

Digital data sources

Digitally sourced data of human anatomical structures required for 3D printing can be obtained from multiple sources. These consist of

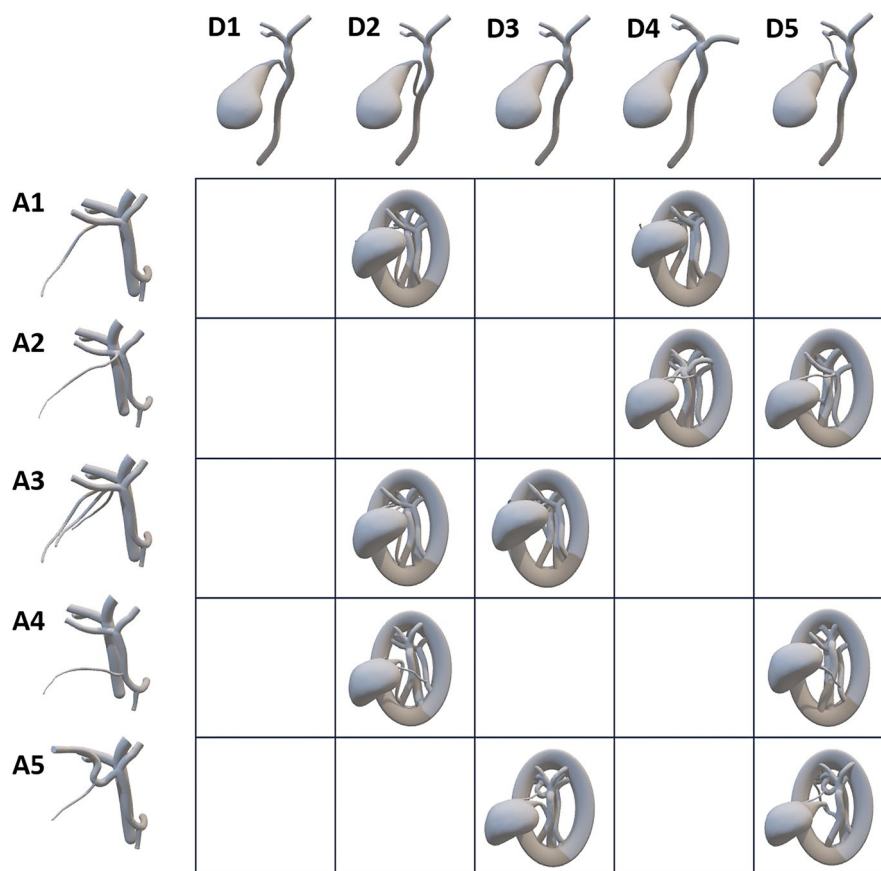


FIGURE 2 Digital model matrix of hepatobiliary variants. A 5 × 5 matrix was created in which rows display arterial variants and columns display ductal variants. Of the possible twenty five variants 10 were randomly selected for 3D printing and illustrated with respect to their position in the matrix. A1 The cystic artery passing anterior to the common hepatic/bile duct (17.9%); A2 a short (<1 cm) cystic artery (9.5%); A3 multiple cystic arteries (8.9%); A4 the cystic artery located inferior to the cystic duct (4.9%); A5 Moynihan's hump (1.3%–13%); D1 angular insertion of cystic duct to common hepatic duct (75%); D2 cystic duct parallel to common hepatic duct (20%); D3 spiral insertion of cystic duct to common hepatic duct (5%); D4 cystic duct enters right hepatic duct (0.6%–2.3%); D5 anomalous right sectional duct (0.5%–1.3%).

patient or donor computed tomography (CT) or magnetic resonance imaging (MRI) scans. However, processing these high resolution images is often labor intensive, even with modern semi-automated segmentation software. An alternative approach is to access open-source databases. Body Parts 3D⁴⁰ is one such database that offers free access to downloadable digital models for the human body and operates under creative commons license CC-BY-SA: <https://dbarc.hive.biosciencedbc.jp/jp/bodyparts3d/lic.html>.

The online repository, BodyParts3D was created from a voxel human model of a male individual called "TARO." The original paper by Nagaoka et al. describes the male volunteer, 22 years old, 172.8 cm tall, and weigh 65 kg, undergoing safe nonionizing imaging (MRI) to produce a whole body data set.⁴¹ A detailed universal informed consent for all potential applications of the digital models is not possible, as the future is unknown (e.g., 3D printing was not available to anatomists at the time of these papers). However, the authors believe that the application described in this work is consistent with the wishes of

the volunteer as it benefits biomedical research and clinical practice (as outlined in Ref. [40]). In addition, the use of the models conforms to the noncommercial licensing agreement of Mitsuhashi et al.⁴⁰ As missing details were supplemented using a 3D editing program by referring to textbooks, atlases, and mock-up models by medical illustrators,⁴⁰ the biliary system available in BodyParts3D is probably not that of TARO. This case highlights the complexities that can surround reproduction of a 3D likeness of a specific anatomical donor which is of growing concern to the medical education community.

Nevertheless, the authors believe that digitally modifying a standard anatomy from a single human subject is a superior approach to waiting for rare variants to appear for CT or MRI scanning, as this cannot be completed within a reasonable timescale for a relatively small body donor program.

The aim of this study was to compare the efficacy of standard 2D image-based teaching of novel digitally designed hepatobiliary variants with teaching conducted using 3D printed physical models.

METHODS

Digital model creation

A digital hepatobiliary model was obtained from Body Parts 3D (<https://lifesciencedb.jp/bp3d/?lng=en>). The model was split into three core parts consisting of the gallbladder/hepatobiliary tree, portal vein, and associated arterial supply. This method of working from a fixed model set meant that the anatomical position and dimensional accuracy could be maintained among the three elements and offered a framework to construct sequential variants. In order to accurately reproduce variants informed by the literature,^{42–51} digital manipulation of the template files was carried out using a computer-aided design (CAD) software, Autodesk® Meshmixer®. Models were later imported into another CAD program, Autodesk® Fusion

360®, and an oval ring was applied to the models and embossed with the models' ID code (Figure 3).

