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Application of a 3D-Printed Endoscopic Retrograde Cholangiopancreatography Simulation Operation Model in Surgical Training and Teaching

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ABSTRACT

Background: The aim of this study is to leverage 3D printing technology to create an endoscopic retrograde cholangiopancreatography training model for the diagnosis and treatment of common bile duct stones. The model includes key anatomical components and is suitable for simulations of critical steps of the operation process.

Methods: The model will serve as a valuable training tool for young doctors, enhancing their skills and understanding of the procedure. Young doctors were divided into two groups: a model-based teaching group and a group that received only theoretical and surgical video training. The two groups were evaluated and analyzed on the basis of six indicators.

Results: Both the model simulation group and the control group showed significant improvements in their grasp of theoretical knowledge. However, the experimental group demonstrated a notably greater improvement in several key areas, including understanding biliary anatomy, patient management, awareness of complications, confidence in performing procedural steps, and overall self-confidence ($P < 0.001$, $P = 0.04$, $P=0.036$, $P < 0.001$, $P=0.012$), than the control group did.

Conclusion: These results suggest that, compared with traditional learning methods, model-based training not only leads to a better mastery of bile duct stone treatment but also boosts confidence in performing the procedure in clinical practice.

Keywords: Common Bile Duct Stones; 3D Printing; Endoscopic Retrograde Cholangiopancreatography

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Introduction

Bile duct stones are common reasons for hepatobiliary surgery and are typically classified into primary bile duct stones and secondary bile duct stones, which develop from gallbladder stones [1]. The main symptoms of common bile duct stones include biliary colic, obstructive jaundice, cholangitis, and pancreatitis [2]. If left untreated, these conditions can lead to more severe complications, potentially progressing to bile duct cancer or pancreatic cancer [3]. For common bile duct stones, endoscopic retrograde cholangiopancreatography (ERCP) is uniquely advantageous for stone removal and is widely recognized as a key method for managing biliary and pancreatic diseases [4]. However, the success of ERCP depends on the skill of the operator, as the procedure is associated with a high risk of complications. When the procedure is performed by an endoscopist with insufficient training or experience, the likelihood of postoperative complications increases [5]. Postoperative complications include pancreatitis, bile duct bleeding, infection, and perforation [6]. Studies have shown that the occurrence of related complications is influenced primarily by two factors: the indication for procedure and the technical skills of the endoscopist [7]. Therefore, simulating the procedure and accumulating relevant experience have always been key objectives in physician training and research. Previous studies on ERCP training models have focused primarily on *in vitro* models and computer-based simulations [8-11]. However, a survey revealed that only a small number of trainees had access to such simulation models [12].

Owing to rapid advancements in 3D printing technology, such models have been widely used in medical education, including preoperative simulations, undergraduate teaching, and other fields. The value of 3D-printed models has been proven, as they provide a more intuitive and realistic sensory experience [13-15]. This suggests that integrating 3D-printed models into ERCP training could lead to increased access to simulation models for more trainees, enhancing both training efficiency and realism. Therefore, we aimed to develop a comprehensive ERCP surgical model using 3D printing technology that is convenient, user friendly, and reusable to support the education of young doctors.

Methods and Materials

Ethical Statement

This study was approved by the Ethics Committee of Guangdong Second People's Hospital (no. 2024-KY-KZ-391-01) and complied with the Helsinki Declaration. The participants provided informed consent and agreed to be published, allowing the use of all the data collected for scientific research only.

Construction and Printing of 3D Models

To create a more realistic ERCP simulation model, we partnered with a 3D printing company. We retrospectively collected CT data from patients who had undergone ERCP procedure and provided these data to our collaborator, Tengwei Technology (Guangzhou), to produce a 3D-printed soft model of the esophagus, stomach, duodenum, and common bile duct (Figure 1A &1B). As shown in Figure 1C, we used a magnetic device to divide the entire model into three parts at the duodenal papilla: the esophagus, stomach, duodenum, common bile duct, and the connection to the papilla. The model was hollowed out to allow the passage of the duodenoscope. We designated four fixation points at the duodenal papilla connection site and used transparent dressings to simulate the surgically incised duodenal papilla. The detachable magnetic design facilitates easy replacement of the transparent dressing, enabling repeated practice. Additionally, clay and straw were used to fill the common bile duct, simulating the selection and insertion of the guide wire. By adjusting the position of the straw, different bile duct shapes were modeled. The entire model was constructed of translucent silicone, allowing clear observation of the position of the duodenoscope during the procedure, which aids simulation practice for junior doctors (Figure 1D).

