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Life-threatening event in laparoscopic hepatic surgery: Training curriculum on sudden hepatic artery haemorrhage

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Abstract

Background Exposure of the hepatic artery is a fundamental step in many surgeries, during which iatrogenic hepatic artery injury may occur. Although the incidence of hepatic artery haemorrhage is low, its occurrence can lead to life-threatening haemorrhage. It is difficult and dangerous to accumulate clinical experience in laparoscopic hepatic artery repair in actual patients, and simulation training models for laparoscopic hepatic artery repair are currently lacking. In this study, a 3D printed model was designed to simulate the training curriculum for sudden hepatic artery haemorrhage, but whether training with the 3D printed model could yield superior skill improvement for surgeons remained to be determined.

Methods A new 3D printed model was designed for this study. Surgeons from the General Surgery Department of Sir Run Run Shaw Hospital participated in this simulation training. The surgical performance of each model was compared, and the authenticity of the model was evaluated and mechanically tested.

Results Experienced surgeons performed better on the 3D printed model. After repeated training, inexperienced surgeons showed significant improvement of their laparoscopic hepatic artery repair skills. The authenticity of the model was generally satisfactory, but shortcomings persisted in the mechanical testing of artery wall tearing, necessitating further improvement.

Conclusions Few studies have investigated laparoscopic simulation training for sudden hepatic artery haemorrhage. This simulation model distinguishes surgeons with different levels of experience and allows those with less experience to improve their laparoscopic hepatic artery repair skills through training on the model.

Keywords Laparoscopic, Hepatic artery haemorrhage, 3D printed, Simulation, Training curriculum

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Introduction

Exposure of the hepatic artery is a fundamental step in many surgeries, including lymphadenectomy for cholangiocarcinoma [1, 2], D2 lymphadenectomy for gastric cancer [3, 4] and pancreaticoduodenectomy [5]. Iatrogenic hepatic artery injury may occur during this procedure. Although the incidence of hepatic artery haemorrhage is low, severe artery injuries can lead to life-threatening haemorrhage [5]. Rapid intraoperative haemostasis and hepatic artery repair are skills that must be mastered by experienced surgeons [6].

With the spread of laparoscopic techniques, many operations involving hepatic artery exposure are now being performed laparoscopically [7, 8]. Previously, open surgery for hepatic artery repair was often the first choice [9]. Today, experienced surgeons may also attempt laparoscopic hepatic artery haemostasis. Laparoscopic surgery performed by experienced surgeons may achieve results similar to those of open surgery in many procedures [10, 11]. However, the skills learned in open surgery are often insufficient for surgeons to handle haemorrhage during laparoscopic surgery due to factors such as the abdominal wall acting as a barrier to the surgical site, indirect hand manipulation and limited visibility.

Inexperienced surgeons rarely have the opportunity to address such crises in clinical settings, which poses a significant risk to patients. Furthermore, based on a survey of 21 attending surgeons at our centre, experienced surgeons who had completed more than 500 cases of hepatic artery exposure encountered this crisis fewer than 20 times. This finding highlights the paradox of the need for experienced surgeons to perform hepatic artery repair; however, most surgeons have few opportunities to gain the necessary experience.

Simulation training can help surgeons master complex operating steps quickly [12, 13]. Currently, simulation training methods include 3D printed models, augmented reality (AR) models, virtual reality (VR) models and animal models [14–17]. By integrating simulation operations into training programmes, surgeons can reduce the number of cases required to master special or complex procedures [18, 19]. Simulation training also allows for more surgical mistakes on highly simulated anatomical models without directly harming patients. However, highly realistic simulation models for hepatic artery repair are currently lacking.

In our previous studies, our 3D printed model was shown to be effective for laparoscopic bilioenteric anastomosis training [20, 21] and stepwise training programmes for laparoscopic pancreaticojejunostomy [22]. In this study, we developed a new 3D printed model simulating hepatic artery haemorrhage on the basis of the original model. We aimed to verify whether training on this model could improve the laparoscopic skills of surgeons in dealing with hepatic artery haemorrhage.

Methods

IRB approval

This study was approved by the Ethics Committee of Sir Run Run Shaw Hospital, Zhejiang University School of Medicine (No. 2022–668-01). Trial Registry: This study was registered at http://www.chictr.org.cn (NO. ChiCTR2400088881).

Participants

Fifteen surgeons were included in this study, consisting of 5 attendings (Group A), 5 fellows (Group F), and 5 residents (Group R). All participants were from the General Surgery Department of Sir Run Run Shaw Hospital. Residency training years were counted as part of their working years. All the participants were required to complete one training session. Two fellows and two residents who had sufficient free time were required to undergo eight training sessions.

3d printed model

The 3D printed model used for laparoscopic hepatic artery haemostasis was designed and produced by XIMOUWEIXUN Medical Technology (Hangzhou, China). The model consisted of the liver (pink), portal vein (blue), bile duct (yellow) and hepatic artery (red). The material used was specialised silicone for 3D printing. The hepatic artery had a 1 mm hole punctured at approximately the 4 o'clock position. The hepatic artery was connected to an infusion set, which was filled with 500 ml of normal saline mixed with red dye to simulate hepatic artery bleeding (Supplementary Figs. 1A, B).