Manufacture of digital models

Completed digital models were imported as .STL files and sliced in Prusa Slicer® version 2.3.0. Two sets of models were printed, training and assessment models, using different materials. Training models were printed with PLA as the 5 ductal and 5 arterial variants were printed as separate prints, that is, one print equaled one variant in isolation, therefore, these training sets did not need to be manipulated, as they were manufactured to display only one structure. While the assessment models were printed in flexible TPU that enabled the user to manipulate the models to reveal underlying or



FIGURE 3 3D printed hepatobiliary variant test models. Ten FDM printed (Filatech FilaFlexible 40 TPU) models that were randomly selected from 25 possible variants were utilized for the assessment of student knowledge. The yellow arrow indicates the position of a ligature on one model. Ligatures were randomly assigned to target structures on each model in order to test structure identification.

TABLE 1 Filament print settings.

	Prusament®	Filatech FilaFlexible 40 TPU
Filament name	'Vanilla White' (Prusa Research, Czech Republic)	'Natural White' (Filatech 3D Printing Industries FZC, United Arab Emirates)
Filament type	PLA	TPU
Nozzle temperature (°C)	215	230
Bed temperature (°C)	60	50
Extrusion multiplier	1	1.1
Layer height (mm)	0.15	0.15
Gyroid infill density (%)	15	0
Perimeter layers	2	2
Top layers	7	7
Bottom layers	5	5

Note: The table displays print setting for chosen filaments, Prusament® PLA 'Vanilla White' (Prusa Research, Czech Republic) and Filatech FilaFlexible 40 TPU 'Natural White' (Filatech 3D Printing Industries FZC, United Arab Emirates).

posterior structures as these models were manufactured with a combination of two variants (one ductal and one arterial). In addition, the assessment models flexibility allowed for the application of ligatures around target structures. Training models were printed, with supports selected, using Prusament® PLA in "Vanilla White" (Prusa Research, Czech Republic). Assessment models were printed with supports selected, using Filatech FilaFlexible 40 TPU filament in "Natural White"; Table 1 describes filament-specific print settings. Filatech FilaFlexible 40 TPU produces a flexible print with a shore hardness of 40 on the D scale (Figure 2). The D scale is one of the Shore durometer hardness scales used to measure the hardness of materials, particularly polymers and elastomers. The scale ranges from 0 to 100, with higher values indicating harder materials. A Shore hardness of 40 on the D scale would be considered relatively soft within the range of materials typically measured using this scale.⁵²

Care was taken when printing with TPU to apply a layer of glue stick to the build surface to prevent destructive bonding with the coated build surface. Postprocessing of all printed models (PLA- and TPU-based) consisted of removal of support material using a needle nose pliers and a heat gun Bosch® (Robert Bosch GmbH 2024®, Germany) set to 250°C.

Models were not printed in color for two reasons. First, the authors thought that coloring the structures would not yield realistic results as the filament color palette is limited. Second, the user's ability to trace the origin and course of a structure to confirm its identity was deemed to be of educational value and approximates more closely a dissection and surgical experience. Blue veins, red arteries, and green bile ducts may be common in commercial models but are not seen in reality. This is why indocyanine green fluorescence is useful to identify bile ducts from vessels.

In relation to the seven principles of design, models are justified, based on first, emphasis: models only focus on variants of hepatobiliary anatomy. Second, alignment and balance: models are minimalist in form, therefore, only contain pertinent anatomy that is required for specific learning objectives. Third, contrast: structures can be differentiated by tracing them back to origins. Fourth, repetition: models are easily reproducible via 3D printing technology. Fifth, proportion: models are dimensionally and anatomically accurate. Sixth, movement: the flexibility of assessment models allows movement for structure identification and ligation. Last, seventh, white space or empty space that surrounds the main elements: this is achieved by the models' oval ring which frames the hepatobiliary anatomy.

Demographic and academic background of participants

As per Table 2, there was no difference with regards to age of participants nor division of male to female among groups. The participants are enrolled in their last years of preclinical study, stage 3 (of 6) undergraduate medicine program and stage 2 (of 4) graduate entry medicine

TABLE 2 Demographic background of participants.

	2D group (n = 18)	3D group (n = 17)	p-value
Age			
Median (IQR)	23 (20–25)	24 (20–27)	
Mean (±SD)	23 (±3)	24 (±4)	0.294 ^a
Gender			
Female	11	11	
Male	7	6	0.825 ^b

Note: The table displays demographic background of the study's participants including age and gender of the participants in the 2D and 3D groups.

Abbreviation: IQR, interquartile range.

^aPaired student's *t*-test.

^bChi-squared test.

program. Graduate entry medical students have previously graduated from other courses (in science, arts, humanities, etc.) but are deemed medical undergraduates and do not have additional hepatobiliary anatomy compared to the 6-year program students. All participants received the same lecture material delivered by the same lecturer. Participants learned about hepatobiliary anatomy 4 weeks prior to the study and received a midterm assessment 2 weeks prior to the study. Baseline knowledge level of the anatomy of this region was established from students' previous midterm examination performance in a module on gastrointestinal and liver anatomy.

Training sessions

The 2D image projection taught group and 3D physical model taught group received a single 10-min training session conducted in separate tutorial rooms. This session covered the same content for both groups and included the importance of variant anatomy, a review of the main structures associated with the hepatobiliary tree and an explanation of each arterial and ductal variants. Two training sets were used; set one displayed ductal variants with the gallbladder as a reference point and set two, the arterial variants with the portal vein as a reference point. Variants were taught to the 2D taught group using screen projected 2D images of the 3D digital models created by PowerPoint's 3D model insertion function (Microsoft®, United States). These presented an anterior projection of models in the anatomical position and an oblique projection, with models viewed at 10 degrees to the transverse plan in a cephalic direction. The 3D taught group were taught variant anatomy using only 3D printed models.