Design of the Duodenal Papilla

The detachable magnetic design of the duodenal papilla not only allows the model to be reused but also enables us to modify the spatial relationships between the clay and the straw to simulate various common bile duct shapes encountered in practice. Additionally, by adjusting the placement angle and direction of the straw, we can create different levels of difficulty (Figure 1E & 1F). The pancreatic and bile duct junction represent the point where the bile duct and pancreatic duct merge before entering the duodenum and is typically located in the descending part of the duodenum. The normal openings of the pancreatic and bile ducts at the duodenal papilla are generally classified into three types:

(1) The common bile duct and main pancreatic duct are completely separate and open into the duodenum individually;

(2) The common bile duct and main pancreatic duct are parallel with no common channel, but both open into the duodenal papilla together; and

(3) The common bile duct and main pancreatic duct merge to form the ampulla of Vater, which then opens into the duodenal papilla. On the basis of the different classifications of the pancreatic and bile duct junction, we designed various components for the openings of the common bile duct and pancreatic duct, adapting them to different scenarios through repeated practice.

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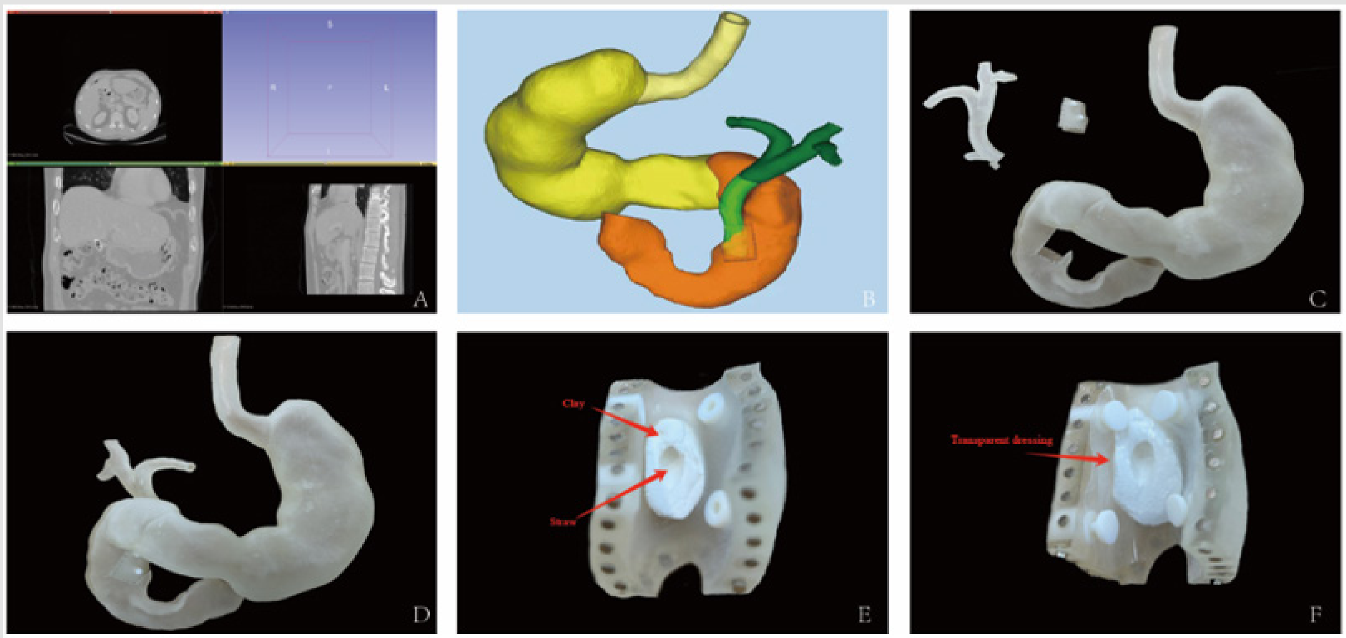

Figure 1: Construction of a 3D-printed model on the basis of CT data.
A. CT scan data of ERCP patients before surgery.
B. Construction of the 3D simulation model.
C. Division of the model into the gastroduodenal, common bile duct, and duodenal connection sections.
D. 3D-printed model after reconstruction.
E-F. Design of the duodenal papilla connection section.