Operation time and blood loss calculation

The operation time was measured from the start of artery repair until completion. The hepatic artery was connected to an infusion set containing 500 ml of mocked blood (normal saline mixed with red dye) to simulate the scenario of hepatic artery bleeding. After the surgery, the remaining liquid in the bag (X ml) was measured. The amount of blood lost was calculated as 500 ml minus X ml. A new bag of 500 ml of mocked blood was used for each simulation training session.

Operation performance evaluation

All the participants were allowed to perform one training session on the model. If the artery wall was severely torn, the attempt was deemed a failure. Goal scores for their operations were recorded as an important evaluation index. The evaluation of hepatic artery repair was based on two main indicators: closure of the hepatic artery hole (repair score) and stenosis of the hepatic artery (narrow score). The severity of blood vessel leakage after repair represented the repair score, while the degree of narrowing was assessed by cutting the artery and observing the extent of constriction. A 5-point Likert scale was used for evaluation by three blinded general surgery experts.

Authenticity evaluation

The authenticity of the model was evaluated by five attending surgeons after their initial training session. A 5-point Likert scale questionnaire was designed to assess various aspects, including visual size, elasticity, ease of tearing, sense of breakthrough during sewing, bleeding scene simulation, and sense of urgency for the operator.

Wearable knot tying force test platform

A wearable knot tying force test platform (Supplementary Fig. 4A) was constructed to accurately measure the tension in the sutures during the surgical suturing process. The platform consisted of a knob, two pulleys, a slider, a steel wire, and a load cell (SBT641C, SIMBATOUCH, China). One end of the suture was secured to the slider via the knob, and the adjacent pulley guided the suture, minimising the impact of hand posture variations on force measurement. The slider was connected to the load cell by a steel wire (d = 0.8 mm) running through the upper pulley. During suturing, the surgeon positioned their index finger through a hole in the device, with the thumb resting on the shell above the pulley next to the load cell. Tension in the suture was directly measured by the load cell as the suture was pulled through the platform.

Data analyses

All the data were analysed using SPSS software (version 20.0; SPSS Inc., Chicago, IL, USA). All the charts were designed using GraphPad Prism software (version 7.0). Descriptive statistics are presented as follows: continuous data are presented as the means ± standard deviations; categorical data are presented as frequencies and percentages. All t tests were two-tailed, and values of $P < 0.05$ were considered statistically significant.

Results

A survey for sudden hepatic artery haemorrhage

Twenty-one attending surgeons from our general surgery department were invited to participate in the survey. The first question concerned how many surgeries they had performed that required hepatic artery dissection or lymphadenectomy around the hepatic artery. One attending surgeon had performed 0 – 50 cases, two surgeons had performed 50 – 100 cases, six surgeons had performed 100 – 200 cases, eleven surgeons had performed 200 – 500 cases, and one surgeon had performed more than 500 cases (Fig. 1A). The second question addressed whether they had ever experienced hepatic artery haemorrhage during such surgeries. Eighteen surgeons reported having experienced hepatic artery haemorrhage (Fig. 1B). The third question asked how many patients experienced hepatic artery haemorrhage. Eleven surgeons had dealt with 10–20 cases, seven surgeons had dealt with 5–10 cases, and three surgeons had dealt with 0–5 cases. The fourth question concerned the artery that as more likely to suffer haemorrhage during surgery, with options including the common hepatic artery (CHA), hepatic artery proper (HAP), right hepatic artery (RHA), and left hepatic artery (LHA) (Fig. 1C). Most surgeons (18/21) believed that HAP was more prone to injury (Fig. 1E). The fifth question addressed the direction in which the HAP haemorrhage was more likely to have occurred from the injury (Fig. 1D). Three surgeons thought it occurred in the 0 – 3 o'clock direction, seven surgeons thought it occurred in the 3 – 6 o'clock direction, five surgeons thought it occurred in the 6 – 9 o'clock direction, and six surgeons thought it occurred in the 9 – 12 o'clock direction (Fig. 1F).

Bleeding speed

Based on the survey, the bleeding hole designed on the HAP of our model was located at approximately the 4 o'clock position. Ten models were randomly selected, and the statistics for blood loss within one minute were obtained. The one-minute blood loss was 14 ml for the seven models; it was 15 ml for the remaining three models. Overall, our model demonstrated good consistency in terms of bleeding speed (Supplementary Fig. 1C).

Baseline characteristics of the participants

Baseline characteristic data of the participants were collected and analysed (Table 1). All the surgeons in the three groups were male. The age of the surgeons was significantly higher in Group A than in Group F (38.0 ± 1.6 vs. 32.8 ± 1.3, $p < 0.001$), and it was significantly higher in Group F than in Group R (32.8 ± 1.3 vs. 29.0 ± 1.6, $p = 0.003$). The number of working years was significantly longer in Group A than in Group F (11.8 ± 2.2 vs. 6.0 ± 1.2, $p = 0.001$), and it was significantly longer in Group F than in Group R (6.0 ± 1.2 vs. 3.0 ± 0.7, $p = 0.001$). The number of laparoscopic cholecystectomies (LCs) completed was significantly larger in Group A than in Group F ($p = 0.008$), and it was significantly larger in Group F than in Group R ($p = 0.008$).

