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ORIGINAL ARTICLE

Case Control Study

Three-dimensional printing for preoperative rehearsal and intraoperative navigation during laparoscopic rectal cancer surgery with left colic artery preservation

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Abstract

BACKGROUND

Prior studies have shown that preserving the left colic artery (LCA) during laparoscopic radical resection for rectal cancer (RC) can reduce the occurrence of anastomotic leakage (AL), without compromising oncological outcomes. However, anatomical variations in the branches of the inferior mesenteric artery (IMA) and LCA present significant surgical challenges. In this study, we present our novel three dimensional (3D) printed IMA model designed to facilitate preoperative rehearsal and intraoperative navigation to analyze its impact on surgical safety.

AIM

To investigate the effect of 3D IMA models on preserving the LCA during RC surgery.

METHODS

We retrospectively collected clinical dates from patients with RC who underwent laparoscopic radical resection from January 2022 to May 2024 at Fuyang People's Hospital. Patients were divided into the 3D printing and control groups for statistical analysis of perioperative characteristics.

RESULTS

The 3D printing observation group comprised of 72 patients, while the control group comprised 68 patients. The operation time (174.5 ± 38.2 minutes *vs* 198.5 ± 49.6 minutes, P = 0.002), intraoperative blood loss (43.9 ± 31.3 mL *vs* 58.2 ± 30.8 mL, P = 0.005), duration of hospitalization (13.1 ± 3.1 days *vs* 15.9 ± 5.6 days, P < 0.001), postoperative recovery time (8.6 ± 2.6 days *vs* 10.5 ± 4.9 days, P = 0.007), and the postoperative complication rate (P < 0.05) were all significantly lower in the observation group.

CONCLUSION
Utilization of a 3D-printed IMA model in laparoscopic radical resection of RC can assist surgeons in understanding the LCA anatomy preoperatively, thereby reducing intraoperative bleeding and shortening operating time, demonstrating better clinical application potential.

Key Words: Rectal cancer; Three-dimensional printing; Inferior mesenteric artery; Left colic artery; Preoperative rehearsal; Intraoperative navigation

Core Tip: Anastomotic leakage is one of the most challenging postoperative complications for surgeons operating on rectal cancer. Preserving the left colic artery significantly reduces the incidence of anastomotic leakage; however, achieving this outcome is technically demanding and time-consuming, particularly for less experienced surgeons. The present study suggests that three-dimensional printing technology can be effectively applied for preoperative simulation to improve intraoperative navigation. This approach helps surgeons optimize the surgical plan, reduces intraoperative bleeding, and shortens operation time.

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INTRODUCTION

Colorectal cancer (CRC) is one of the most common malignant cancers of the digestive tract and rectal cancer (RC) worldwide, accounting for approximately one-third of all cases and mortality events associated with CRC[1,2]. Most RC cases are detected at an advanced stage, at which point they pose a significant threat to patient survival. With the increase in life expectancy and the increasingly widespread use of electronic colonoscopy screenings, the incidence of CRC has been gradually rising. The treatment for RC involves a multidisciplinary approach centered on surgery, with significant contributions from medical oncology, radiation oncology, and gastroenterology[3,4]. In clinical practice, the success rates of anus-preserving surgeries for low-lying RC have significantly increased due to several advances in patient care, including the standardization of total mesorectal excision, the adoption of neoadjuvant chemoradiotherapy, the implementation of total neoadjuvant therapy, the application of rectal magnetic resonance imaging, improvements in mechanical stapling technology, and the introduction of improved operating techniques such as transanal total mesorectal excision and intersphincteric resection[5-7]. Anastomotic leakage (AL) is the most serious postoperative complication in RC surgery, causing significant distress for both surgeons and patients[8]. With advancements in laparoscopic surgical techniques and the completion of numerous clinical trials, preservation of the left colic artery (LCA) has been shown to significantly reduce the incidence of AL following operation[9,10].