Simulation of Key Steps of ERCP Procedure

We invited two senior endoscopists to perform ERCP simulation. Both physicians have more than 10 years of experience in endoscopic operation and teaching young doctors. They evaluated and verified the accuracy of the model and its preoperative guidance significance. The results showed that the simulator was rated as useful for training and unanimously considered to be a valuable supplement to medical education. As shown in Figure 2, we inserted the duodenoscope through the esophagus, and after an appropriate amount of paraffin oil was applied, the endoscope was successfully advanced into the duodenum. The duodenal papilla was identified via the lens, and a guidewire was inserted. After confirming that the guidewire had entered the common bile duct, the papilla was carefully incised with a duodenotomy knife, and a stone removal basket was introduced. To minimize the risk of repeated radiation exposure and enhance the portability of the procedure, we opted for direct visualization and common bile duct lithotomy. The stones were then removed from the duodenal opening using a basket.

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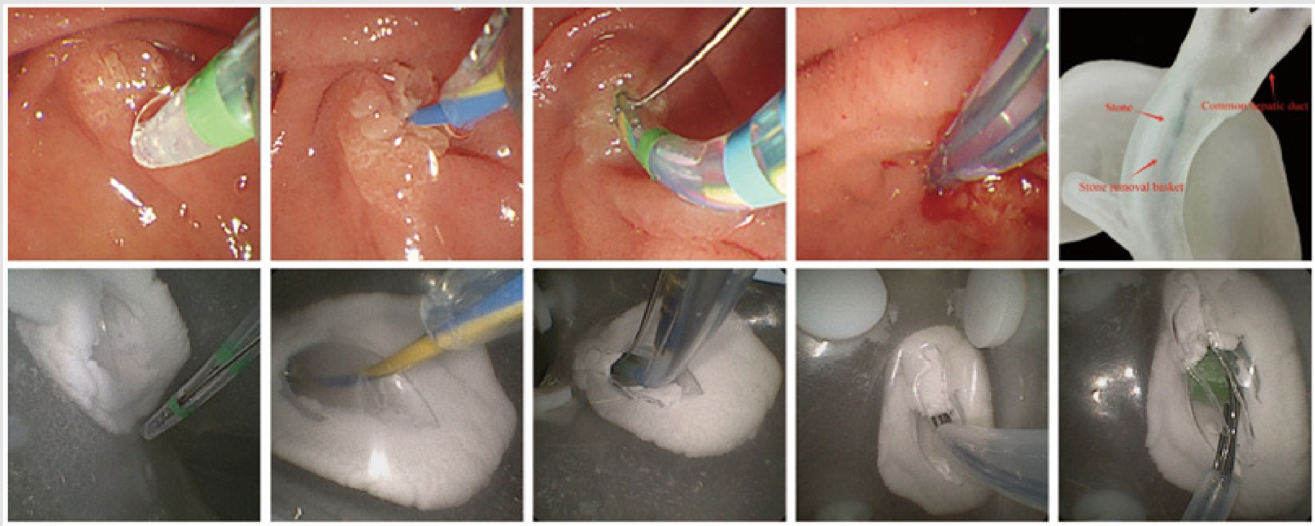

Figure 2: Simulation of the ERCP surgical process. Comparison of practical (top) and model operation (bottom). From left to right: Duodenal papilla identification; Guidewire insertion; Papillary incision; Stone basket insertion; Stone extraction.