First training assessment

The performances of the three groups are presented in Table 2. The operation time was significantly shorter in

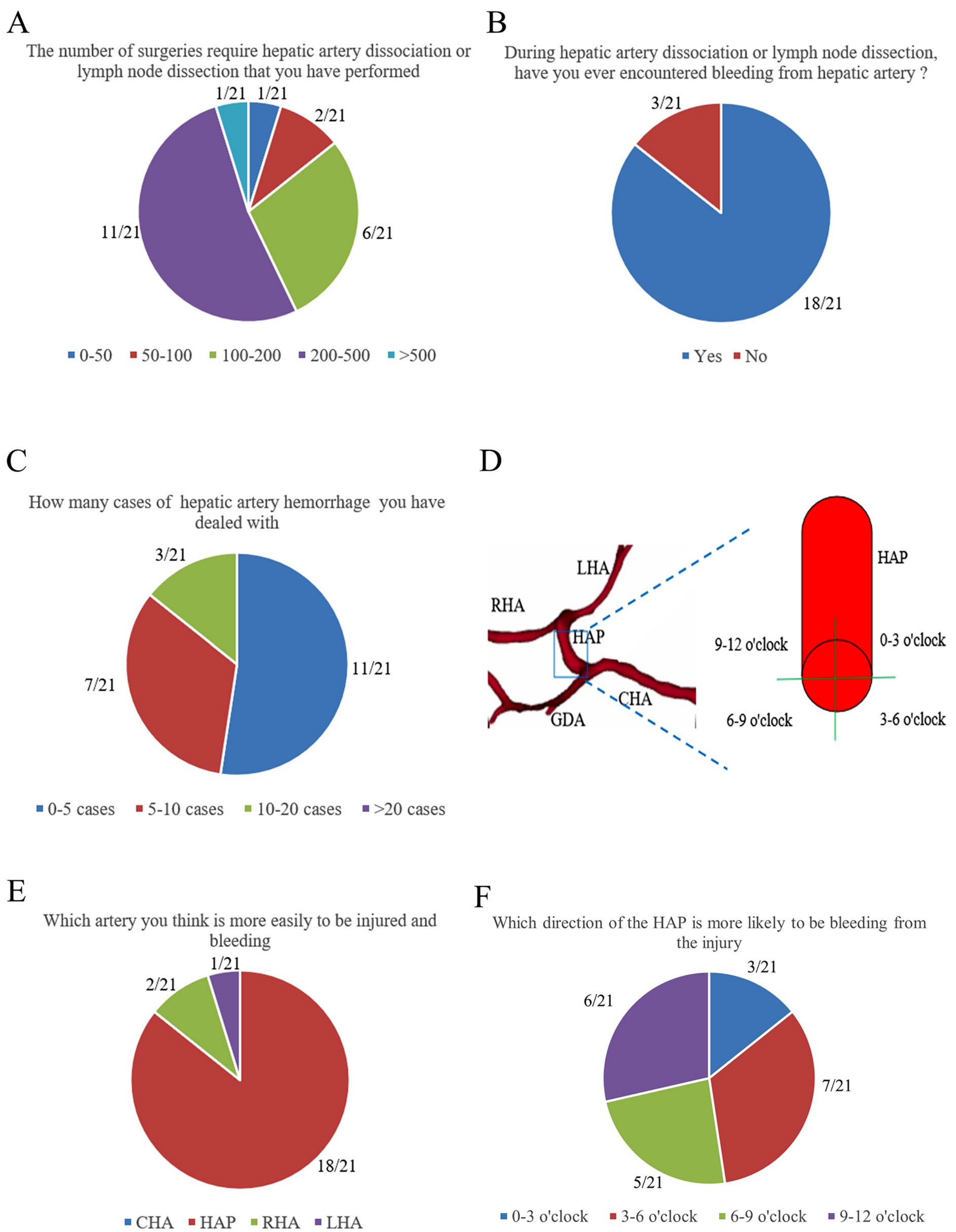

Fig. 1 **A** survey of 21 attending surgeons in the general department of Sir Run Run Shaw hospital. (A) Surgical number statistics of operations that require hepatic artery dissection or lymphadenectomy around the hepatic artery. **B** Statistics for the surgeons who encountered hepatic artery haemorrhage in such surgeries. **C** Surgical number statistics for hepatic artery haemorrhage in such surgeries. **D** Representation of different regions of the hepatic artery and different locations of the HAP. **E** Statistics for different regions of the hepatic artery that are more easily to be injured. **F** Statistics for different locations of the HAP which that are more easily to be injured