Assessment

Once training was complete, both the 2D and 3D taught groups received the same assessment, which consisted of two separate 10 multiple choice questions (MCQs). The assessment was delivered

using a traditional spotter format in the Anatomy Laboratory, where a 3D model and 2D projection image of variations were placed on individual tables, along with an MCQ-style question. Each 10-part MCQ was either focused on a 2D image (part A) or a 3D printed model (part B) and both paper and model were tagged to highlight a target structure for identification. Students were asked to identify the target structure by placing an "X" beside the correct answer on the answer sheet given (Figure 4). Students were randomly assigned to a table to begin with and worked through the examination of all 10 variations by moving from one table to the next in a timed manner. The timer was reset every minute, which was the allocated maximal duration for each question. Students were allowed to hold and manipulate the 3D printed assessment models. On completion of each question, the students noted the time in seconds from the timer displayed on an overhead digital monitor screen.

The 10 taught variations comprised of (Figure 2 references variant codes)

1. A1 The cystic artery passing anterior to the common hepatic/bile duct (17.9%) and D2 cystic duct parallel to the common hepatic duct (20%).
2. A1 The cystic artery passing anterior to the common hepatic/bile duct (17.9%) and D4 enter the right hepatic duct (0.6%–2.3%).
3. A2 a short (<1 cm) cystic artery (9.5%) and D4 cystic duct enters right hepatic duct (0.6%–2.3%).
4. A2 a short (<1 cm) cystic artery (9.5%) and D5 anomalous right sectional duct (0.5%–1.3%).
5. A3 multiple cystic arteries (8.9%) and D2 cystic duct parallel to common hepatic duct (20%).
6. A3 multiple cystic arteries (8.9%) and D3 spiral insertion of cystic duct to common hepatic duct (5%).
7. A4 the cystic artery located inferior to the cystic duct (4.9%) and D2 cystic duct parallel to common hepatic duct (20%).

8. A4 the cystic artery located inferior to the cystic duct (4.9%) and D5 anomalous right sectional duct (0.5%–1.3%).
9. A5 Moynihan's hump (1.3%–13%) and D3 spiral insertion of the cystic duct to the common hepatic duct (5%).
10. A5 Moynihan's hump (1.3%–13%) and D5 anomalous right sectional duct (0.5%–1.3%).

Statistical analysis

MCQ assessment design

The optimal number of distractors for a 10 question MCQ was determined using the binomial confidence interval.⁵³ The following online calculator was used: <https://statpages.info/confint.html>. In order to be 95% confident that students would not achieve a pass score of 40% by guessing, a one out of 10 choice format was used. For this particular format, the expectation due to guessing is 10%, and 95% of values lie below 39% only when 10 questions are used.

Power analysis

A one grade increase in student performance was deemed to represent a significant size of effect (Cohen's *d*) between the two modes of training. The authors' institute uses a grading system from A to G and each grade has three subdivisions (e.g. A+, A, A-). A score is converted to a grade using a linear transformation where every subdivision is worth 5%. Therefore, to move from grade A to B requires a 15% change (stepwise from A- to B+ to B). This difference of one letter grade or 15% was selected as an academically significant size of effect. The estimated co-efficient of variation (SD/mean) was derived from students' previous midterm examination performance in

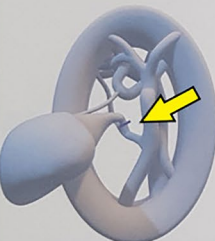
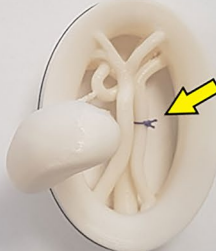
From the list, place a cross indicating the correct structure marked in A and B

Question 1.

	A		B
Portal Vein	☐	Portal Vein	☐
Cystic Duct	☐	Cystic Duct	☐
Common Bile Duct	☐	Common Bile Duct	☐
Right Hepatic Duct	☐	Right Hepatic Duct	☐
Left Hepatic Duct	☐	Left Hepatic Duct	☐
Right Sectional Duct	☐	Right Sectional Duct	☐
Proper Hepatic Artery	☐	Proper Hepatic Artery	☐
Cystic Artery	☐	Cystic Artery	☐
Right Hepatic Artery	☐	Right Hepatic Artery	☐
Left Hepatic Artery	☐	Left Hepatic Artery	☐

Time

Question 1

(A)

(B)

FIGURE 4 Assessment question and answer sheets. The left panel shows a sample multiple choice sheet for question 1 parts A and B. For each assessment station, the question stem was "On which anatomical structure is the ligature tied?" Each question had nine distractors to minimize success due to guessing. The students were asked to mark the best answer with a cross and include the time to complete each question in seconds. The right panel shows a 2D image projection (Q1 part A) and a 3D printed physical model (Q2 part B). The yellow arrows indicate digitally marked or physically ligated target structures for Question 1 (part A and B).

a module on gastrointestinal and liver anatomy (mean 76%, SD 12%, CV 16%). The following formula was used to calculate the number of students (n) per group at 80% power, and an alpha value of 0.05: $n = 16 [(CV/d)^2]$; $n = 16 [(16/15)^2]$, therefore, $n = 18$ per group, $n = 36$ total. Wang advises that power analysis should not be applied retrospectively and recommends presenting study effect size, our effect size was zero. Compare Figure 5 medians are identical and interquartile range overlap.⁵⁴

Normality test

A test of normality (Shapiro–Wilk test) was performed for data sets of total time, mean time per question, total MCQ scores, and scores for the two forms of assessment (2D images and 3D models). Data that were not normally distributed are expressed as median and IQR (25%–75%). MCQ scores were analyzed with a two-tailed Wilcoxon-signed rank test. Normally distributed data are expressed as mean (SEM). A paired Student's t -test was used to compare total time and mean time per question. The criterion for statistical significance was $p < 0.05$.

