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Application of Computer-Aided Design-Modified 3D Printed Models in Video-Assisted Thoracoscopic Sublobar Resection for Early-Stage Lung Cancer

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Abstract:

Objective: To compare the application effects of three-dimensional visualization (3DV) models, three-dimensional printing (3DP) models, and computer-aided design (CAD)-modified 3DP models in video-assisted thoracoscopic surgery (VATS) for sublobar resection. *Methods:* A retrospective analysis was conducted on the clinical data of patients who underwent VATS sublobar resection at Hebei University Affiliated Hospital from November 2021 to August 2022. The patients were divided into three groups: the 3DV group, the 3DP group, and the CAD-3DP group. Perioperative data and subjective evaluations from surgeons and patients' families were compared among the three groups. *Results:* A total of 22 patients were included, consisting of five males and 17 females, aged 32 to 77 (56.95 ± 12.50) years. There were nine patients in the 3DV group, six in the 3DP group, and seven in the CAD-3DP group. There were no statistically significant differences in surgical time, intraoperative blood loss, drainage volume, hospital stay, or postoperative complications among the three groups ($P > 0.05$). In the subjective evaluations by surgeons, the CAD-3DP group performed better than the 3DV group in terms of preoperative planning efficiency ($P = 0.008$), intuitiveness ($P = 0.015$), and ease of doctor-patient communication ($P = 0.011$). Compared to the 3DP group, the CAD-3DP group showed superior performance in overall satisfaction ($P = 0.008$), ease of preoperative planning ($P = 0.015$), and planning efficiency ($P = 0.005$). In the subjective evaluations by patients and their families, the CAD-3DP group outperformed the 3DP group in helping them understand the tumor's surrounding vasculature ($P = 0.005$), surgical steps ($P = 0.007$), treatment plan options ($P = 0.010$), and overall satisfaction ($P = 0.022$). Compared to the 3DV group, the CAD-3DP group was better at helping patients and families understand tumor size ($P = 0.013$) and in overall satisfaction ($P = 0.033$). *Conclusion:* CAD-modified 3DP models offer certain advantages in preoperative planning, intraoperative navigation, and doctor-patient communication for VATS sublobar resection.

Keywords:

Computer-aided design
Thoracoscope
3D printing
Sublobar resection

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1. Introduction

For patients with stage IA lung cancer with a tumor diameter ≤ 2 cm and a solid tumor ratio > 0.5, compared to traditional lobectomy, video-assisted thoracoscopic surgery (VATS) sublobar resection (including segmentectomy, subsegmentectomy, and combined subsegmentectomy) can preserve more lung function, with fewer postoperative complications and a shorter hospital stay [1]. Its application in the treatment of early-stage lung cancer is increasing. However, during VATS sublobar resection, surgeons mainly view the surgical field through a two-dimensional screen, lacking stereoscopic vision and tactile feedback, which often leads to misjudgment of lung vascular anatomical relationships. Therefore, we believe that preoperative identification of the pulmonary segments and subsegments, including the pulmonary veins that need to be resected, planning the scope of lung parenchyma resection, and clarifying the possible variations in pulmonary artery anatomy, can significantly improve surgical safety.

The traditional method typically involves confirming the pulmonary vein and pulmonary artery anatomy in the tumor region through preoperative CT imaging. However, this method is difficult to master and imprecise for sublobar resection. The current new approach utilizes 3D technologies such as three-dimensional reconstruction and three-dimensional printing (3DP) techniques to assist in preoperative planning and intraoperative procedures [2,3], allowing surgeons to visually understand tumor size and location. Many studies [4-8] have reported the effectiveness of three-dimensional visualization (3DV) and 3DP models in assisting the preoperative exploration of pulmonary blood vessels and bronchi. However, most 3DV models still rely on two-dimensional screens, lacking stereoscopic vision and tactile feedback, while 3DP models cannot highlight nodules and target segment-related vasculature through display and hiding operations like 3DV models.

Computer-aided design (CAD) refers to the sum of technologies that utilize computer software or other devices to aid in the design process, widely used in various fields. This technology enables three-dimensional modeling operations. Therefore, this study attempts to integrate the advantages of both models by adding a hollowed-out sublobar separation structure at the root and through the structure using CAD in the 3D-printed physical model. The corresponding CAD-modified 3DP model is printed, which provides both stereoscopic vision and tactile feedback, while simultaneously highlighting the target tissue structure and facilitating the observation and protection of adjacent vascular structures. It is applied in VATS sublobar resection to evaluate its effectiveness in assisting preoperative planning, intraoperative navigation, and doctor-patient communication.