To preserve the LCA during surgery, the surgeon must open the vascular sheath along the inferior mesenteric artery (IMA), and retain the LCA while cutting the sigmoid artery (SA) and the superior rectal artery (SRA)[11]. However, this approach is technically demanding and time-consuming, particularly for less experienced surgeons. The increased surgical difficulty arises from the uncertain anatomical relationships among the branches of the IMA, including the LCA, SA, and SRA[11-13]. Studies have identified four vascular types of the LCA, as follows: (1) Type I, where the LCA arises independently from the IMA; (2) Type II, where the LCA and SA both branch from a common trunk of the IMA; (3) Type III, where the LCA, SA, and SRA all branch at the same location; and (4) Type IV, where the LCA is absent, leaving only the SA and SRA[11,13,14]. Additionally, the length of the IMA trunk and the distance from the origin of the LCA to the root of the IMA shows significant variations among patients[15,16]. Unclear preoperative IMA classification and the origin of the LCA present significant challenges for surgeons. Overcoming this complication is crucial for ensuring surgical success.

Three-dimensional (3D) reconstruction and 3D printing technology can be applied in the medical field to perform preoperative simulation and facilitate intraoperative navigation, thus helping surgeons to select the appropriate surgical plan[17,18]. In addition, 3D printing can aid in the construction of personalized implants, such as hip and knee joints, as well as customized dental crowns, bridges, orthodontic appliances, and implants[19]. Additionally, 3D printing can be used to build precise anatomical models for use in medical education and training, customize 3D-printed surgical guides to help doctors with accurate positioning and cutting, and create personalized drug doses and combinations based on patient needs, thereby enhancing treatment effectiveness and patient compliance[20,21]. However, the use of 3D printing in RC surgery is still in its infancy. In this study, we created a 3D-printed model of the IMA to clarify the morphology of its branches and locate the origin of the LCA prior to surgery. Additionally, we evaluated the role of the 3D-printed model in preoperative rehearsal and intraoperative navigation during laparoscopic RC surgery.

MATERIALS AND METHODS

Patients and study design

In this retrospective cohort study, participants with RC scheduled to undergo laparoscopic radical resection were divided into a 3D printing group (observation group) and a control group, using a random number table. The study was conducted at Fuyang People's Hospital from January 2022 to May 2024. The inclusion criteria were as follows: (1) Age over 18 years old; (2) RC confirmed histopathologically prior to operation; (3) Scheduled to undergo laparoscopic radical resection of RC with Dixon reconstruction of the digestive tract; (4) Achievement of R0 resection; (5) Patients with optimal cardiac and pulmonary function; (6) Patients who underwent an abdominal double-phase enhanced scan prior to surgery; and (7) Patients who provided informed written consent to participate in the study. The exclusion criteria were as follows: (1) Occurrence of distant metastasis; (2) Presence of other concurrent malignancies; (3) Surgical procedures which did not include digestive tract reconstruction (Miles or Hartmann); (4) Comorbid severe heart and lung disease; and (5) Comorbid schizophrenia or other mental health disorders, lack of independent behavior ability, or inability to cooperate with treatment. This study was approved by the Ethics Committee of Fuyang People's Hospital. The study design and flow chart are shown in Figure 1.

Construction of 3D IMA model

Enhanced computed tomography (CT) images were imported in DICOM format into 3D modeling software (3D Slicer 5.2.2 and Mimics 19.0) for 3D reconstruction. The abdominal aorta (AA), left iliac artery, right iliac artery, IMA, LCA, SA, SRA, and inferior mesenteric vein were selected for 3D reconstruction. Using the 'multiple slice edit' function, the target arteries and veins were marked in the transverse, sagittal, and coronal planes. The surface of the 3D virtual model was refined using a smoothing process. After confirmation that there were no reconstruction errors by another 3D reconstruction technician, the IMA model was 3D-printed in white resin material using a high-precision SLA 3D printer. The 3D models were subsequently cured, polished, and color-coded, with red representing arteries and blue representing veins. The completed model was subsequently provided to the surgeon prior to the surgery for preoperative evaluation and surgical planning. Before entering the operating room, the model was disinfected with 75% alcohol. The model was positioned next to the laparoscopic monitor to assist with intraoperative navigation of the LCA's origin and course, and the types of IMA. We confirmed the successful preservation of the LCA based on our intraoperative observations as well as postoperative CT evaluations.