Use of Models in Teaching Junior Doctors

To help junior doctors better understand the diagnosis and treatment of bile duct stones, as well as the key techniques involved in ERCP, we plan to use 3D-printed models for teaching purposes. Additionally, we aim to explore the role of these models in the learning process through questionnaire surveys. Figure 3 illustrates the pedagogical framework used in this study. The goal is to assess junior doctors' understanding of cholelithiasis and ERCP from six key aspects: biliary anatomy, theoretical knowledge, patient management, complication management, procedural steps, and self-confidence. On the basis of this framework, we designed two sets of questionnaires: one objective and one **subjective questionnaire**. The **objective questionnaire** covers theoretical knowledge, including bile duct anatomy, perioperative patient management in ERCP, and bile duct stone management. The subjective evaluation questionnaire focuses on junior doctors' self-assessment of their understanding of bile duct stone patients and surgical techniques. After the scores were standardized according to the scoring system, the final score reflected junior doctors' mastery of the relevant knowledge. We recruited 30 young doctors from the hepatobiliary surgery training program and collected their basic information, including sex, age, and education level. All participating doctors met the following criteria:

(1) Strong communication and comprehension skills,

(2) Regular attendance,

(3) No failing grades in prior examinations, and

(4) The ability to complete assigned learning tasks conscientiously. The doctors were randomly assigned to two groups, each consisting of 15 participants. Prior to the teaching session, they were asked to review materials on bile duct stones and complete two questionnaires. Senior hepatobiliary surgeons were invited to deliver lectures, covering the etiology, anatomy, clinical manifestations, and surgical methods of bile duct stones. The focus was on explaining the precautions before, during, and after ERCP operation, as well as guiding the students through real case analyses and teaching rounds. In the experimental group, 3D-printed models were introduced to enhance understanding, offering a more intuitive approach than control group. To further improve the young doctors' proficiency in ERCP, the control group primarily learned the ERCP process through surgical videos, with the instructor analyzing each step. On this basis, the experimental group used 3D-printed models for hands-on simulation. Each doctor in the experimental group had the opportunity to practice with duodenoscopes and 3D-printed models under the guidance of instructors. After the session, both groups completed the same questionnaires again, and the results were compared to assess their understanding of the teaching content.

Data Analysis

Statistical analysis was performed using SPSS 26.0 software. For normally distributed data, the t test was applied. For nonnormally distributed data, the rank sum test was used. $P < 0.05$ was considered statistically significant.