Academic performance

In order to check academic parity between groups, students' grade point average (GPA) were analyzed with a two-tailed Wilcoxon-signed rank test set to $p < 0.05$. The GPA score was based on the students' performance in gastrointestinal and liver anatomy modules.

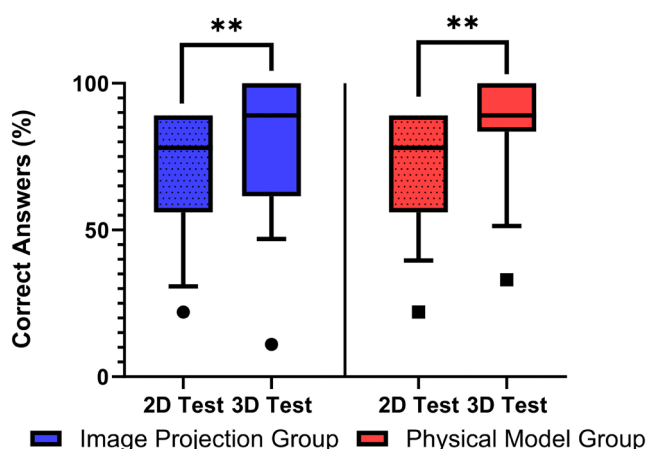


FIGURE 5 2D taught group versus 3D taught group assessment results. The box and whisker plots illustrate the percentage of correct answers for the 2D and 3D tests. The group taught with image projection is indicated in blue, and the group taught with physical models is indicated in red. Although the form of training had no effect on scores, the form of assessment did. Both groups showed a significant increase in scores when assessed with 3D models (2D taught group and 3D taught group, $**p = 0.008$, $p = 0.003$, respectively, two-tailed Wilcoxon signed-rank test).

Ethical approval

This study was approved as a low-risk study by University College Dublin's Human Research Ethics Committee Sciences with research ethics reference number: LS-C-23-93-Myles-Jones.

RESULTS

Assessment models printed using Filatech FilaFlexible 40 TPU produced a flexible model in which anterior structures could be manipulated to identify the posterior anatomy, allowing target structures to be ligated similar to a prosected specimen used in a spotter examination. In addition, a hollow gallbladder and biliary ductal system conferred a more realistic feel to the models (Figure 3).

Thirty-six students were required for the study, and in the end, 35 students volunteered. One student partially completed the study (Part A only) and as the study design involved paired analysis, these results had to be omitted from the study. This left 17 participants in the 2D taught group and 17 participants in the 3D taught group. Due to a clerical error, the MCQs were marked out of nine questions instead of ten.

Students' GPA comparison among two groups found no significant difference in academic performance using a two-tailed Wilcoxon-signed rank test ($p = 0.28$). The median GPA for the 2D taught group was 3 (2.9–3.7 IQR), and 3D taught group was 3.6 (2.9–3.8 IQR). Equally there was no difference in the performance of the two randomly created groups in the midterm assessment using a two-tailed Wilcoxon-signed rank test ($p = 0.25$), where median midterm assessment score for 2D taught group was 85% (68.75%–90% IQR), and 3D taught group was 90% (77.5%–92.7% IQR).

While the data relating to total time and mean time per question were normally distributed for both the 2D taught group and the 3D taught group, the MCQ scores were not normally distributed.

No significant difference was observed with total time and mean time per question comparing 2D and 3D taught groups using a two-tailed paired Student's t -test ($p = 0.59$, $p = 0.67$, respectively). Mean total times for 2D taught group and 3D taught group were 300s (SEM 13.6) and 274s (SEM 21.6). Both groups had similar mean time per question, 33s (SEM 1.5) 2D taught group and 31s (SEM 2.4) 3D taught group.

No significant difference was observed comparing total correct answers for the 2D and 3D taught groups using a two-tailed Wilcoxon-signed rank test ($p = 0.25$). The median total correct answer for the 2D taught group was 83% (62%–94% IQR), and the median total correct answer for the 3D group was 83% (70%–94% IQR).

A significant difference was observed for MCQ scores, with the questions related to the printed models achieving higher scores for both groups. A significant difference was observed in MCQ score related to the 3D prints in both the 2D taught group and the 3D taught group ($p = 0.008$, $p = 0.003$, respectively). The 2D taught group median scores for the 2D projection image was 78% (56%–89%) and this rose significantly to 89% (62%–100%) when tested on the printed models ($p = 0.008$). The 3D taught group also exhibited

this phenomenon, the median score for the paper test was 78% (56%–89%) but significantly higher at 89% (84%–100%) when tested with the printed models ($p=0.003$) (Figure 5).

DISCUSSION

This study succeeded in creating a novel and expansive set of anatomical variants relating to the human hepatobiliary tree. Three-dimensional printing can produce low-cost models of this regional anatomy and across common and uncommon variations.

Models were initially formed by an online repository, and variant anatomy was created from extensive sources of literature comprising two donor studies ($n=82$,⁴⁴ $n=40$ ⁴³), four laparoscopic cholecystectomy studies ($n=1850$,⁴³ $n=600$,⁴⁵ $n=4326$,⁴⁶ $n=600$ ⁴⁷), two MRCP studies ($n=307$,⁴⁹ $n=198$ ⁵⁰), and one meta-analysis study consisting of four donor studies⁵¹ ($n=41$, $n=100$, $n=150$, $n=50$), two cholangiogram studies ($n=8194$, $n=300$), and one MRCP study ($n=299$) to evaluate the quality of the models. Anatomical accuracy of the models was evaluated by professors of anatomy and surgery.

