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ORIGINAL ARTICLE

A realistic and diathermable 3D printed model for cholecystectomy incorporating the "Moynihan hump" origin of the cystic artery

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Abstract

Background: Cholecystectomy is associated with bile duct and vascular injury. The aim of this study was to create a realistic and diathermable 3D printed model for cholecystectomy with the "Moynihan hump" vascular variant of the right hepatic artery. A hybrid 3D printed/silicone injection method was developed as silicone offers excellent biomechanical properties for surgical simulation. However, due to its hydrophobic nature and low electrical conductance, it has limited wetting-based applications, for example in hydrographics, diathermy or adherence to hydrophilic substances. **Methods:** All 3D objects were sculpted in Blender modelling software, with reference to anatomical atlases and published literature. Polyvinyl alcohol (PVA) printed moulds were pressure injected with silicone (shore 10A) before dissolving the PVA support. Silicone models were immersed in a 3 $mg.mL^{-1}$ dopamine solution (37°C, pH 8.5, 20 h). In order to simulate the diathermy of the connective tissue and peritoneum the electrical conductivity of PVA was increased by adding normal saline. The model validity was assessed by three surgeons. **Results:** A high-fidelity, diathermable model with key anatomical landmarks and a cystic artery variant was created. The polydopamine coating significantly changed the water contact angle from 102 ± 2° to 86 ± 2° ($P = 3.6 \times 10^{-5}$) and improved hydrographic sheet adherence to the silicone models. The conductivity of the PVA–saline solution was 15 $mS.cm^{-1}$ and permitted successful employment of electrical diathermy during dissection. **Conclusions:** Silicone moulded anatomical models can be made more realistic and diathermable through this low-cost method. This model offers realistic surgical training in cholecystectomy and exposure to challenging anatomical variants.

Keywords: *3D printing; cholecystectomy; silicone modification; silicone-based model; realistic simulator, hydrographic*

Introduction

Cholecystectomy is one of the most commonly performed surgeries in the world; however, it is still associated with bile duct and vascular injury. The role of surgical simulation models in training surgical neophytes outside the operating theatre has now become more important mainly due to limited working hours.[1]

Strasberg termed identification of the cystic structures in laparoscopic cholecystectomy as a "critical view of safety" (CVS) in 1995.[2,3] This approach is the current gold standard when performing laparoscopic cholecystectomy. The fibrous and adipose tissues in the hepatocystic triangle are carefully dissected and the lower one-third of the gallbladder is separated from the cystic plate. Two structures that enter the gallbladder, the cystic duct and cystic artery, are identified and ligated.[3] In a patient with the "Moynihan hump" of the right hepatic artery, it is possible to misidentify the right hepatic artery as the cystic artery, and inadvertently ligate the right hepatic artery which lies in the hepatocystic triangle (or Budde–Rocko triangle).[4] The incidence of this variant varies from 1.3 to 13.3% of cholecystectomies.[5]

Silicone models offer excellent biomechanical properties for surgical simulation[6–8]; however, due to their hydrophobic nature, they have limited wetting-based applications, for example, adherence to hydrophilic substances and hydrographic sheets.

Current silicone-based cholecystectomy training models that are commercially available are expensive and unrealistic.

The cholecystectomy training module manufactured by LAPARO Medical Simulators costs USD 135. It is a simple silicone-based model with replaceable parts. Their recommended instruments for exercise include scissors, dissector, grasper and clipper.[9] Simulab Corporation designed a laparoscopic cholecystectomy model with a replaceable gallbladder containing the cystic artery, connective tissue, cystic duct and common bile duct filled with artificial bile. It costs GBP 757. Their model can be adapted for use in a laparoscopic trainer or for open cholecystectomy training.[10]

Cacas-Murillo et al. created low-cost silicone-based 3D printed laparoscopic cholecystectomy models, incorporating anatomical variants of the cystic duct.[11] The price of the consumables used was USD 20.50. A commercial, yellow-coloured slime was used to simulate connective tissue. Their model was validated and recommended for laparoscopic cholecystectomy training. About 61% of the evaluators in their study rated the model as far above the standard in terms of realism. However, some refinements could further enhance the realism of their model. For example, the gallbladder's green colour does not represent its natural appearance. Additionally, the identification of the cystic artery and cystic duct using a laparoscopic grasper without a diathermy further diminishes the model's realism.