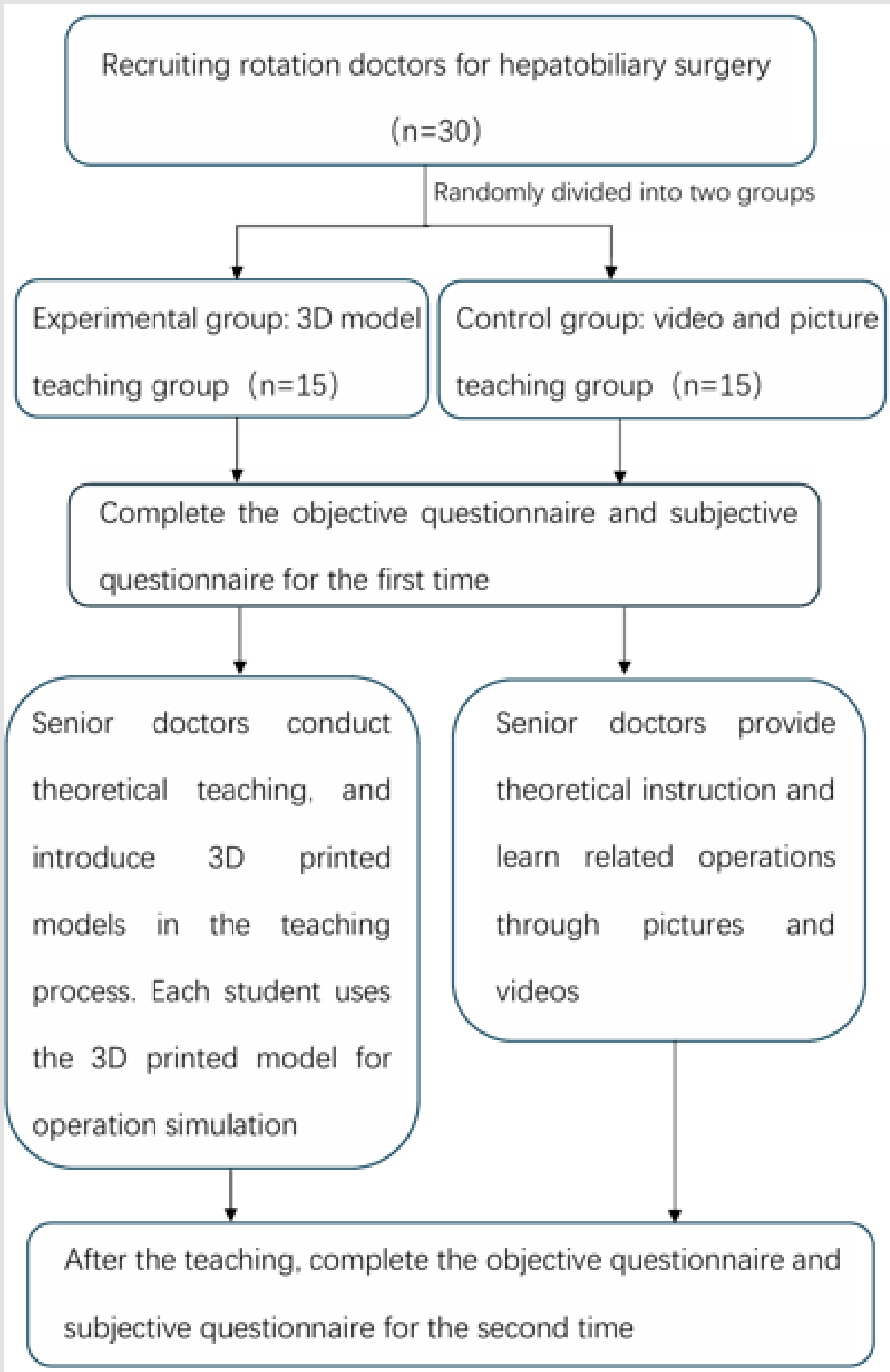

Figure 3: Diagram of the teaching model.

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Results

The basic information of the 30 young doctors was statistically compared. As shown in Table 1, there were no significant differences between the two groups in terms of sex, age, education level, duration of exposure during hepatobiliary surgery, prior experience using models for endoscopy exercises, or preteaching scores ($P > 0.05$). Most young doctors reported having had little or no exposure to 3D-printed models and had limited knowledge of bile duct stone diagnosis, treatment, and ERCP procedures. After the second questionnaire was completed, all indicators significantly improved after teaching, regardless of the teaching method, as summarized in Table 2, demonstrating the effectiveness of the teaching method. While all questionnaire scores improved after the session, there was no statistically significant difference between the experimental and control groups in terms of theoretical scores on the objective test questionnaire. (70.0±7.9 vs. 71.0±6.3, P=0.614). However, compared with the control group, the experimental group showed statistically significant improvements in the understanding of biliary anatomy (8.1 ± 0.5 vs. 6.4 ± 0.5, P < 0.001), patient management (7.5 ± 0.5 vs. 7.1 ± 0.5, P = 0.04), complication management (7.1 ± 0.4 vs. 6.7 ± 0.5, P = 0.036), procedural steps (7.3 ± 0.8 vs. 5.7 ± 0.4, P < 0.001), and self-confidence (7.3 ± 0.2 vs. 6.9 ± 0.6, P = 0.012). These results indicate that model-based teaching has significant advantages over purely theoretical instruction.

Table 1: Preoperative clinical data in the two groups.

Variables	General Teaching (n=15)	Model Teaching (n=15)	$x^2 value$	*P* Value
Gender, male/female	12/3	13/2	0.475	0.638
Age ($\bar{x} \pm s$,year)	26.4±2.0	26.6±1.7	-0.297	0.769
Education level (Undergraduate/Master/PhD)	10/5/0	10/4/1	-0.323	0.749
Time spent in hepatobiliary surgery($\bar{x} \pm s$,year)	2.1±0.7	1.7±0.8	1.213	0.235
Time spent in endoscopy ($\bar{x} \pm s$,year)	0.2±0.4	0.1±0.4	0.475	0.07

Table 2: Difference analysis of teaching objectives.