Table 1 Baseline characteristics of these 3 groups

	Sex (male)	Age	Working year	LC*
Attending (A)	100%	38.0 ± 1.6	11.8 ± 2.2	1 (100%)
Fellow (F)	100%	32.8 ± 1.3	6.0 ± 1.2	2 (100%)
Resident (R)	100%	29.0 ± 1.6	3.0 ± 0.7	3 (100%)
P-value (A vs F)	1	**< 0.001**	**0.001**	**0.008**
P-value (F vs R)	1	**0.003**	**0.001**	**0.008**

LC*: surgery number: 1–100, score: 1; 100–800, score: 2; > 800, score: 3. Bold font means p < 0.05

Group A than in Group F (267.2 ± 67.8 s vs. 434.4 ± 71.3 s, p = 0.005), whereas it was significantly shorter in Group F than in Group R (267.2 ± 67.8 s vs. 675.4 ± 127.0 s, p = 0.006). The amount of blood loss was significantly reduced in Group A than in Group F (57.0 ± 17.7 ml vs. 104.4 ± 19.1 ml, p = 0.004), whereas the operation time was significantly shorter in Group F than in Group R (104.4 ± 19.1 ml vs. 164.0 ± 33.1 ml, p = 0.008). The goal score was significantly higher in Group A than in Group F (20.8 ± 1.6 vs. 16.8 ± 1.8, p = 0.006), whereas it was significantly higher in Group F than in Group R (16.8 ± 1.8 vs. 11.8 ± 1.9, p = 0.003). The repair score and narrowness score were higher in Group A but lower in Groups F and R. Arterial narrowing after the operation is also shown in Supplementary Fig. 2.

Eight time training assessments

Two surgeons each in Group F and Group R, who had sufficient time, were invited to receive a total of eight training sessions for laparoscopic hepatic artery repair. One fellow surgeon (F2) and one resident surgeon (R1) each has one failed operation because the wall of the hepatic artery was torn during suturing. The operation times, blood loss rates and goal scores of these eight training sessions from the 4 surgeons are shown in Fig. 2A-C. Basically, as the number of training sessions increased, the required operation time and surgical blood loss decreased, whereas the goal score increased. As the number of training sessions increased, the repair score and narrow score also gradually improved (Fig. 2D, E).

Analysis of clinical hepatic arterial haemorrhage and suggestions for repair

The 21 attending surgeons were invited to describe the most likely cause of hepatic arterial haemorrhage in the survey. Eight attending surgeons mentioned heat damage or other damage caused by the ultrasonic knife (including false aneurysms), 7 surgeons mentioned injury caused by arterial anatomical variation or small branching, 6 surgeons mentioned that the anatomic hierarchy was misjudged, 1 surgeon mentioned poor visibility, and 1 surgeon mentioned that an assistant surgeon may not cooperate well (Fig. 3A). These surgeons were also asked to provide some surgical suggestions for laparoscopic hepatic artery repair (one surgeon could provide more than one suggestion). Eighteen surgeons suggested blood flow control, including blocking bands, pressure haemostasis, and titanium clips, to temporarily control bleeding. Ten surgeons suggested further dissection to identify the exact location of bleeding and then to perform the repair. Seven surgeons emphasised clearing accumulated blood and maintaining a clear line of vision, and 7 surgeons emphasised using Prolene for suturing (Fig. 3B). In our training sessions on the hepatic artery haemorrhage model, we also found that experienced surgeons seemed to pay more attention to clearly exposing the bleeding spot before performing accurate suturing (Supplementary Fig. 3A). During the procedure, dissection forceps might be used more often to block the hepatic artery to reduce blood loss (Supplementary Fig. 3B). After suturing, they were more inclined to strain the suture to see if the repair was satisfactory before knotting (Supplementary Fig. 3C).

Simulation model evaluation

The five attending surgeons recruited in the first training session were also invited to evaluate the authenticity of this hepatic artery haemorrhage model. The results are

Table 2 Operation performance in these 3 groups

	Operation time (s)	Blood loss (ml)	Goals score	Repair score*	Narrow score*
A	267.2 ± 67.8	57.0 ± 17.7	20.8 ± 1.6	3 (20%); 4 (40%); 5 (40%)	4 (40%); 5 (60%)
F	434.4 ± 71.3	104.4 ± 19.1	16.8 ± 1.8	3 (40%); 4 (60%)	3 (60%); 4 (40%)
R	675.4 ± 127.0	164.0 ± 33.1	11.8 ± 1.9	1 (40%); 2 (20%); 3 (40%)	2 (40%); 3 (60%)
P-value (A vs F)	**0.005**	**0.004**	**0.006**	/	/
P-value (F vs R)	**0.006**	**0.008**	**0.003**	/	/

Repair Score*: After the surgery was completed, two senior surgeons will evaluate the closure degree of the artery (Likert scale: the better of the closure, the higher of the score). Narrow Score*: After the surgery was completed, two senior surgeons will evaluate the narrow degree of the artery (Likert scale: the more severe of the artery stenosis, the lower of the score). Bold font means p < 0.05