The main aim of this study was to create a low-cost, realistic and diathermable silicone moulded training model for cholecystectomy with an unusual "Moynihan hump" vascular variant of the right hepatic artery.

Materials and methods

Construction of virtual 3D model

With reference to anatomical atlases and published literature, 3D objects of the liver, gallbladder, right hepatic artery with the Moynihan hump and biliary tree were created in open-source 3D modelling software Blender 2.90.0 (Blender, Blender Foundation, Netherlands).[5,12–15] Figures from atlases were used as reference images and a UV sphere mesh was sculpted at different angles to create a 3D replica.

Silicone moulded model

Negative moulds of the 3D objects with injection ports were created in Autodesk© Fusion 360 (Autodesk Inc.).[16] The g-code for the print was created in Prusa 3D slicer (Prusa Research, Prague, Czech Republic). The moulds were printed using a fused deposition modelling (FDM) Prusa© i3 MK3S (Prusa Research, Prague, Czech Republic) using RS pro polyvinyl alcohol (PVA) filament (RS online, accessible from: https://ie.rs-online.com/web/). The following print settings were used: printing temperature 205°C, primary layer height 0.10mm, infill 10% and infill pattern gyroid. A PVA mould of the liver was injected with Smooth-On Dragon Skin 10 MEDIUM silicone with brown and blood Silc Pig silicone colour pigments (Smooth-On, Inc., PA, USA).

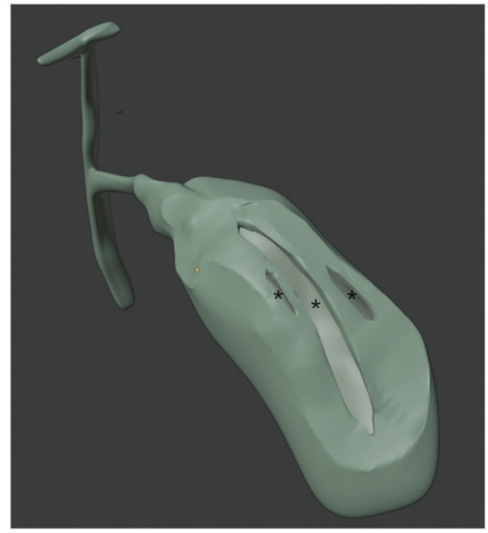

Figure 1. Digital design of a 3D gallbladder with three pseudo-incisions (marked with asterisks).

A closed double-layered 3D gallbladder object with three pseudo-incision shaped defects was designed in Blender 2.90 to create a hollow gallbladder (Fig. 1). A single negative mould with injection ports was then created in Autodesk© Fusion 360. The incisions act as supports for the inner PVA core. The PVA mould was injected with Smooth-On Dragon Skin 10 MEDIUM silicone (Smooth-On, Inc., PA, USA) without pigment and dissolved by using Ultimaker PVA Removal Station (Ultimaker, Geldermalsen, Netherlands). The inner PVA mould dissolved through the three incision sites. The incisions were then closed using Sil-Poxy – Silicone Adhesive (Smooth-On, Inc., PA, USA).

Silicone cylinders of diameter 33 mm and height 11 mm were made to determine the wettability of untreated ($N = 8$) and polydopamine coated silicone ($N = 8$).

A black base was printed using Prusa© i3 MK3S (Prusa Research, Prague, Czech Republic) using black polylactic acid (PLA) filament.

Dopamine treatment of silicone models

In order to create a suitable pH buffer solution, 0.08 g of Tris base (Trizma base T6066, Merck KGaA, Darmstadt, Germany) was added to 400 mL of distilled water. An amount of 1 M HCl in deionised water (prepared from Sigma-Aldrich 258148, Merck KGaA, Darmstadt, Germany) was added to the solution drop by drop and brought the pH to approximately 8.5 by using a pH meter (HANNA instruments pH 211 microprocessor pH meter, Barloworld Scientific Limited Stone, Staffordshire, ST15 0SA, UK).[17] An amount of 10 mM Tris-HCl buffer was then prepared by adding 100 mL of distilled water. An amount of 300 mg of dopamine hydrochloride (Sigma-Aldrich H8502-5G, Merck KGaA, Darmstadt, Germany) was dissolved in 50 mL Tris-HCl buffer solution at room temperature (20°C) using a stirrer (Stuart SB161 Magnetic Stirrer, Stuart). A disc-shaped silicone sample was immersed in a 3 $mg.mL^{-1}$ dopamine solution buffered at pH 8.5 at 37°C for 20 h. The test sample was washed with distilled water to remove unreacted dopamine and dried at room temperature (20°C).