Observation index

The basic characteristics of the two groups were assessed through the evaluation of seven factors: Gender, age, clinical stage, diverting stoma, neoadjuvant therapy, tumor location, and IMA types. We subsequently analyzed additional factors, including the operating time, intraoperative blood loss, number of lymph nodes dissected, and occurrences of lymph vessel and nerve invasion. We further considered tumor invasion depth (T stage), presence of lymph node metastasis (N stage), time of stay in the hospital, postoperative recovery time, costs, and the incidence of postoperative complications, including AL, intestinal obstruction, and wound infection. Postoperative recovery time was defined as the interval from surgery to hospital discharge, whereas hospital stay duration refers to the time from admission to discharge.

Statistical analysis

Using GraphPad Prism 8 software for statistical analysis, measurement data were analyzed using the Student's t-test or Mann-Whitney U test, while enumeration data were analyzed using the χ^2 or Fisher's exact tests. Statistical significance was set at $P < 0.05$.

RESULTS

IMA types and 3D printing models

We performed 3D reconstruction and printed 3D models based on the patients' preoperative enhanced CT images, as shown in Figure 2 and Supplementary Table 1. The 3D printing group included 35, 16, 20, and 1 cases of IMA type I, II, III, and IV, respectively. The mean distance from the origin of the LCA to the root of the IMA was 42.4 ± 9.2 mm, ranging from 17.1 to 70.4 mm. A comparison between photos obtained during operation and the 3D printing IMA model is shown in Figure 3.

Clinical characteristics

Between January 2022 and May 2024, 172 RC patients who underwent laparoscopic radical resection were included (Figure 1). Among them, 3 patients with liver metastasis who underwent laparoscopic radical resection of RC and partial hepatectomy were excluded. A further 29 patients who underwent abdominoperineal resection (Miles) or laparoscopic radical resection of RC without digestive tract reconstruction (Hartmann) were further excluded. Finally, a total of 140 eligible patients were selected and randomly divided into two groups. The control group (n = 68) underwent surgery without the use of a 3D printing model for preoperative rehearsal and intraoperative navigation, while the observation group (n = 72) underwent surgery following the construction of a 3D printing model. The two groups had similar baseline characteristics, including gender, age, clinical stage, diverting stoma, neoadjuvant therapy, tumor location, and

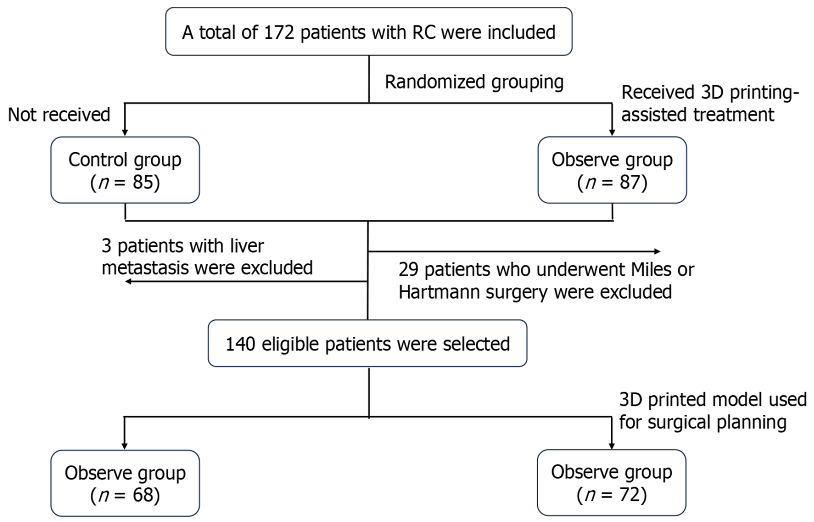

Figure 1 Flowchart of this retrospective case control study. RC: Rectal cancer; 3D: Three dimensional.

IMA type (P > 0.05). Detailed baseline characteristics are shown in Table 1.