	Indexes ($\bar{x} \pm s$)	General Teaching (n=15)	Model Teaching (n=15)	$x^2 value$	*P* Value
Before teaching	Theoretical performance	41.3±9.9	40.0±8.2	0.401	0.692
	Understanding of biliary anatomy	2.3±0.7	2.2±0.6	0.462	0.647
	Patient management	2.0±0.5	2.0±0.3	0.182	0.857
	Understanding of complications	2.1±0.5	2.3±0.6	-1.148	0.261
	Procedural steps	1.5±0.3	1.7±0.3	-1.855	0.07
	Confidence	1.7±0.3	1.8±0.3	-0.915	0.368
After teaching	Theoretical performance	71.0±6.3	70.0±7.9	0.510	0.614
	Understanding of biliary anatomy	6.4±0.5	8.1±0.5	-9.276	<0.001*
	Patient management	7.1±0.5	7.5±0.5	-2.150	0.040*
	Understanding of complications	6.7±0.5	7.1±0.4	-2.225	0.036*
	Procedural steps	5.7±0.4	7.3±0.8	-7.166	<0.001*
	Confidence	6.9±0.6	7.3±0.2	-2.787	0.012*

Note: *Significant difference.

Discussion

Bile duct stones commonly develop in the digestive system, as evidenced by an incidence rate of approximately 18% in the general population [16]. According to relevant guidelines and owing to the potential health complications they cause, patients diagnosed with common bile duct stones are recommended to undergo lithotomy whenever possible [17]. Over the years, significant progress has been made in the treatment of bile duct stones. Currently, common surgical methods include laparoscopic common bile duct exploration (LCBDE), laparoscopic transcystic common bile duct exploration (LTCBDE), and endoscopic retrograde cholangiopancreatography. Compared with laparoscopic surgery, ERCP is favored for its minimal invasiveness, significant efficacy, and association with faster recovery times. However, most young doctors lack opportunities to simulate the ERCP procedure, and the use of improper techniques can lead to serious complications such as perforation and bleeding. Studies on the ERCP learning curve suggest that trainees typically need to perform approximately 255 ERCP procedures to achieve competency in routine biliary ERCP [18]. Beginners cannot experience the sensations of intubation and biliary sphincterotomy in real patients and therefore must engage in continuous simulation practice to gain hands-on experience. Traditionally, ERCP training models have been categorized into four types: mechanical, *in vitro*, hybrid, and digital [19]. *In vitro* animal models are difficult to store and require expensive consumables.

Digital models lack tactile feedback, and mechanical models still require further development to improve their simulation accuracy. In recent years, 3D-printed models have revolutionized the medical field because of their ability to improve surgical success rates, portability, and usefulness in simulating clinical procedures. They have been widely applied in orthopedics, urology, hepatobiliary surgery, dentistry, and other areas, particularly in preoperative simulations [20-22]. Yao et al. divided 62 patients who underwent laparoscopic liver resection into two groups: a 3D model-guided group and a traditional enhanced CT or MRI-guided group, with 31 patients in each group. The results showed that the 3D model group had a lower incidence of intraoperative bleeding and fewer major complications 30 days after surgery. Multivariate analysis indicated that the 3D model was an independent protective factor for reducing the incidence of postoperative complications [23]. Zhang et al. used a 3D-printed liver tumor model for preoperative *in vitro* positioning, guiding ultrasonic microwave ablation of liver tumors. This approach reduced the number of repeated punctures and improved the accuracy and safety of percutaneous microwave ablation of the liver [24]. Building on these advancements, we aim to use 3D printing technology to create personalized ERCP models for preoperative simulations. However, owing to the lengthy printing process, it is not feasible to complete the model before the patient's surgery.

As a result, we have opted to use the models for practice and teaching purposes, allowing young doctors the opportunity to simulate the ERCP process. This remains one of the current limitations. In a recent study, Lu et al. combined stereolithography 3D printing with self-healing materials that mimic the liver-like modulus. Using 4-acryloylmorpholine and methoxy poly acrylate, they were able to quickly create a liver model with self-healing properties [25], offering new insights into reducing model construction time as a result of using better materials in the future. In this study, we aimed to enhance the realism of our ERCP training model by using CT data from real patients. We constructed a 3D-printed model that includes the esophagus, stomach, duodenum, and common bile duct. However, during this process, we identified several challenges that need to be addressed. The first issue was that the silicone model lacked the softness and flexibility of human organs. To reduce discrepancies between the model and real organs, we adjusted the model's curvature by enlarging and reducing certain areas, ensuring that the duodenoscope could pass through smoothly. The second challenge was the reusability of the model. 3D printing is expensive, and the printing process is time-consuming, making it impractical for repeated use. To overcome this, we designed a model that was modular, with detachable parts. The main sections of the model (the stomach and duodenum) were created as one piece, whereas the common bile duct was a separate component.