It was the authors' intention to make digital models easily printable with addition of an oval ring to aid in 3D printing by increasing print bed adhesion and reducing support materials. The oval ring was a key feature to keep structures in the anatomical position and extend the models' longevity.

A key feature of the assessment models was their flexibility, as the two variant TPU manufactured combinations (one ductal and one arterial) enabled the user to manipulate the components to reveal underlying or posterior structures for identification purposes. In addition, assessment models' flexibility allowed for the application of ligatures around target structures.

While training models were printed with rigid PLA as the 5 ductal, and 5 arterial variants were printed as separated prints, that is, one print equaled one variant in isolation, therefore, these training sets did not need to be manipulated, as they were manufactured to display only one structure.

In modern curricula, there is limited time for careful dissection of hepatobiliary structures. Often the removal of the liver is the primary dissection aim which leaves the biliary ducts and associated vasculature damaged collaterally. In addition, the teaching of hepatobiliary variants may be confined to a single slide in a lecture series. However, it is easy to argue that the hepatocystic triangle should be a core concept in the anatomy curriculum.⁵⁵ Damage to the common bile duct is still a relatively common untoward effect of laparoscopic cholecystectomy⁵⁶ which is one of the most common surgical operations in the world. A digital library of anatomical variants or a registry of encountered variations as suggested by Ref. [1] and on-demand 3D printing overcomes the logistical difficulty of collating a complete prosected set of unusual variants.

A surprising finding of the present study is the lack of difference in the efficacy of teaching via 2D projected images versus teaching with 3D physical models as judged by student knowledge and speed of response. This lack of effect is unlikely to be due to an

underpowered study as a prospective power analysis had been conducted and the median scores between the two groups were not just similar but identical. This effect is also not due to an underlying difference in prior knowledge of the two groups. Although the students were randomized to groups, there was no chance difference in baseline academic aptitude between student groups (i.e. their prior GPA scores were similar and there was no difference in the performance of the two randomly created groups in the midterm assessment).

The finding suggests that the standard of teaching was equal between groups and/or that 3D printed models offer equivalent educational value to conventional 2D projected images. However, the crossover design showed that regardless of the format of teaching, exam performance for both groups can be enhanced if students are examined with 3D printed models. Unfortunately, our design did not allow us to determine if the students spent more (or less) time examining the 3D model than looking at projected images as only the total time was measured for parts A and B of the assessment.

The addition of 3D printed models into spotter assessment is a recommendation of the authors based on our findings. We believe that the inclusion of these models will enhance assessment by providing testable resource material that is not present in the institute's current donor population or prosections. Furthermore, labor, cost of equipment, facility, health, and safety impacts of producing and storing donor and prosection materials are far more in comparison to producing 3D prints.^{17,18} Additionally, 3D printed models can include different degrees of difficulty by adding or subtracting major or minor anatomical structures. This tailored approach allows a series or spotter-specific set of models with varying degrees of difficulty, and via 3D printing can be multiplied to run spotters with higher student numbers at far faster and more efficient rates compared to traditional spotters. This multiplicative approach could solve the disadvantage of spotter assessment described by Smith and McManus,⁵⁷ where resource duplication could permit simultaneous examination.

Our study, similar to that of Garg et al.⁵⁸ used two viewpoints to display a digital model in a training session (key view for Garg et al. and in our case the 2D projection group). From our findings and that of Garg et al. it was evident that two viewpoints were sufficient to obtain understanding of anatomy. However, the Garg et al. study design restricted manipulation of a digital model to a single axis in the multiple-view cohort. However, there is a greater potential for identifying a structure based on its position and anatomical relations when a model can be viewed in multiple axes.

Potential reasons why use of 3D models outperformed 2D images are that students could interact with 3D models during the assessment, manipulating models to optimal viewpoints to determine structure identity. Students were familiar with identifying anatomical structures in 3D from donor dissection, prosections, and model interaction due to prior practical experiences. There could be an association with location, as assessment was in the dissection laboratory, which is mainly used for 3D learning, whereas the lecture theater is predominantly associated with 2D projection. The novelty of 3D models may have attracted the attention of the students to

spend longer time accurately identifying 3D models, as students' prior exposure to 3D printing would have been limited in order anatomy modules. However, it was not possible to ascertain if students paid more attention to the 3D printed models compared to the 2D images because we did not separately time each one but rather noted the overall exam time.

It may be considered that a single static 2D image is inherently inferior to a 3D physical model which can be manipulated and therefore the results may appear unsurprising. However, every 2D image was optimally rotated and projected to clearly visualize the tagged item (Figure 4). In addition, our cross-over design has shown that the 2D taught group performed similar to the 3D taught group (Figure 5). This is unexpected if 2D projected images negatively impact identification of structures. Furthermore, it should be noted that 2D and 3D modalities were tested sequentially *en bloc* without interruption or feedback.

Our findings suggest that allowing students to interact with 3D physical models during an anatomy "spotter" can produce higher test scores for structure identification. This result also suggests that the recent move away from the traditional spotter format of assessment to an online assessment platform may negatively affect student scores. This move to a digital mode of assessment has already been made by many institutes after the COVID-19 pandemic, with many seeing benefits in terms of reduction in staff labor, resources, logistics, and student stress⁵⁹ However, traditional spotters may still be worthwhile, as it is less likely that question banks leak to future student cohorts, and questions are generally object-specific. In addition, students are examined on familiar resources (donors, dissections, models, and images) that they have been examined on throughout their practical sessions. Spotters can include higher levels of Bloom's taxonomy⁶⁰ and our findings suggest that students' grades may increase with physical models compared to 2D images only. A practical subject such as anatomy, which is taught through interaction with physical objects, is suitably assessed by the same means.