2. Materials and methods

2.1. Inclusion and exclusion criteria and grouping

This study retrospectively included patients with early-stage lung cancer who underwent sublobar resection performed by the same surgical team and primary surgeon at the Department of Thoracic Surgery, Affiliated Hospital of Hebei University, from November 2021 to August 2022. The patients were divided into three groups based on the assistive tools used: 3DV group, 3DP group, and CAD-3DP group. Diagnostic criteria for early-stage lung cancer: Referring to the "Chinese Medical Association Guidelines for Clinical Diagnosis and Treatment of Lung Cancer (2018 Edition)" [9], patients presented with cough, expectoration, hemoptysis, or nonspecific clinical manifestations. The presence of a definite lesion was confirmed by techniques such as chest CT, and the TNM staging was from stage I to II.

Inclusion criteria for sublobar resection cases: (1) CT showed a maximum nodule diameter ≤ 2 cm; (2) nodule ground-glass component ≥ 50%; (3) nodule was malignant; (4) no age or gender restrictions; (5) preoperative diagnosis excluded distant metastasis through CT or MRI, and routine cardiopulmonary function evaluation excluded surgical contraindications; (6) nodule doubling time ≥ 400 days, pathology was adenocarcinoma *in situ* or minimally invasive adenocarcinoma; (7) no neoadjuvant chemotherapy or radiotherapy was administered. Exclusion criteria: (1) poor cardiopulmonary function or comorbidities that could not tolerate surgery; (2) CT showed a maximum nodule diameter > 2 cm; (3) widespread pleural metastasis or extensive pleural adhesions.

2.2. Preoperative three-dimensional reconstruction and 3D printing

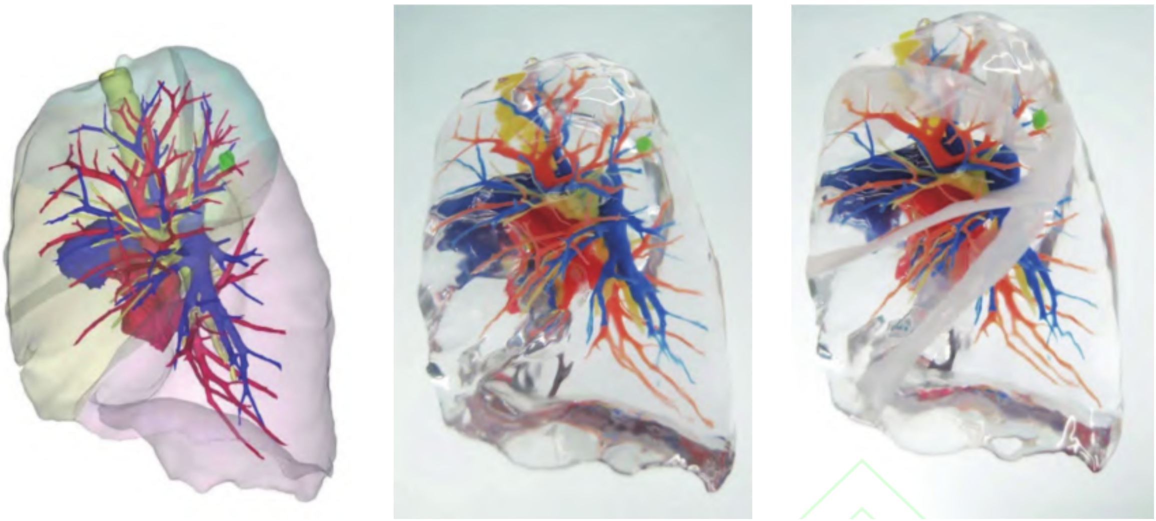
All three groups of patients underwent routine thin-slice CT angiography before surgery to obtain CT imaging data. In the 3DV group, Mimics 23.0 and 3-matic 15.0 software (Materialise, Belgium) were used to reconstruct the patient's CT scan images into a 3DV model including lung parenchyma, bronchi, pulmonary arteries, pulmonary veins, and tumors for preoperative planning. Both the 3DP group and the CAD-3DP group first obtained the 3DV model following the steps of the 3DV group. Additionally, the CAD-3DP group determined the precise boundaries between subsegments using the "cut through points" feature in Mimics software, based on the method of dividing through curved surfaces at the ends of each subsegmental pulmonary artery. CAD-modified sublobar separation structures, including hollowed-out roots and traversing structures, were added to the 3DV model. The STL-formatted 3DV models of both groups were then imported into VoxelDance Additive 3.0 preprocessing software (VoxelDance, China). After inspection and repair, they were finally imported into a J401Pro 3D printer (Zhuhai Seine Technology Co., Ltd., Zhuhai, China) to print out the 3DP model and the CAD-modified 3DP model, respectively (**Figure 1**).