The duodenal papilla served as the removable connection point. We also used readily available materials such as straws, transparent films, and clay as consumables. Clay and straws were used to simulate guidewire insertion, whereas transparent film was used to simulate surgical incisions. With this design, trainees could easily replace the consumable parts between practice sessions, allowing for multiple uses. Additionally, if different bile duct shapes need to be simulated, the clay components could be swapped out quickly, making the model highly adaptable. The third challenge was portability and operability. Typically, the ERCP procedure requires the use of contrast agents for bile duct visualization, as well as radiation, to locate stones. This not only restricts the operating environment to specialized ERCP rooms but also necessitates protective measures such as lead suits. To mitigate the need for radiation and a complex setup, we simplified the stone removal process. We designed the bile duct to be translucent, allowing trainees to visualize the location of the stones directly without the use of contrast agents. After placing the stone removal basket, trainees could directly observe the position of the stones and perform the removal procedure. These improvements made the model more practical for repeated use in training settings, allowing young doctors to simulate ERCP procedures in a safer and more cost-effective manner. Additionally, we explored the role of the model in teaching young doctors.

The first questionnaire revealed that most young doctors, even those specializing in hepatobiliary surgery, had limited knowledge of ERCP and had never used a duodenoscope to complete the procedure. When we compared the two teaching groups, we found no significant difference in improvement in theoretical knowledge. However, the key advantage of using a 3D-printed model is that it allows young doctors to visualize abstract anatomical structures, thereby enhancing their understanding of biliary diseases. By rendering anatomical structures in tangible three-dimensional form, 3D models minimize the cognitive effort required for spatial visualization, thereby enhancing structural comprehension and procedural clarity. Furthermore, the inclusion of the model enriched the classroom experience, improving student engagement and focus. Practical demonstrations and hands-on training with the model improved engagement in the classroom and therefore teaching effectiveness. 3D-printed models simulate realistic clinical scenarios, enabling learners to acquire knowledge through hands-on engagement in authentic contexts. The questionnaire survey also revealed a significant increase in the confidence levels of the students in the 3D printing group, suggesting that they would approach future clinical work with greater composure when managing patients. Despite these advantages, our study has several limitations. First, as mentioned above, we simplified the stone removal process and omitted the use of fluoroscopic guidance, meaning that the ERCP procedure could not be fully replicated.

Second, all the participants were from the same hospital, which may have introduced bias into the results. To better assess the role of 3D-printed models, the sample size should be expanded, participants from multiple hospitals should be included, and the long-term progress of young doctors should be reassessed periodically. In the future, we aim to explore ways to shorten the time needed to construct a 3D printed model; thus, if the time can be effectively shortened, more preoperative simulations can be performed, potentially reducing the incidence of postoperative complications in patients. Additionally, we plan to include more complex biliary conditions, such as stenosis and tumors, in our models to allow simulations of procedures for a wider range of biliary diseases beyond just stones. Furthermore, by upgrading the printing materials and methods, both the realism of the model and the operational flexibility have been improved. Last but not least, our models are not limited to ERCP; they can also be applied in Spy Glass procedures and other endoscopic practices. In summary, we developed a silicone-based soft model for ERCP practice that offers young doctors the opportunity for repeated training through the simple replacement of materials. The model is both portable and realistic, providing an effective platform for hands-on learning. Our findings suggest that the use of 3D-printed models in teaching significantly enhances young doctors' understanding of biliary anatomy, patient management, complication handling, and procedural steps and increases their confidence.

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Author Contributions

Xiancheng Zeng, Cheng Li and Xiaofeng Li contributed to the conception and design of the study; Wenjun Zhou wrote the manuscript, collected the data, and conceptualised and designed the study. Jiawei Qin and Xiaoqiao Yang conceptualised, designed, analyzed, and interpreted the study. Lei Zhang, Jianfan Wen, Biao Liang involved in teaching.

Conflict of Interest

The authors declare that they have no conflict of interest.

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