The water contact angle measurements were carried out using the sessile drop method on the KRŰSS-Scientific DSA25E goniometer (KRŰSS-Scientific, Hamburg, Germany). Unpaired Student's *t*-test was used to compare the mean water contact angle of untreated and treated silicone samples. The analysis was conducted in RStudio Version 1.4.1717 (R version 4.1.0 2021-05-18).[18] The criterion for statistical significance was $P < 0.05$.

The Shore hardness measurements of untreated and dopamine treated silicone models were carried out using a Shore A hardness tester with resolution 0.5 HD (HTTK-37A, Tekcoplus Ltd Kowloon Hong Kong).

The silicone-based gallbladder was coated with polydopamine.

Two-dimensional printed hydrographic coating

A high-quality picture of a gallbladder was taken from a YouTube video and printed on a clear hydrographic sheet purchased from Amazon UK [Water Transfer Paper Clear A4 Size (210 × 297 mm) 20 Sheets Water Transfer Slide Decal Paper Water Transfer Inkjet Water Transfer Paper Transparent Clear for Inkjet Printer, Brand: Colorful Hydrographics Coating].[19] The printed hydrographic sheet was evenly single coated with crystal clear gloss (Rust-oleum Crystal Clear Protective Top Coat Spray Paint – Gloss 400ml) and dried at room temperature for 2 h. The printed sheet was then submerged in tap water for 45 seconds until the decal paper separated from the base paper. The printed decal paper was placed on the polydopamine-coated gallbladder by gently sliding the base paper off. Air bubbles were carefully removed. The gallbladder was then dried at room temperature for 4 h.

PVA–saline solution

Three parts of clear polyvinyl alcohol glue (Icon Craft 500 mL Clear PVA Craft glue) were mixed with two parts of 10 mM phosphate buffered saline solution (prepared from 1 × PBS tablet 18912-014, Gibco, Life Technologies, UK). One part of activator [Elmer's 8.75 oz magical liquid for slime making, sodium hydrogen carbonate ≤ 2.5% boric acid ≤ 0.3% 2-methylisothiazol-3(2H)-one ≤ 0.1%] was added to one part of the mixture.[20] The medium was mixed with yellow and blood Silc Pig silicone colour pigments (Smooth-On, Inc., PA, USA) to create lifelike connective tissue and peritoneum.

Conductivity of the diathermable PVA–saline solution

The conductivity of normal saline 0.9 g% (9 $g.L^{-1}$ sodium chloride) and PVA–saline solution (at concentrations described above) was measured using cyclic voltammetry. Solutions were contained in 40 × 20 × 1 mm (length × width × depth) wells with electrodes place at either end at a distance, L, apart equal to 2.298 cm. Current–voltage curves were generated using a Biologic SP-200 (SN 1232) potentiostat with an ultra-low current module (picoA – A range) and a bandwidth filter of 50 kHz. Three scans at a scan rate of 0.075 $V.s^{-1}$ were taken within a potential window of −1 to +1 V. Noise was further reduced numerically using a moving average filter with a window size set to 11 points applied after measurement and slopes were determined using EC-Lab V11.34 software.

A radiofrequency electrosurgical unit (LED Surtron 50D, model QS50D, LED SpA, Aprilia, Italy) with a power of 50W and a frequency of 600kHz was used to dissect the connective tissue of the hepatocystic triangle and identify the cystic artery and cystic duct prior to ligation.

Validation of the simulation model

Two surgical registrars and a consultant each performed separate open cholecystectomy procedures and assessed the content, face and construct validity of the model by completing a post-procedure questionnaire (Fig. 2). The questionnaire focused on anatomical accuracy, realism of materials, visual appearance and use of diathermy. The answers were scaled using a six-point system, with 1 representing poor and 6 representing very similar.

Construct validity was assessed by evaluating the participants' ability to accurately identify the target variant (the Moynihan hump) and whether they had prior knowledge of it.

The overall value of the model as a surgical simulation was assessed using a six-point Likert scale, with 1 deemed not useful and 6 rated as extremely useful.