Perioperative characteristics

Patient perioperative characteristics are shown in Table 2. Operating time (174.5 ± 38.5 minutes in observation group *vs* 198.5 ± 49.6 minutes in control group, P = 0.002) and intraoperative blood loss (43.9 ± 31.3 mL in observation group *vs* 58.2 ± 30.8 mL in control group, P = 0.005) were significantly lower in the observation group than in control group. However, there were no significant differences between the two cohorts in number of lymph node dissections, lymph vessel or nerve invasion, depth of tumor invasion, presence of lymph node metastasis, AL occurrence, wound infection, or intestinal obstruction. However, the duration of hospitalization (13.1 ± 3.1 days observation group *vs* 15.9 ± 5.6 days in control group, P < 0.001), postoperative recovery time (8.6 ± 2.6 days observation group *vs* 10.5 ± 4.9 days in control group, P < 0.007), and cost of care (35.1 ± 5.9 thousand RMB in observation group *vs* 40.1 ± 10.1 thousand RMB in control group, P < 0.001) were all significantly lower in the observation group than in the control group. Finally, the incidence of postoperative complications was significantly lower in the observation group than the control group (P < 0.05).

DISCUSSION

Preserving the anus and reconstructing the digestive tract are critical aspects of RC surgery in clinical practice. However, AL remains a common and serious postoperative complication, posing a major concern for surgeons. Studies have shown that preserving the LCA can enhance blood supply to the anastomosis, and reduce the risk of AL. However, the IMA exhibits various types and variations, with the origin of the LCA from the IMA differing significantly among patients. According to this study, the distance from the origin of the LCA to the root of the IMA is 42.4 ± 9.2 mm ranging from 17.1 mm to 70.4 mm. Prior research has identified four common types of anatomical variations of the IMA: In type I, the LCA branches off from the IMA early and separately, while the SA and SRA subsequently branch together from the IMA. In type II, the LCA and SA initially branch together from the IMA, then, after traveling a certain distance, the LCA branches off separately from the common trunk. Further, the SRA branches off independently from the IMA. In type III, the LCA, SA, and SRA branch together from the IMA. In type IV, the LCA is absent, with only the SA and SRA being present[11,14]. Preoperative identification of the IMA types and LCA anatomical variations is crucial for the successful completion of laparoscopic RC resection with LCA preservation. In this article, we propose the use of 3D printing technology to preoperatively identify IMA types and LCA anatomical variations, as well as to conduct preoperative rehearsals. During surgery, the 3D model serves as a navigational aid, thereby reducing the difficulty of LCA-preserving procedures. In our study, we found that the operating time (174.5 ± 38.5 minutes in observation group *vs* 198.5 ± 49.6 minutes in control group, P = 0.002) and intraoperative blood loss (43.9 ± 31.3 mL in observation group *vs* 58.2 ± 30.8 mL in control group, P = 0.005) were both significantly lower in the 3D printing group than in control group. As such, we surmised that utilizing a 3D-printed model could help surgeons to effectively locate the LCA during surgery, thereby reducing the difficulty and increasing the safety of the procedure. Some studies have previously suggested that 3D printing models can improve the comprehension and assessment of blood vessels, thereby effectively mitigating intraoperative hemorrhage. This notion aligns with the findings of the present study[22,23].

Enhanced CT of the abdomen or pelvis is commonly applied as a preoperative examination for RC, and is widely applied in clinical practice. Although enhanced CT scans can be used to detect the IMA and LCA, it remains challenging for surgeons to mentally visualize the data as precise 3D images. Additionally, classification of the IMA using enhanced CT is difficult and prone to errors. Furthermore, surgeons may forget the specific location of the LCA and become confused, as their attention is focused on the ongoing surgical procedure. In this study, we 3D-printed accurate IMA

Table 1 Baseline characteristics of the enrolled rectal cancer patients

Characteristic	The control group (*n* = 68)	The observation group (*n* = 72)	t/χ^2	*P* value
Age (years)				
mean ± SD	64.9 ± 12.4	66.2 ± 10.5	0.636	0.513
Median (IQR)	67.0 (59.0-73.0)	69.0 (60.0-72.0)		0.644
Gender			0.759	0.448
Male	43	41		
Female	25	31		
Clinical stage			0.752	0.687
I	25	23		
II	20	26		
III	23	23		
Diverting stoma			1.703	0.192
Yes	46	41		
No	22	31		
IMA types			1.947	0.584
I	28	35		
II	19	16		
III	21	20		
IV	0	1		
Neoadjuvant therapy			0.176	0.675
Yes	24	23		
No	44	49		
Tumor location			0.471	0.790
High	19	17		
Middle	35	41		
Low	14	14		