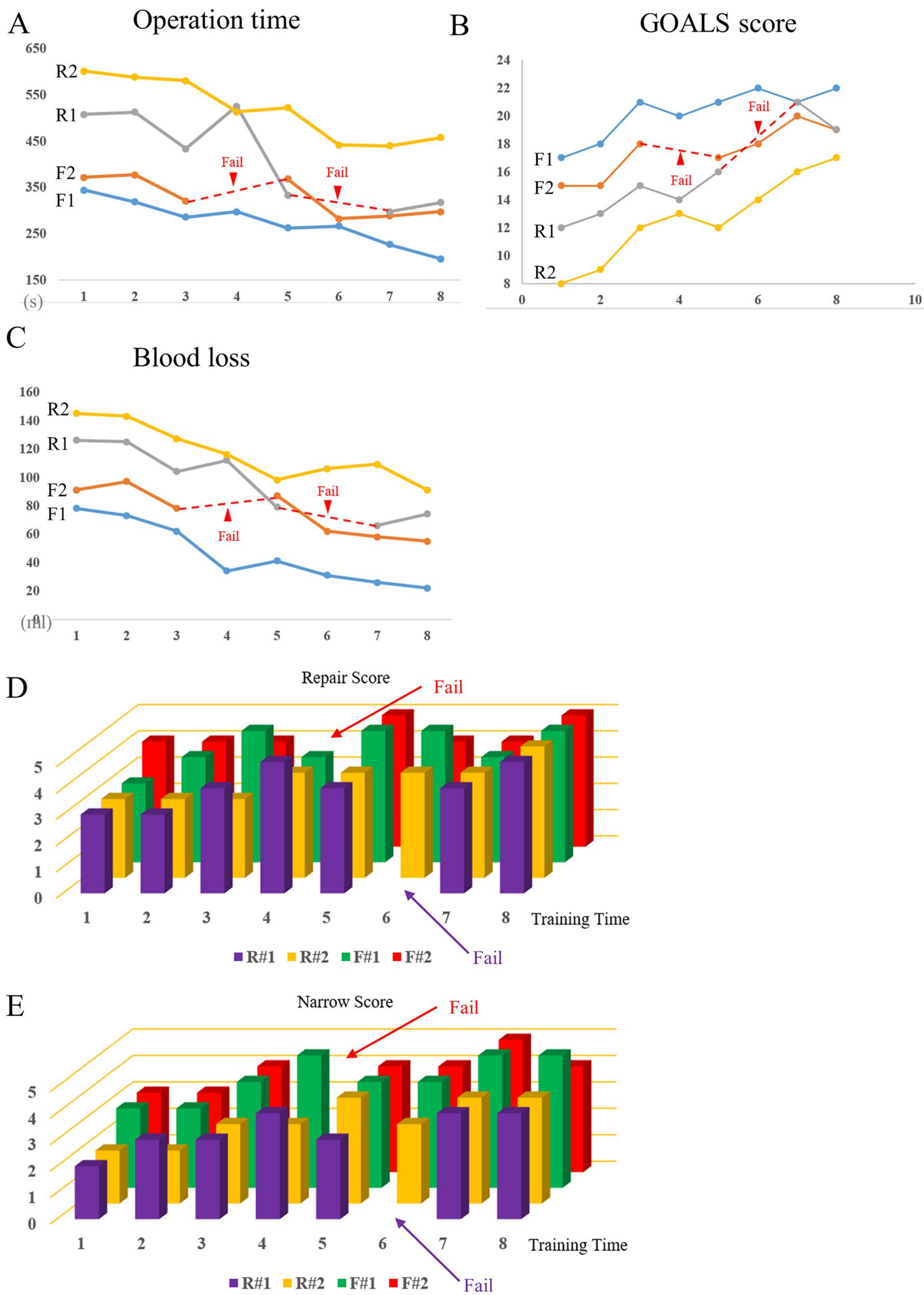

Fig. 2 Operation performances for trainers in eight time sessions are shown; surgeons performed better after repeated training (the "fail" marking in the figure indicates a failed surgery due to a serious hepatic artery wall tear). **A** The operation time curve for the four trainers in the eight time trainings. **B** Blood loss curve for the four trainers in the eight time trainings. **C** Goal score curve for the four trainers in the eight time trainings. **D** Repair score histogram for the four trainers in the eight time trainings. **E** Narrow score histogram for the four trainers in the eight time trainings