Questionnaire

Training stage		
Face Validity Please circle a response for each statement or question on a scale of 1 to 5 1 = unlike, 2 = very different, 3 = similar, 4 = very similar, 5 = identical		
Anatomical accuracy	This open cholecystectomy model is anatomically realistic	
	a. Gallbladder	1 2 3 4 5
	b. Liver	1 2 3 4 5
	c. Vascular and biliary structures	1 2 3 4 5
	d. Peritoneum and fibrous tissue	1 2 3 4 5
Realism of materials	The fidelity of the model compared to the normal tissue	
	a. Gallbladder	1 2 3 4 5
	b. Liver	1 2 3 4 5
	c. Vascular and biliary structures	1 2 3 4 5
	d. Peritoneum and fibrous tissue	1 2 3 4 5
	e. Overall impression	1 2 3 4 5
Visual appearance	This open cholecystectomy model closely resembles the normal tissue in terms of its appearance	1 2 3 4 5
Diathermy	Please rate the likeness of dissection by diathermy in comparison to surgery on a live patient	1 2 3 4 5
Content Validity On a scale of 1 to 5: 1 is strongly disagree and 5 is strongly agree		
This model is useful for surgery training		1 2 3 4 5
This model with an anatomical variant could increase operative confidence		1 2 3 4 5
This model is useful for assessing a trainee's skill progress		1 2 3 4 5
This model offers realistic simulations of surgical scenarios		1 2 3 4 5
Construct Validity		
Time taken to complete the procedure (dissection of the peritoneum and hepatocystic triangle, identification of key structures)		
Damage to the right hepatic artery (Yes/No)		
Damage to the common bile duct (Yes/No)		
Damage to the common hepatic duct (Yes/No)		
Were you able to identify the variant (Yes/No) If yes, can you name it?		
Were you aware of the variant beforehand (Yes/No)		
Overall rating 1 = not at all, 2 = minimally, 3 = adequate, 4 = useful, 5 = extremely useful		
Overall value as a surgical simulation		1 2 3 4 5

How could the training experience with this model be improved?

Please provide any additional comments, suggestions, or feedback you have regarding the model.

Figure 2. Validation questionnaire for assessing the model's performance.

Safety and precautions

The model was operated on by using insulated forceps in a well-ventilated area. Gloves were worn during the testing.

Ethics approval

Ethical approval for the field study has been granted by UCD's Human Research Ethics Committee – Sciences (LS-LR-23-94-Myles-Jones).

Results

The virtual 3D model is shown in Fig. 3.

Fig. 4 shows that treatment with dopamine, to form a polydopamine coating, significantly improved the hydrophilicity of silicone and changed the water contact angle of silicone models from 102 ± 2° to 86 ± 2° ($P = 3.6e\text{-}05$). The Shore hardness of untreated silicone models was recorded as ranging between 9.5 and 10 on the durometer A scale. Dopamine treatment had no effect on the hardness of silicone (also 9.5–10 A).

It was observed that hydrographic sheets (which were 2D colour printed images of gallbladders) adhered more firmly to polydopamine coated silicone surfaces than to hydrophobic untreated silicone surfaces (Fig. 5).

Conductivity of the diathermable PVA–saline solution

In order to validate the electrical conductivity method, we calculated the value of normal saline 0.9 g% (9 $g.L^{-1}$ sodium chloride) at room temperature and this was estimated as 13.3 $mS.cm^{-1}$ (which is comparable to that reported in the literature, 12 $mS.cm^{-1}$ at 20°C).[21] PVA–saline solution achieved a conductivity reading of 15.1 $mS.cm^{-1}$ at 22°C.

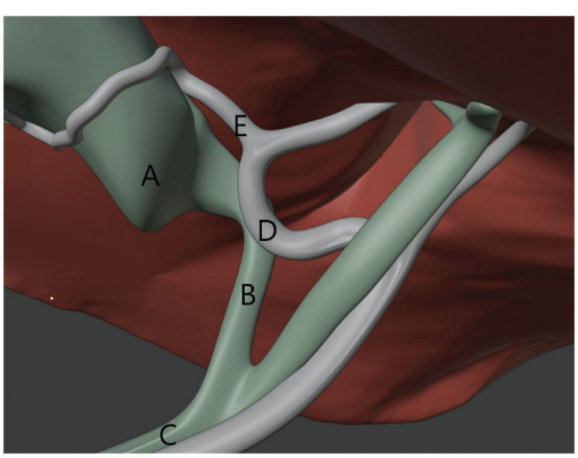

Figure 3. Virtual 3D model showing the hepatocystic triangle. (A) Infundibulum of the gallbladder; (B) cystic duct; (C) common bile duct; (D) Moynihan hump of the right hepatic artery; (E) cystic artery.