IQR: Interquartile range; IMV: Inferior mesenteric vein.

models preoperatively, and provided them to the surgical team for practice and visualization. Generally, the 3D reconstruction of the IMA took approximately 20 minutes, 3D printing required around 150 minutes, and the coloring process lasted approximately 25 minutes. Surgical team used the 3D models for preoperative rehearsal, determining the steps required to preserve the LCA during the operation. Additionally, the surgical team placed the 3D models next to the laparoscopic television monitor during the operation, thus enabling rapid identification of the LCA through comparison of the anatomical features of the IMA with the 3D model during the surgical procedure. During surgery, we measured and compared the size of the 3D model with the actual vascular anatomy of the patients using sterile silk, which revealed negligible differences.

In this study, we found that postoperative recovery time (8.6 ± 2.6 days *vs* 10.5 ± 4.9 days, $P < 0.007$), duration of hospitalization (13.1 ± 3.1 days *vs* 15.9 ± 5.6 days, $P < 0.001$), and cost of care (35.1 ± 5.9 *vs* 40.1 ± 10.1, $P < 0.05$) were all significantly lower in the observation group than the control cohort. Preoperative identification of the LCA location and IMA types enables the surgeon to develop a personalized and precise surgical plan, thereby avoiding excessive traction of the LCA during surgery, and minimizing thermal injury to the LCA from ultrasonic and electric scalpels[24]. Shorter surgical duration and reduced intraoperative blood loss can both significantly decrease the incidence of postoperative complications[25,26].

Nevertheless, we acknowledge that there may be some biases and limitations to our results. First, this study was a single-center retrospective cohort study, and its design was therefore not as robust or reliable as that of a prospective cohort study. To overcome this limitation, we plan to perform a multicenter, prospective randomized controlled clinical trial in the future to further explore this issue. Furthermore, our analysis did not reveal any significant reduction in the incidence of AL and intestinal obstruction in the observation group, which could be attributed to the limited sample size. Subsequently, we included all complications in our analysis and observed significant differences. In the present study, we

Table 2 Perioperative characteristics of rectal cancer patients

Characteristic	The control group (*n* = 68)	The observation group (*n* = 72)	t/χ^2	*P* value
Operating time (minute)				
mean ± SD	198.5 ± 49.6	174.5 ± 38.2	3.188	0.002
Median (IQR)	200.0 (165.0-225.0)	170.0 (150.0-208.8)		0.004
Intraoperative blood loss (mL), mean ± SD	58.2 ± 30.8	43.9 ± 31.3	2.857	0.005
Number of lymph node dissections, mean ± SD	14.5 ± 5.1	14.8 ± 5.5	0.336	0.738
Lymph vessel invasion			0.776	0.438
Yes	21	18		
No	47	54		
Nerve invasion			1.582	0.554
Yes	15	13		
No	53	59		
T			0.416	0.677
T1/T2	24	28		
T3/T4	44	44		
N			0.237	0.813
N0	45	49		
N+	23	23		
Postoperative recovery time (day)				
mean ± SD	10.5 ± 4.9	8.6 ± 2.6	2.754	0.007
Median (IQR)	9.0 (8.0-10.75)	8.0 (7.0-9.0)		0.001
Duration of stay in the hospital (days)				
mean ± SD	15.9 ± 5.6	13.1 ± 3.1	3.639	0.001
Median (IQR)	14.0 (13.0-18.0)	12.5 (11.0-14.8)		0.001
Cost (thousand RMB)				
mean ± SD	40.1 ± 10.1	35.1 ± 5.9	2.105	0.001
Median (IQR)	38.7 (34.7-42.7)	35.1 (31.4-38.6)		0.001
Intestinal obstruction				0.432
Yes	4	2		
No	64	70		
Anastomotic leakage				0.265
Yes	5	2		
No	63	70		
Wound infection				0.356
Yes	3	1		
No	65	71		
Postoperative complications			4.026	0.048
Yes	12	5		
No	54	67		

IQR: Interquartile range.