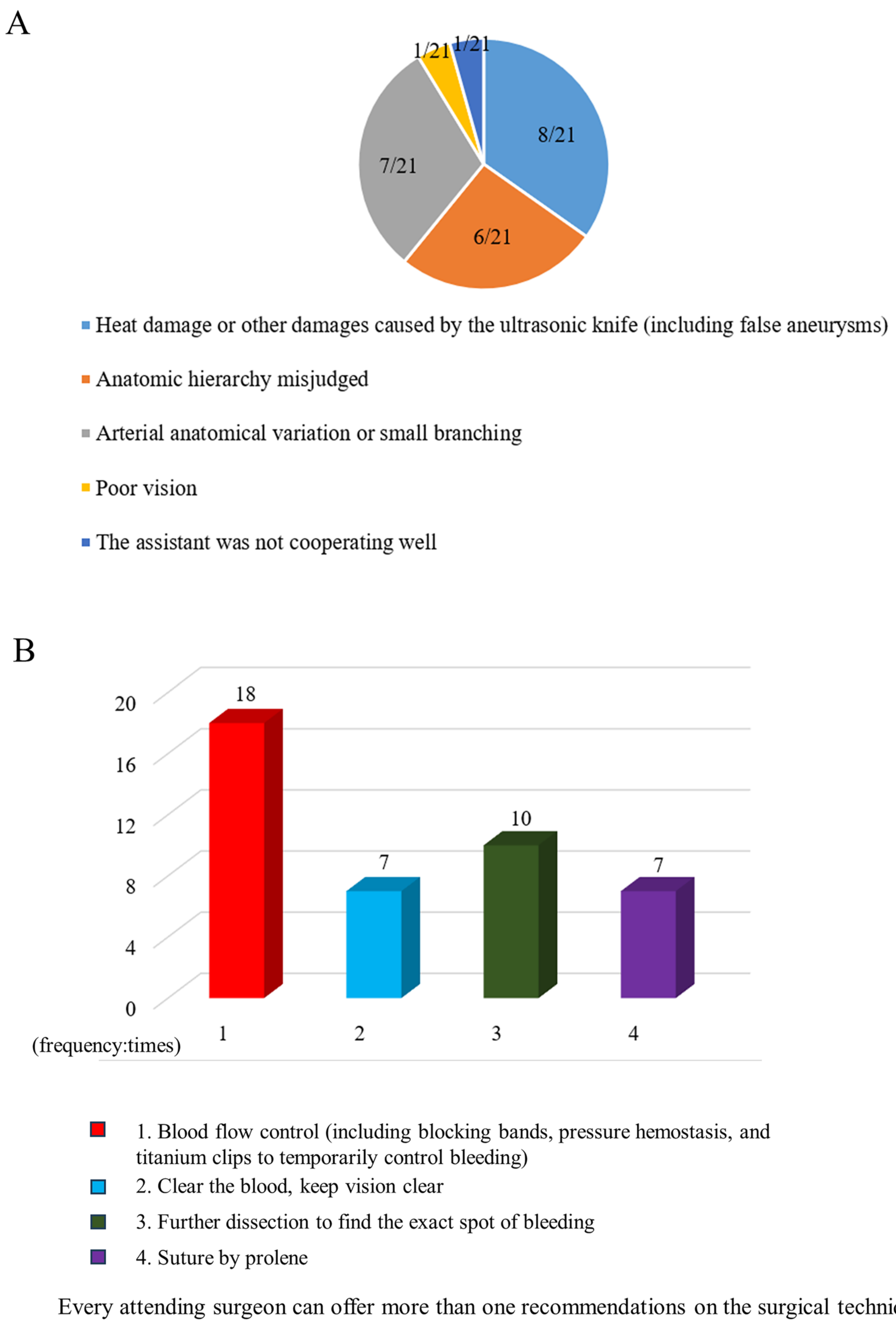

Fig. 3 A continued survey of 21 attending surgeons from the general department of Sir Run Run Shaw hospital. **A** Statistics for the surgeons' opinion about the most likely cause of hepatic artery haemorrhage. **B** Statistics for the surgeons' recommendations on how to better manage hepatic artery bleeding

shown in Table 3. Most indicators, including visual size, elasticity, sense of breakthrough upon sewing, bleeding scene simulation and sense of urgency for operators, were given high scores, which indicated that the five senior surgeons were relatively satisfied with these aspects of the model. The score for ease of tear (3.80 ± 1.30) was lower, which indicated that the artery wall might be easier to tear.

Force test

The mechanical values of hepatic artery tearing in 3D printed silicone models and isolated swine hepatic arteries were tested via the wearable knot tying force test platform (Fig. 4A). Three 3D printed models were randomly selected for testing. The external figure-of-8 suture method using 6–0 Prolene was utilised for the hepatic artery repair (Fig. 4B). The mechanical critical values of hepatic artery tears were 1.589 N, 1.790 N and 1.792 N, and the average mechanical strength was 1.724 N (Fig. 4C). Three isolated swine hepatic arteries were tested using the same suture method (Fig. 4D). The hepatic artery from the isolated swine did not tear before the Prolene broke. The mechanical values of the 6–0 Prolene fractures in the three tests were 3.489 N, 3.355 N and 3.041 N, respectively, and the average mechanical strength was 3.295 N (Fig. 4E).

Discussion

The rate of intraoperative hepatic artery haemorrhage is low; however, when it occurs, it can pose a significant threat to life. Currently, most studies focus on prevention [23, 24], diagnosis [25], embolization therapy [26, 27], or surgical treatment of postoperative hepatic artery haemorrhage. Few studies address hepatic artery haemorrhage during intraoperative procedures, and even fewer focus on simulation training for this specific challenge. However, many surgeries involve isolation of the hepatic artery or dissection of the lymph nodes around the hepatic artery [1–5]. Intraoperative haemorrhage from hepatic artery injury leads to significant blood loss and can be life-threatening in severe cases. Successfully managing this emergency is a severe test of a surgeon's surgical ability. Despite this, many junior surgeons and some senior surgeons lack experience in laparoscopic hepatic artery repair. As the proportion of laparoscopic surgeries increases, many hepatic artery repairs or reconstructions are being performed laparoscopically. Therefore, training in laparoscopic hepatic artery repair is highly desirable, especially for inexperienced young surgeons.