Simulation model

A lifelike high fidelity and diathermable cholecystectomy training model was created (Fig. 6), and can be seen in Supplementary Video 1 (https://youtu.be/IBYEbxNK_HI).

The Shore hardness of the liver, gallbladder, artery and biliary duct was 10 A. The Shore units of the normal liver are 15 ± 2.6 SU (measured using a 00 durometer scale reader).[22] The dimensions of the gallbladder are: thickness 5 mm (normal value = 3 mm), length 7.5 cm (normal range = 7–10 cm) and width 3 cm (at its widest part, normal value = 4 cm).[23,24] The model contains key anatomic landmarks, for example the Rouvière's sulcus, which help reduce bile duct injuries.[25] This model incorporates a single loop variant of the Moynihan hump that runs posterior to the common hepatic duct.

The liver and black PLA base can be reused. The replaceable parts include gallbladder, blood vessels and biliary tree (cost EUR 21), and PVA–saline mix (cost EUR 1).

Face validity result

In terms of anatomical accuracy, the gallbladder was rated 6/6, the liver 5.3/6, the vascular and biliary structures 5.7/6, and the peritoneum and fibrous tissue 6/6. Regarding the realism of materials, the gallbladder received a rating of 5.7/6, the liver 4.3/6, the vascular and biliary structures 5/6, and the peritoneum and fibrous tissue 6/6. The overall impression of the model's fidelity was rated 5.7/6. The visual appearance of the model and the likeness of dissection by diathermy were rated 4.7/6.

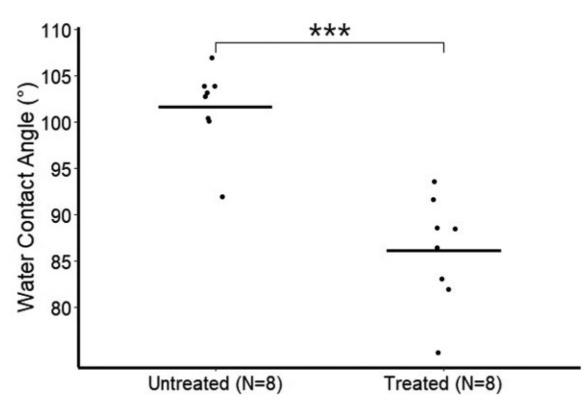

Figure 4. Mean water contact angles of untreated and dopamine treated silicone surfaces are shown. P-value < 0.001 (***).