The advances in modern printable materials and imaging and 3D printing technology are allowing the use of 3D printed models to gradually move from static display models to procedural-based models, where dissection and surgeries can be simulated.^{61,62} Medical students of the future may be dissecting 3D printed donors to achieve broader, richer skill sets as clinical knowledge is increasingly delegated to artificial intelligence systems.

LIMITATIONS OF THE STUDY

One student had to be omitted from the study due to an incomplete answer sheet. As the individual timings for parts A and B of the test were not measured, it was not possible to ascertain if students paid more attention to the 3D printed models compared to the 2D images. This study was constrained in its analysis of students' retention of anatomical information. The test immediately followed the teaching session. There was no follow-up testing to evaluate if the students of the two groups retained knowledge differently.

Another potential limitation of the study is the finding that 2D and 3D taught groups both scored highly in their midterm assessment, and it may be the case that they reached a saturation point in learning, making it harder to detect differences between cohorts. However, albeit students learned the common textbook biliary anatomy well prior to this investigation, they were not familiar with the variant anatomy.

CONCLUSIONS

Teaching variant anatomy of the human hepatobiliary system through the use of either 2D projected images or 3D printed physical models yields equivalent results in terms of knowledge and speed of response. However, allowing students to interact with 3D physical models during an anatomy "spotter" produces higher test scores for tests of structure identification. In conclusion, this 3D printed collection of hepatobiliary variants carries value in the assessment of anatomical knowledge.

AUTHOR CONTRIBUTIONS

Christian Myles: Conceptualization; methodology; formal analysis; data curation; writing – review and editing; writing – original draft; visualization; software; resources; validation; investigation; project administration. **Laura Gorman:** Methodology; software; formal analysis; data curation; visualization; writing – review and editing; investigation; conceptualization; validation; writing – original draft. **James F. X. Jones:** Conceptualization; formal analysis; supervision; writing – review and editing; methodology; investigation; validation; writing – original draft; funding acquisition; visualization.

ACKNOWLEDGMENTS

The authors would like to acknowledge the medical students of University College Dublin who volunteered to be a part of this study.

ORCID

Christian Myles  <https://orcid.org/0000-0002-8138-6544>

James F. X. Jones  <https://orcid.org/0000-0002-1997-4257>

REFERENCES

1. Alraddadi A. Literature review of anatomical variations: clinical significance, identification approach, and teaching strategies. *Cureus*. 2021;13(4):e14451.
2. Raikos A, Smith JD. Anatomical variations: how do surgical and radiology training programs teach and assess them in their training curricula? *Clin Anat*. 2015;28(6):717–24.
3. Asghar A, Patra A, Naaz S, Kumar R, Babu CSR, Singh B. Investigating the integration of anatomical variabilities into medical education as a potential strategy for mitigating surgical errors. *J Anat Soc India*. 2024;73(1):70–81.
4. Ghorbani A, Forouzesh M, Kazemifar AM. Variation in anatomical position of vermiform appendix among Iranian population: an old issue which has not lost its importance. *Anat Res Int*. 2014;2014:313575.
5. Vikse J, Sanna B, Henry BM, Tattera D, Sanna S, Pekala PA, et al. The prevalence and morphometry of an accessory spleen: a