Previous studies have shown that simulation training can shorten a surgeon's learning curve and help them better master complex surgical procedures [18, 19, 28]. Consequently, in this study, we modified the previously reported biliary–enteric anastomosis model into a new hepatic artery haemorrhage model. A survey of 21 attending surgeons revealed that hepatic artery haemorrhage most commonly occurred in the hepatic artery proper (HAP) and was predominantly located between the 3 and 6 o'clock positions. To increase the clinical relevance of the model, the hole requiring repair was placed at the 4 o'clock position on the hepatic artery proper.

According to our study results, senior surgeons with more working experience and greater surgical exposure exhibited shorter operation times and better performance, including less blood loss, reduced arterial stenosis, higher goal scores, and better repair outcomes. This result confirmed that the model could effectively discriminate between experienced and inexperienced surgeons, a crucial feature of a successful model. Repeated training for fellows and residents resulted in gradual improvements in operation time, reduced blood loss, and better control of arterial stenosis, indicating that the surgical skills of laparoscopic hepatic artery repair could be improved through repeated training with this model. These findings validated the reliability of this hepatic artery haemorrhage model for simulating laparoscopic hepatic artery repair.

Survey feedback from the 21 attending surgeons indicated that heat damage or other damage caused by the ultrasonic knife, arterial anatomical variations [29], or misjudgement of small branches and anatomical hierarchies were the most common causes of hepatic artery haemorrhage in clinical practice. These surgeons emphasised the importance of blood flow control, further dissection to identify the precise bleeding location, clearing of accumulated blood to maintain a clear line of vision, and use of Prolene for suturing. Experienced surgeons performed better in clearly exposing the

Table 3 Authenticity evaluation of the model by five attendings

Model visual evaluation	
The size of the artery	4.40 ± 0.89
The size of the bile duct	4.60 ± 0.55
The size of the portal vein	4.60 ± 0.55
The spatial distribution of the three tubes	4.40 ± 0.55
Model tactile and operational evaluation	
Elasticity	
Artery	4.00 ± 1.00
Easy to tear	
Artery	3.80 ± 1.30
Sewing sense of breakthrough	
Artery	4.20 ± 0.84
Bleeding scene simulation	4.40 ± 0.55
Sense of urgency for operators	4.20 ± 0.84