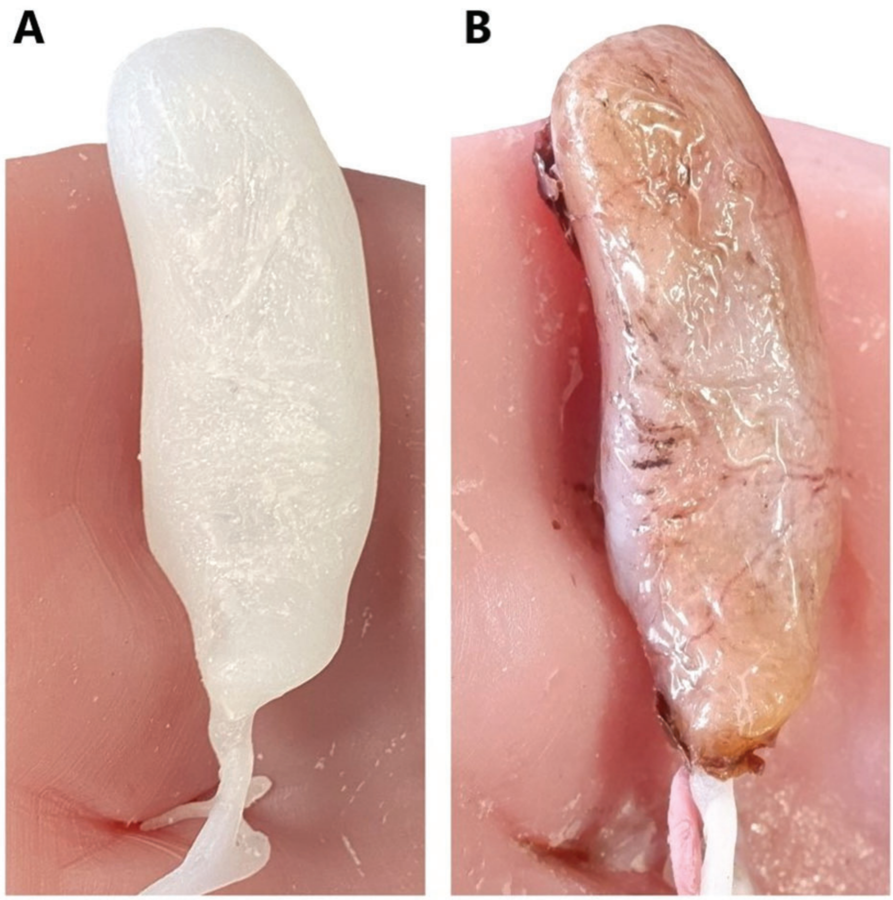

Figure 5. (A) An untreated gallbladder. (B) A dopamine-treated gallbladder covered with a hydrographic sheet, revealing the presence of small blood vessels on the gallbladder wall.

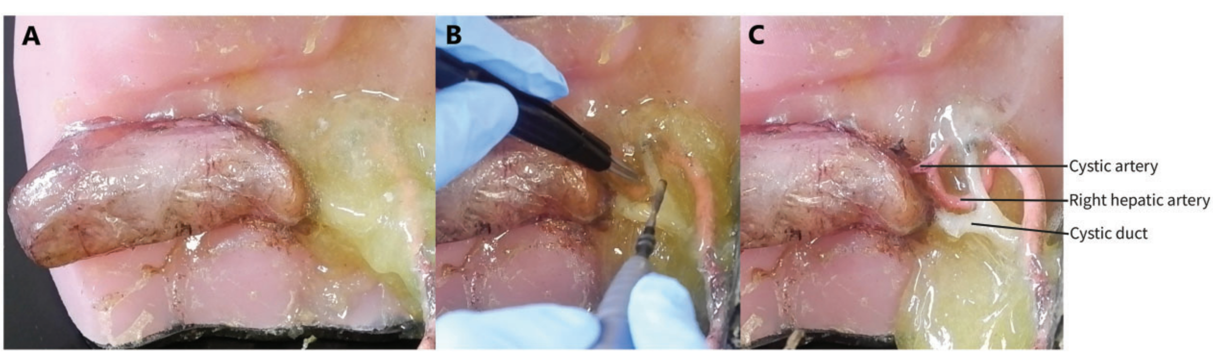

Figure 6. Images of the model undergoing dissection by diathermy. (A) The first still frame depicts the intact anatomical model before dissection. (B) In the second still frame, the model is shown in the process of being dissected using diathermy and forceps. (C) The last still frame displays the Moynihan hump of the right hepatic artery within the hepatocystic triangle post-dissection. Full video is available at https://youtu.be/IBYEbxNK_HI.

Content validity

Participants strongly agreed (6/6) with the following aspects of the model: (1) the model is useful for surgery training; and (2) the model with an anatomical variant could increase operative confidence.

The following aspects of the model were rated as agreed (5.7/6): (1) the model is useful for assessing a trainee's skill progress; and (2) the model offers realistic simulations of surgical scenarios.

Construct validation

None of the three participants were able to recognize the target variant and were also not aware of the variant before this study.

The overall value of the model as a surgical simulation was rated 5.7/6.

Discussion

Ninety-seven percent of bile duct injuries occur due to visual misperception, whereas technical errors/skills deficits account for a mere 3%.[26] This result seems to provide fitting motivation for creating a training model for the cholecystectomy procedure with an unusual vascular variant that can present complexities, thus preparing surgeons to handle challenging scenarios. In a patient with the Moynihan hump of the right hepatic artery variant, there is a risk of accidentally ligating the right hepatic artery instead of the cystic artery.

Commercially available models are expensive, and do not include anatomical variants. Practice with simulation models incorporating an unusual and surgically important variant allows surgical trainees to acquire not only necessary skills but also exposure to challenging anatomical variants that they might encounter in clinical settings.