- meta-analysis and systematic review of 22,487 patients. *Int J Surg*. 2017;45:18–28.
6. Chiang FY, Lu IC, Chen HC, Chen HY, Tsai CJ, Hsiao PJ, et al. Anatomical variations of recurrent laryngeal nerve during thyroid surgery: how to identify and handle the variations with intraoperative neuromonitoring. *Kaohsiung J Med Sci*. 2010;26(11):575–83.
 7. Kowalczyk KA, Majewski A. Analysis of surgical errors associated with anatomical variations clinically relevant in general surgery. Review of the literature. *Transl Res Anat*. 2021;23:100107.
 8. Wysiadecki G, Varga I, Klejbor I, Balawender K, Ghosh SK, Clarke E, et al. Reporting anatomical variations: should unified standards and protocol (checklist) for anatomical studies and case reports be established? *Transl Res Anat*. 2024;35:100284.
 9. Naeem MQ, Ahmed MS, Hamid K, Shazlee MK, Qureshi F, Asad UM. Prevalence of different hepatobiliary tree variants on magnetic resonance cholangiopancreatography in patients visiting a tertiary care teaching hospital in Karachi. *Cureus*. 2020;12:e12329.
 10. Brunt LM, Deziel DJ, Telem DA, Strasberg SM, Aggarwal R, Asbun H, et al. Safe cholecystectomy multi-society practice guideline and state of the art consensus conference on prevention of bile duct injury during cholecystectomy. *Ann Surg*. 2020;272(1):3–23.
 11. Gupta R, Kumar A, Hariprasad CP, Kumar M. Anatomical variations of cystic artery, cystic duct, and gall bladder and their associated intraoperative and postoperative complications: an observational study. *Ann Med Surg*. 2023;85(8):3880–6.
 12. Mariolis-Sapsakos T, Zarokosta M, Nikas D, Foutsitzi A, Angelis S, Noussios G, et al. Duplication of the artery to the cystic duct: a case report of a rare anatomical variation with surgical significance. *Oman Med J*. 2022;37:e410.
 13. Yu JJ, Morell M, Lee JG, Imagawa DK. A case report on a rare anatomic variant of cystic duct insertion. *J Surg Case Rep*. 2017;2017:rjx131.
 14. Rashid A, Mushtaque M, Bali RS, Nazir S, Khuroo S, Ishaq S. Artery to cystic duct: a consistent branch of cystic artery seen in laparoscopic cholecystectomy. *Anat Res Int*. 2015;2015:847812.
 15. Michael Brunt L, Deziel DJ, Telem DA, Strasberg SM, Aggarwal R, Asbun H, et al. Safe cholecystectomy multi-society practice guideline and state of the art consensus conference on prevention of bile duct injury during cholecystectomy. *Ann Surg*. 2020;34:2827–55.
 16. O'Reilly MK, Reese S, Herlihy T, Geoghegan T, Cantwell CP, Feeney RNM, et al. Fabrication and assessment of 3D printed anatomical models of the lower limb for anatomical teaching and femoral vessel access training in medicine. *Anat Sci Educ*. 2016;9(1):71–9.
 17. Smith CF, Tollemache N, Covill D, Johnston M. Take away body parts! An investigation into the use of 3D-printed anatomical models in undergraduate anatomy education. *Anat Sci Educ*. 2018;11(1):44–53.
 18. Lim KHA, Loo ZY, Goldie SJ, Adams JW, Mcmenamin PG. Use of 3D printed models in medical education: a randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy. *Anat Sci Educ*. 2016;9(3):213–21.
 19. Chen S, Pan Z, Wu Y, Gu Z, Li M, Liang Z, et al. The role of three-dimensional printed models of skull in anatomy education: a randomized controlled trial. *Sci Rep*. 2017;7(1):575.
 20. Kong X, Nie L, Zhang H, Wang Z, Ye Q, Tang L, et al. Do 3D printing models improve anatomical teaching about hepatic segments to medical students? A randomized controlled study. *World J Surg*. 2016;40(8):1969–76.
 21. Mogali SR, Yeong WY, Tan HKJ, Tan GJS, Abrahams PH, Zary N, et al. Evaluation by medical students of the educational value of multi-material and multi-colored three-dimensional printed models of the upper limb for anatomical education. *Anat Sci Educ*. 2018;11(1):54–64.
 22. Backhouse S, Taylor D, Armitage JA. Is this mine to keep? Three-dimensional printing enables active, personalized learning in anatomy. *Anat Sci Educ*. 2019;12(5):518–28.
 23. Garas M, Vaccarezza M, Newland G, Mcvay-Doornbusch K, Hasani J. 3D-printed specimens as a valuable tool in anatomy education: a pilot study. *Ann Anat*. 2018;219:57–64.
 24. Ye Z, Dun A, Jiang H, Nie C, Zhao S, Wang T, et al. The role of 3D printed models in the teaching of human anatomy: a systematic review and meta-analysis. *BMC Med Educ*. 2020;20(1):335.
 25. Li Z, Li Z, Xu R, Li M, Li J, Liu Y, et al. Three-dimensional printing models improve understanding of spinal fracture—a randomized controlled study in China. *Sci Rep*. 2015;5(1):11570.
 26. Wu A-M, Wang K, Wang J-S, Chen C-H, Yang X-D, Ni W-F, et al. The addition of 3D printed models to enhance the teaching and learning of bone spatial anatomy and fractures for undergraduate students: a randomized controlled study. *Ann Transl Med*. 2018;6(20):403.
 27. Wang Z, Liu Y, Luo H, Gao C, Zhang J, Dai Y. Is a three-dimensional printing model better than a traditional cardiac model for medical education? A pilot randomized controlled study. *Acta Cardiol Sin*. 2017;33(6):664–9.
 28. Bangeas P, Drevelegas K, Agorastou C, Tzounis L, Chorti A, Paramythiotis D, et al. Three-dimensional printing as an educational tool in colorectal surgery. *Front Biosci (Elite Ed)*. 2019;11(1):29–37.
 29. Vaccarezza M, Papa V. 3D printing: a valuable resource in human anatomy education. *Anat Sci Int*. 2015;90(1):64–5.
 30. Huang Z, Song W, Zhang Y, Zhang Q, Zhou D, Zhou X, et al. Three-dimensional printing model improves morphological understanding in acetabular fracture learning: a multicenter, randomized, controlled study. *PLoS One*. 2018;13(1):e0191328.
 31. Cai B, Rajendran K, Bay BH, Lee J, Yen CC. The effects of a functional three-dimensional (3D) printed knee joint simulator in improving anatomical spatial knowledge. *Anat Sci Educ*. 2019;12(6):610–8.
 32. Loke Y-H, Harahsheh AS, Krieger A, Olivieri LJ. Usage of 3D models of tetralogy of fallot for medical education: impact on learning congenital heart disease. *BMC Med Educ*. 2017;17(1):54.
 33. Tanner JA, Jethwa B, Jackson J, Bartanuszova M, King TS, Bhattacharya A, et al. A three-dimensional print model of the pterygopalatine fossa significantly enhances the learning experience. *Anat Sci Educ*. 2020;13(5):568–80.
 34. Chen Y, Qian C, Shen R, Wu D, Bian L, Qu H, et al. 3D printing technology improves medical interns' understanding of anatomy of gastrocolic trunk. *J Surg Educ*. 2020;77(5):1279–84.
 35. Feldman H, Kamali P, Lin SJ, Halamka JD. Clinical 3D printing: a protected health information (PHI) and compliance perspective. *Int J Med Inform*. 2018;115:18–23.
 36. Cheung RCC, Yang J, Fang C, Leung MF, Bridges SM, Tipoe GL. Show them what they can't see! An evaluation of the use of customized 3D printed models in head and neck anatomy. *Anat Sci Educ*. 2024;17(2):379–95.
 37. Fleming C, Sadaghiani MS, Stellan MA, Javan R. Effectiveness of three-dimensionally printed models in anatomy education for medical students and resident physicians: systematic review and meta-analysis. *J Am Coll Radiol*. 2020;17(10):1220–9.
 38. Bonfiglio C, Richter S, editors. Three dimensional printed models of anatomic variation: a pilot study. Hoboken, NJ: Wiley; 2020.
 39. Shahrubudin N, Lee TC, Ramlan R. An overview on 3D printing technology: technological, materials, and applications. *Procedia Manuf*. 2019;35:1286–96.
 40. Mitsuhashi N, Fujieda K, Tamura T, Kawamoto S, Takagi T, Okubo K. BodyParts3D: 3D structure database for anatomical concepts. *Nucleic Acids Res*. 2009;37:D782–D785.
 41. Nagaoka T, Watanabe S, Sakurai K, Kunieda E, Watanabe S, Taki M, et al. Development of realistic high-resolution whole-body voxel models of Japanese adult males and females of average height and weight, and application of models to radio-frequency electromagnetic-field dosimetry. *Phys Med Biol*. 2004;49(1):1–15.