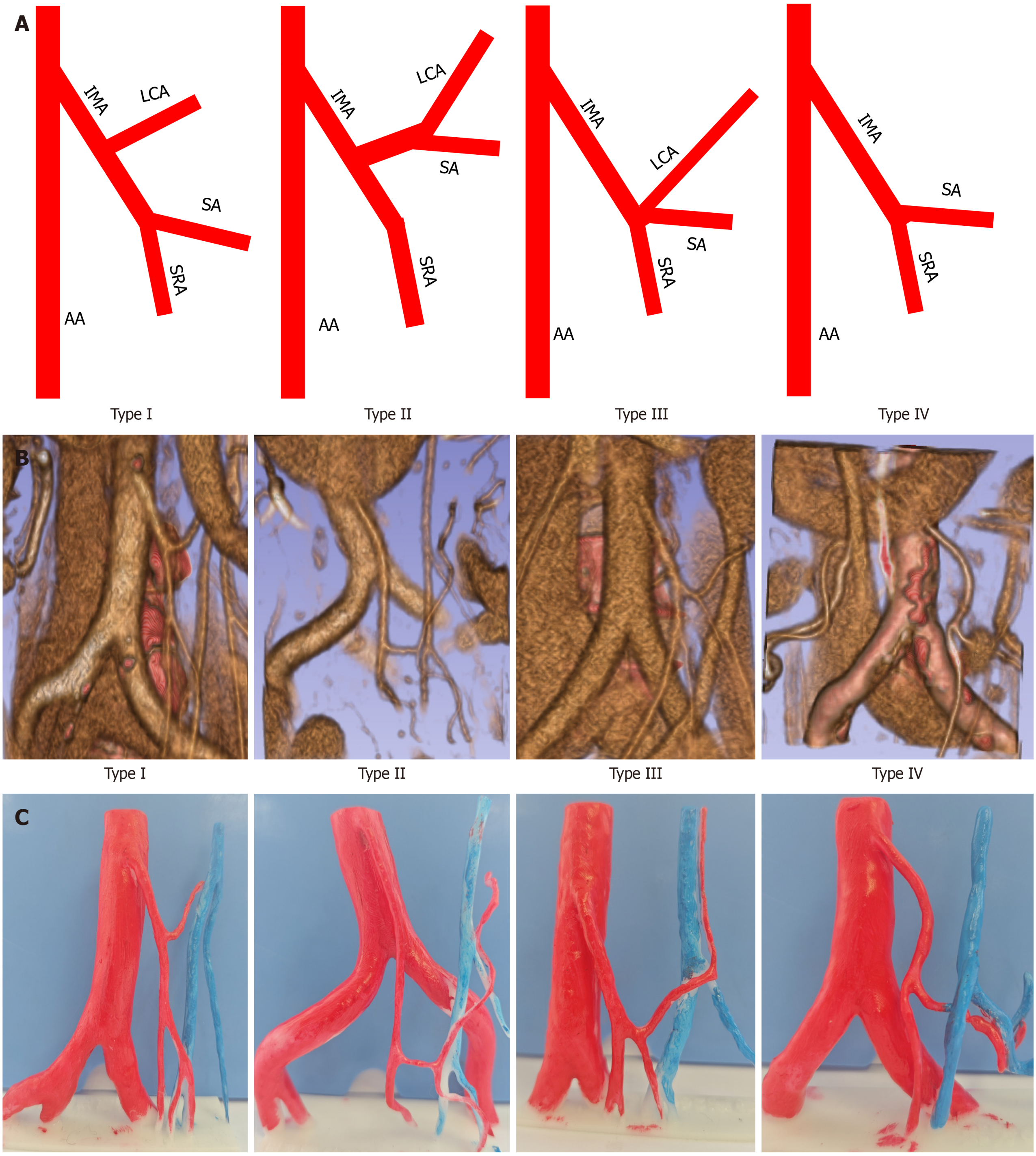

Figure 2 Overview of the four types of inferior mesenteric artery classification. A: Schematic diagrams; B: Based on enhanced computed tomography display; C: Display using three-dimensional printing models. AA: Abdominal aorta; IMA: Inferior mesenteric artery; LCA: Left colic artery; SA: Sigmoid artery; SRA: Superior rectal artery.