The Moynihan hump, or the caterpillar turn, of the right hepatic artery is a dangerous variant. Different forms of the Moynihan hump have been described in the literature.[5,14,15] The right hepatic artery runs downward and upward producing a hump. A single loop can sometimes lie in front of the cystic duct and gives off a short cystic artery. The hump can also have a double loop, and the cystic artery may originate from the proximal or distal loop. The right hepatic artery can be located posterior or anterior to the common hepatic duct.[5] The tortuous hump of the right hepatic artery may be accidentally ligated instead of the cystic artery. The negative repercussions include ischaemic necrosis of the right lobe of the liver, hepatic artery pseudoaneurysm due to partial injury and potentially life-threatening intraoperative haemorrhage that can obscure the surgeon's vision of the hepatocystic triangle.[4,5]

Sutherland's "B-SAFE" mnemonic includes five main subhepatic landmarks to avoid bile duct injury: Bile duct, Sulcus of Rouvière, Arteria hepatica, Fissura umbilicus, and Enteric viscera (pylorus, duodenum).[27] Three of the five main anatomical landmarks (B, S, A) are included in our model. Our model can be adopted into a standard laparoscopic box trainer to simulate laparoscopic cholecystectomy which allows surgical trainees to develop hand–eye coordination skills. Subtotal cholecystectomy or partial cholecystectomy is sometimes performed as a bail-out strategy in cases of difficult gallbladder or if the critical view of safety is not achieved.[27,28] The present simulation model offers trainees the opportunity to practice this procedure as the silicone-moulded gallbladder is hollow.

To generate a 3D anatomical object, there are two primary methods: (1) downloading objects from open source websites BodyParts3D (accessible at: http://lifesciencedb.jp/ag/bp3d/) or Z-anatomy (accessible at: https://www.z-anatomy.com/), and (2) converting DICOM (digital imaging and communications in medicine) images to Standard Tessellation Language files using commercial or open-source software.[29,30] We retrieved published 2D images or figures from commonly used anatomical atlases and published literature, and used them as references in Blender 2.90.0 and constructed our own 3D objects with variants. This method allows us to create anatomical objects with variants for 3D printing without the need for DICOM images of a patient with the variant of interest.

A hollow silicone-based organ can be made using the "parting-and-assembly" strategy.[6] The gallbladder can be divided into two parts and assembled using the Sil-Poxy – Silicone Adhesive (Smooth-On, Inc., PA, USA). This can be done by building two negative outer polylactic acid (PLA) moulds for two parts of the gallbladder and a removable inner core. The inner core can be attached to the PLA mould before pouring (or injecting) the silicone and removed once the silicone cures. Even though this strategy involves cheap PLA material and reusable components, this strategy would leave an obvious linear mark defect that circumscribes the gallbladder. We propose a "pseudo-incision and closure" strategy inspired by dissection and suturing techniques to create a hollow organ. This strategy involves making incision-like defects in the digital design. A single negative mould consisting of an outer mould and an inner core made up of PVA material is printed. The incisions act as support materials that attach the inner core to the outer mould. The outer PVA mould is first dissolved, and the PVA material of the inner core dissolves through the incision design. The incisions are then closed by using a silicone adhesive agent. These incisions are designed on the side of the gallbladder that attaches to the cystic plate, leaving no evidence of assembly.

Silicone is considered to be the best material suited for surgical simulation as it offers excellent mechanical strength, elasticity and tear resistance similar to that of real tissue.[6,7] Even though multiple silicone colour pigments can be used to create coloured silicone models, they are still unrealistic and depart from surgical anatomy. The major breakthrough in this study is the modification of the surface chemistry of silicone to improve the adherence of a hydrographic sheet on dopamine treated silicone. This low-cost polydopamine coating method can be used to create any lifelike anatomical model. Facile formation of polydopamine layers on silicone has been reported in the literature.[31] A high-quality image of the target tissue or organ is printed on a hydrographic sheet. It conforms and adheres to the dopamine treated silicone.