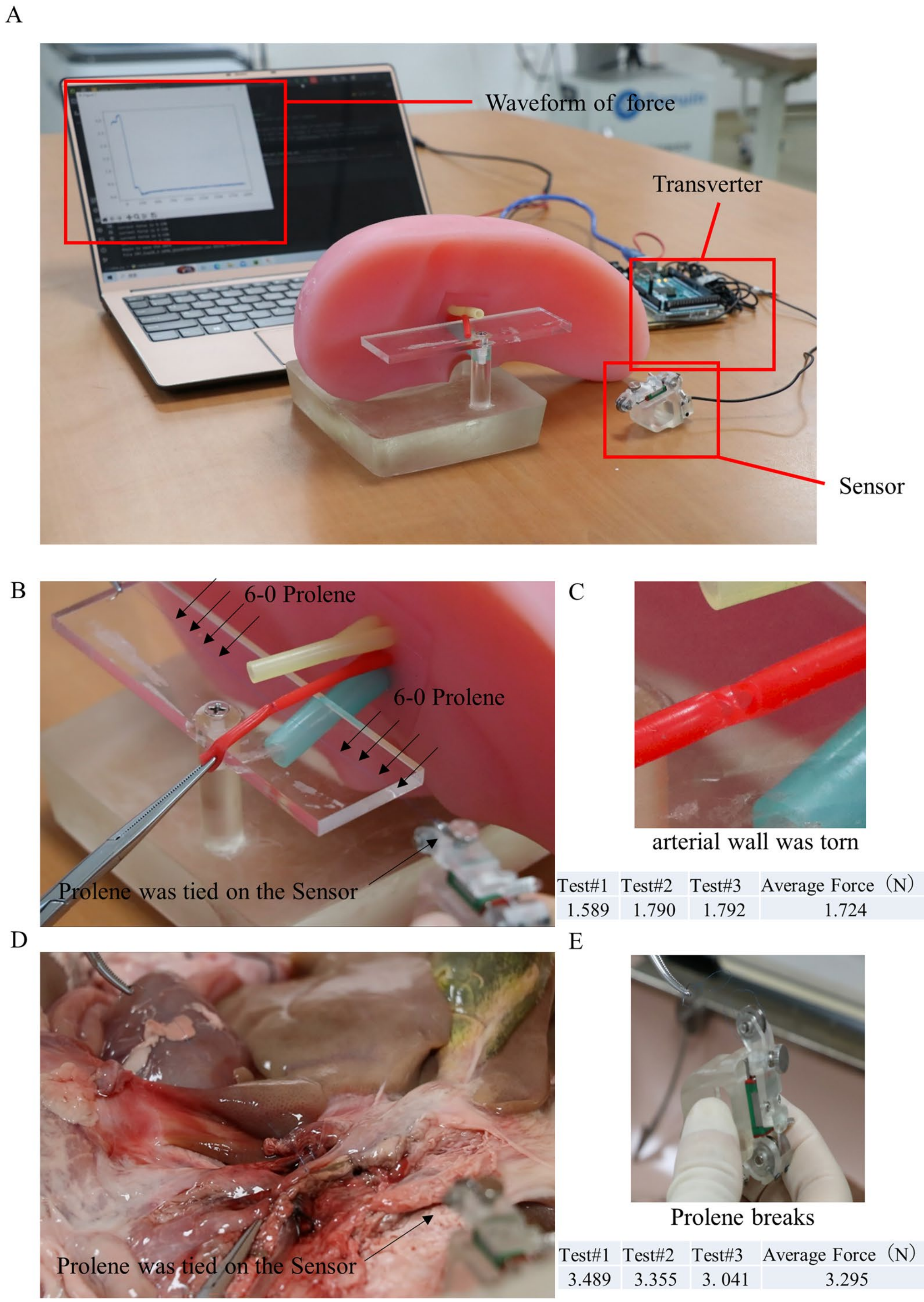

Fig. 4 Mechanical value test for the hepatic artery wall in the 3D printed model and isolated swine organ. **A** A wearable knot tying force test platform consisting of a knob, two pulleys, a slider, a steel wire, and a load cell was constructed to accurately measure the tension in sutures during surgical suturing process. **B** An external figure-of-8 suture method using 6–0 Prolene was used for the hepatic artery repair, and the mechanical value of the hepatic artery wall tear was measured using the force test platform. **C** Three 3D printed models were randomly selected for testing, and the mechanical critical values of the hepatic artery tears are presented. **D** Three isolated swine organs were selected for testing and the mechanical critical values of the hepatic artery tears are presented. **E** The hepatic artery from the isolated swine did not tear before the Prolene broke. The mechanical values of the 6–0 Prolene fractures are presented

bleeding location and controlling hepatic artery bleeding during the training sessions. Observations of trainees participating in eight training sessions revealed improved performance in revealing bleeding locations and precise suturing in later sessions.

Surgeons were invited to evaluate the model. Most indicators of the model demonstrated a good simulation effect. However, the ease of tearing the arterial wall requires further enhancement. During the eight training sessions, one fellow and one resident each failed one operation due to tearing of the hepatic arterial wall during knotting. These findings indicated that the tear characteristics of the hepatic arterial wall in the model required improvement. We designed a mechanical measurement platform to evaluate the minimum mechanical value required to tear the arterial wall of the model [30, 31]. The results revealed that the arterial wall of the 3D printed model tore at an average tension of 1.724 N, whereas the arterial wall of the isolated swine tissue did not tear before 6–0 Prolene rupture. The minimum average mechanical value of Prolene breakage during figure-eight suturing and knotting was 3.295 N. Therefore, the hepatic artery of this 3D printed model should withstand a strength of at least 3.295 N without tearing. Further studies are needed to improve the materials used in 3D printing models.

This study also has several limitations. First, the surgeons involved in the analysis were from a single centre. A multicentre randomised controlled trial would enhance the persuasiveness of the conclusions. Second, fifteen surgeons trained for the first time, and four surgeons trained 8 times. Thus, the sample size was limited. Finally, the transferability of training effects to clinical practice needs to be compared in future studies when dealing with hepatic artery haemorrhage.

Conclusion

Few studies have focused on simulation training for sudden hepatic artery haemorrhage. Our simulation model distinguishes between surgeons with different levels of experience and allows those with less experience to improve their laparoscopic technique for hepatic artery repair through training on the model. However, the tear resistance of the model needs to be further improved in subsequent work.

Abbreviations

AR	Augmented Reality
VR	Virtual Reality
CHA	Common Hepatic Artery
HAP	Hepatic Artery Proper
RHA	Right Hepatic Artery
LHA	Left Hepatic Artery

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13017-024-00562-7.

Supplementary material 1

Supplementary material 2

Supplementary material 3

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Author contributions

Jiliang Shen had the idea of using the model as a simulator, critically read the literature, wrote the manuscript, and approved its final version. Jin Yang participated in the idea, helped in refining the simulator, critically read the manuscript, and approved its final version. Jiasheng Cao, Yaoting Xue, Yaping, Zhang, Bin Zhang, Jiahao Hu, Yuxuan Shen, Chengcheng Wu, Xiaochen Zhang, Liang Shi, Hua Liu, Bin Zheng helped in collecting data and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Sir Run Run Shaw Hospital, Zhejiang University School of Medicine (No. 2022–668-01).

Consent for publication

Not applicable.

Competing interest

The authors declare no competing interests.

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