only collected data regarding AL, wound infection and postoperative intestinal obstruction as indicators of postoperative complications, neglecting other complications, such as pneumonia, deep vein thrombosis, and gastroparesis, among others. Therefore, we plan to conduct a prospective randomized controlled clinical trial in the future to further investigate these questions. Further, it should be noted that the printing material is inelastic and cannot be pulled or manipulated as in the operation. Furthermore, due to the traction applied during surgery, the spatial orientation of the IMA branches may differ somewhat from the model (Figure 3). Additionally, the creation of 3D models involves both time and cost. In future studies, we plan to assess the cost-effectiveness of 3D models across different clinical scenarios to identify more economically viable solutions. Further, our 3D printing model focuses solely on IMA classification and the location of the LCA, excluding other critical tissues and organs (*e.g.*, the ureters and pelvic organs). Organs such as the ureters and pelvic organs play significant anatomical roles, which may guide the surgeon into the correct anatomical spaces. We plan to further refine the 3D models in future studies and to explore their applications across various clinical scenarios.

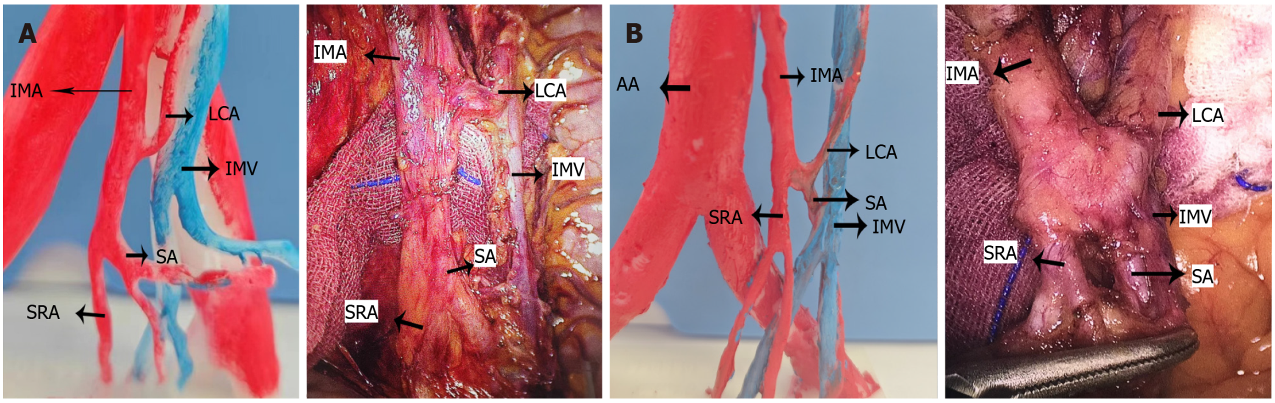

Figure 3 Clinical application of three-dimensional inferior mesenteric artery model in laparoscopic radical resection with preservation of the left colic artery. A: Comparison between the three-dimensional printed model and intraoperative photograph (inferior mesenteric artery type I); B: Comparison between the three-dimensional printed model and intraoperative photograph (inferior mesenteric artery type III). AA: Abdominal aorta; IMA: Inferior mesenteric artery; LCA: Left colic artery; IMV: Inferior mesenteric vein; SA: Sigmoid artery; SRA: Superior rectal artery.

CONCLUSION

Overall, the present study showed that utilizing 3D printing IMA models in laparoscopic radical resection of RC can significantly enhance the surgeon's understanding of the complex anatomy of the IMA prior to surgery. Preoperative rehearsal and intraoperative navigation using the IMA model demonstrated considerable clinical application potential. This approach could help to reduce intraoperative bleeding, shorten operating time, and promote faster postoperative recovery in patients.

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FOOTNOTES

Author contributions: Zhao ZX designed the study and wrote the manuscript; Hu ZJ instructed the whole study and prepared the figures; Su XY and Zhu S collected and analyzed the data; Yao RD and Sun J assisted in the collection of imaging data; Hu ZJ and Yao Y performed the operations; all authors have approved the final version of the manuscript.

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Informed consent statement: Signed informed consent was obtained from all participants. Patient anonymity has been maintained.

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