Silicone is an insulator, so it cannot be cauterized. Conductive materials are required to simulate soft tissue structures for the use of diathermy or cautery. Conductive hydrogels can be used in surgical simulators. Maruyama et al. created a hydrogel heart model for surgical training in cardiac catheter ablation, and their model showed similar Young's modulus, electrical resistivity and specific heat capacity to that of the human heart.[32] Han et al. created a transparent, adhesive and conductive hydrogel made out of polydopamine-doped polypyrrole nanofibrils.[33] This can be made more opaque by increasing the concentration of polydopamine-doped polypyrrole nanofibrils.[33] This method is expensive to replicate and its use in surgical simulation remains to be reviewed. In contrast, Clifton et al. used a conductive thermoplastic polymer to simulate electrically conductive soft tissue.[34] In the present study, a cheap PVA–saline solution was used to simulate the peritoneum and the connective tissue of the hepatocystic triangle. When an activator (boric acid) is added to the PVA–saline solution, the chains of PVA cross-links to form a conductive, deformable, diathermable material. The materials used to create this diathermable material are all low-priced (Table 1). The total cost of the model is around EUR 85. The model contains reusable parts (liver and PLA base), making it cost-effective. The replaceable parts include the gallbladder, artery and biliary tree that can be 3D printed in a single mould and mass-produced. It takes 5 days 15 h 10 min to produce a completed model.

The anatomical accuracy and realism of the dopamine and hydrographic coated gallbladder were rated as very similar with scores of 6/6 and 5.7/6 respectively. Similarly, the anatomical accuracy and realism of the peritoneum were rated as very similar with scores of 6/6 and 6/6 respectively. Furthermore, the dissection of the hepatocystic triangle by diathermy performed on the model, in comparison to surgery on a live patient, was rated as similar with a score of 4.7/6.

The target variant went unrecognized by all three participants, and they were not aware of its presence. This might indicate a potential lack of anatomical knowledge of the variations of the cystic artery and right hepatic artery. Despite the failure of all surgeons to recognise the anatomical variant, adherence to the critical view of safety avoided accidental injury to proximal structures. The participants strongly agreed that the model with an anatomical variant could increase operative confidence and that it is useful for surgery training.

Limitations and future studies

Our model has the potential for further refinement to enhance its realism and authenticity. One area of improvement could be to create a more firm and rigid artificial connective tissue that is sensitive to diathermy. The cystic artery and

Table 1. The cost of the consumables used in this study and time taken for each step are outlined in this table

	Material	Cost (euros)	Time
Two moulds:	PVA filament	36	
(1) Liver			(1) 2 days 3 h 37 min
(2) Gallbladder, blood vessels and biliary tree			(2) 1 day 10 h 3 min
Black base frame	PLA filament	3	13 h 5 min
Dopamine	Dopamine hydrochloride, Tris base, hydrochloric acid	2	20 h
Hydrographics coating	Waterslide transfer paper	1	6 h
	Clear gloss spray	17	
Silicone	Smooth-On Dragon Skin 10 medium silicone	25	Pot life: 20 min Curing time: 5 h PVA dissolving time: 5 h
Polyvinyl alcohol–saline solution	Clear PVA glue, saline solution, Elmer's activating solution	1	5 min
Total		≈85 per model	5 days 15 h 10 min

Abbreviations: PVA: polyvinyl alcohol; PLA: polylactic acid.

cystic duct could be made hollow and filled with artificial blood and bile. Moreover, the model can be adapted into a laparoscopic box trainer that reflects the insufflated abdomen. To further enhance the training experience, the liver could be made liftable, reflecting its retraction using a laparoscopic holder.

The model was validated by only three surgeons. A larger sample size is needed for a more reliable analysis of the surgical realism and similitude of the diathermic dissection of an artificial peritoneum. The model can be validated clinically through timed cholecystectomy on normal and variant anatomy. Other anatomical variations of the vasculature and biliary tree can be explored. However, this will be the subject of a future study.

Conclusions

In this study, we created a realistic silicone moulded cholecystectomy model with diathermable soft tissue structures that may provide surgical trainees with an opportunity to acquire the necessary skills, and offer exposure to challenging anatomical variants. The "pseudo-incision and closure" strategy can be used to create a hollow silicone-based organ. The polydopamine treatment with hydrographic coating allows us to create a lifelike silicone moulded anatomical object. The PVA–saline solution is a cost-effective method to simulate conductive soft tissue structures for the use of electrocautery.

Supplementary material

Supplementary video 1: available at https://youtu.be/IBYEbxNK_HI

Conflict of interest

None declared. The authors report no proprietary or commercial interest in any product mentioned or concept discussed in this article.

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Data availability

The datasets and STL files used during the current study are available from the corresponding author upon reasonable request.

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