42. Andall RG, Matusz P, Du Plessis M, Ward R, Tubbs RS, Loukas M. The clinical anatomy of cystic artery variations: a review of over 9800 cases. *Surg Radiol Anat.* 2016;38(5):529–39.
43. Dandekar U, Dandekar K. Cystic artery: morphological study and surgical significance. *Anat Res Int.* 2016;2016:1–6.
44. Fateh O, Wasi MSI, Bukhari SA. Anaotmical variability in the position of cystic artery during laparoscopic visualization. *BMC Surg.* 2021;21(1):263.
45. Ding Y-M. New classification of the anatomic variations of cystic artery during laparoscopic cholecystectomy. *World J Gastroenterol.* 2007;13(42):5629.
46. Kim MJ, Yoon YC. Double cystic artery originating in a right and a segment IV hepatic artery: a case report. *J Minim Invasive Surg.* 2020;23(1):49–51.
47. Singh H, Singh NK, Kaul RK, Gupta A, Tiwari S. Prevalence of anatomical variations of cystic artery during laparoscopic cholecystectomy. *Int Surg J.* 2019;6(10):3781.
48. Asghar A, Priya A, Patra A, Gupta P, Kumar A. Moynihan's hump of the right hepatic artery in Calot's triangle: a systematic review and meta-analysis of its incidence and surgical importance. *Surg Radiol Anat.* 2023;45(5):643–51.
49. Gündüz N, Doğan MB, Alacagöz M, Yağbasan M, Orhan Söylemez UP, Atalay B. Anatomical variations of cystic duct insertion and their relationship with choledocholithiasis: an MRCP study. *Egypt J Radiol Nucl Med.* 2021;52(1):202.
50. Sarawagi R, Sundar S, Gupta SK, Raghuwanshi S. Anatomical variations of cystic ducts in magnetic resonance cholangiopancreatography and clinical implications. *Radiol Res Pract.* 2016;2016:3021484.
51. Priya A, Ghosh SK, Walocha JA, Pasternak A, Iwanaga J, Loukas M. Variations in extra-hepatic biliary tree morphology and morphometry: a narrative review of literature with focus on cystohepatic triangle. *Folia Morphol (Warsz).* 2023;82(3):498–506.
52. Qi H, Joyce K, Boyce M. Durometer hardness and the stress-strain behavior of elastomeric materials. *Rubber Chem Technol.* 2003;76:419–35.
53. Brown LD, Cai TT, Dasgupta A. Interval estimation for a binomial proportion. *Stat Sci.* 2001;16(2):101–33.
54. Wang LL. Retrospective statistical power: fallacies and recommendations. *Newborn Infant Nurs Rev.* 2010;10(1):55–9.
55. Smith CF, Finn GM, Stewart J, Atkinson MA, Davies DC, Dyball R, et al. The anatomical society core regional anatomy syllabus for undergraduate medicine. *J Anat.* 2016;228(1):15–23.
56. Terho P, Sallinen V, Lampela H, Harju J, Koskenvuo L, Mentula P. The critical view of safety and bile duct injuries in laparoscopic cholecystectomy: a photo evaluation study on 1532 patients. *HPB.* 2021;23(12):1824–9.
57. Smith CF, Mcmanus B. The integrated anatomy practical paper: a robust assessment method for anatomy education today. *Anat Sci Educ.* 2015;8(1):63–73.
58. Garg AX, Norman G, Sperotable L. How medical students learn spatial anatomy. *Lancet.* 2001;357:363–4.
59. Bond AP, Butts T, Tierney CM. Spot(ter)s the difference: bringing traditional anatomical examinations online. *Clin Anat.* 2024;37(3):284–93.
60. Choudhury B, Gouldsborough I, Shaw FL. The intelligent anatomy spotter: a new approach to incorporate higher levels of Bloom's taxonomy. *Anat Sci Educ.* 2016;9(5):440–5.
61. Shaylor RM, Chao IT, Young JS, Coles-Black JM. A tale of three countries: three-dimensional printing for procedural simulation in the digital era. *Anaesth Intensive Care.* 2021;49(2):140–3.
62. Cheheili Sobbi S, Pauli M, Fillet M, Maessen JG, Sardari Nia P. The development of direct 3-dimensional printing of patient-specific mitral valve in soft material for simulation and procedural planning. *JTCVS Tech.* 2024;27:104–11.

AUTHOR BIOGRAPHIES

Christian Myles, BSc., MSc. is a PhD candidate in the School of Medicine, University College Dublin, Dublin, Ireland. He has been teaching anatomy to medical students for 8 years, coordinates the School's Body Donation Programme, and his research interest is in anatomical 3D printing for medical education.

Laura Gorman, BSc., MSc., PhD is an assistant professor/lecturer in anatomy in the School of Medicine, University College Dublin, Dublin, Ireland. She has been teaching anatomy to allied health and medical students for 6 years, and her research interests are in anatomical 3D printing for medical education and procedural skills training in the clinic.

James F. X. Jones, M.D., Ph.D. is the professor of anatomy and Chair and Head of Anatomy in the School of Medicine, University College Dublin, Dublin, Ireland. He has been teaching physiology and anatomy to medical students for 35 years and his research interest is in autonomic neuroscience.

How to cite this article: Myles C, Gorman L, Jones JFX. 3D printing variation: Teaching and assessing hepatobiliary variants in human anatomy. *Anat Sci Educ.* 2025;18:885–896. <https://doi.org/10.1002/ase.70073>