2.3. Preoperative planning and consultation

The surgeon primarily used the aforementioned three assistive tools to confirm the location of the nodule and the surrounding pulmonary arteries and veins. Simultaneously, the distances from the nodule to the intersegmental and intersubsegmental veins were measured. Under the premise of ensuring a safe surgical margin, a surgical plan that can preserve more normal lung tissue and provide a better prognosis for the patient was selected. The surgical plan was then explained in detail to the patient and their family members, along with communication about the condition and answering any questions.

2.4. Surgical method

All patients underwent double-lumen endotracheal intubation under intravenous general anesthesia, with lateral decubitus position on the healthy side and single-lung ventilation. Firstly, the visceral pleura was opened, and the interlobar fissure was dissected. Then, the target pulmonary arteries and veins were isolated and identified individually, and ligated and divided using an endoscopic stapler. The bronchial branches in the target area were also closed and divided using an endoscopic stapler. The intersegmental and intersubsegmental boundaries were determined using the inflation-collapse method. The resected range was then verified by comparing it with the auxiliary surgical model, and the intersegmental and intersubsegmental planes were



(a) 3DV model (b) 3DP model (c) CAD-3DP model

Figure 1. Schematic diagram of models (The lung parenchyma of the solid model is made of transparent photosensitive resin, with bronchi in yellow, pulmonary arteries in blue, pulmonary veins in red, nodules in green, and the CAD-designed sublobar separation structure in white and semi-transparent).

divided using an endoscopic stapler after verification. During the entire surgical process, the three groups used the 3DV model, 3DP model, and CAD-modified 3DP model, respectively, to assist in intraoperative navigation. The specimen was removed and sent for frozen section intraoperative rapid pathology. Lymph node sampling was performed, and if the pathological result was positive, systematic lymph node dissection was performed. A chest tube was placed for closed drainage.

2.5. Main observation indicators

Perioperative indicators such as operation time, intraoperative blood loss, chest tube indwelling time, total drainage volume, postoperative hospital stay, and complications were collected. The subjective evaluations of four surgeons in the surgical team on the three tools assisting sublobar resection were collected, including the intuitiveness, difficulty, and efficiency of preoperative planning, the effectiveness and practicality of intraoperative navigation, the ease of preoperative communication, and overall satisfaction. Simultaneously, the subjective evaluations of patients and their families on the three tools were collected, including their assistance in understanding the condition and surgical effects such as tumor location, size, and surrounding vasculature, surgical steps and plan selection, postoperative complications, and overall satisfaction. The scoring was done using a 5-point Likert scale, where 1–5 represented very dissatisfied, dissatisfied, neutral, satisfied, and very satisfied, respectively.

2.6. Statistical analysis

Statistical analysis was performed using SPSS23.0 statistical software. Measurement data following a normal distribution were described using mean ± standard deviation (SD), and comparisons between groups were made using one-way ANOVA. Count data were described using frequency, and comparisons between groups were made using the chi-square test. Subjective evaluation scores were analyzed using the Kruskal–Wallis H test, and $P \leq 0.05$ was considered statistically significant.

2.7. Ethical review

This study was approved by the Ethics Committee of the Affiliated Hospital of Hebei University (HDFY-LL-2022-146). The included patients and their families were informed about the study and signed informed consent forms.

3. Results

3.1. Comparison of general patient information

This study included a total of 22 patients, including five males and 17 females, aged between 32 and 77 years (mean ± SD: 56.95 ± 12.50 years). There were nine patients in the 3DV group, six patients in the 3DP group, and seven patients in the CAD-3DP group. There were no statistically significant differences between the three groups in terms of gender, age, nodule diameter, smoking history, and comorbidities (such as hypertension and diabetes) ($P > 0.05$). **Table 1** shows the details. The surgical site and number of sublobar resections are presented in **Table 2**.

3.2. Comparison of perioperative data

There were no statistically significant differences between the three groups in terms of operation time, intraoperative blood loss, drainage volume on the first day after surgery, total drainage volume, chest tube indwelling time, hospital stay, and postoperative complications ($P > 0.05$). None of the three groups had cases of conversion to thoracotomy (**Table 3**).

3.3. Comparison of subjective evaluations

3.3.1. Comparison of surgeons' subjective evaluations

The CAD-3DP group was superior to the 3DP group in terms of preoperative planning difficulty ($P = 0.015$), efficiency ($P = 0.005$), and overall satisfaction ($P = 0.008$). It was also superior to the 3DV group in terms of preoperative planning efficiency ($P = 0.008$), intuitiveness ($P = 0.015$), and ease of communication between doctors and patients ($P = 0.011$). The 3DV group was superior to the 3DP group in terms of intraoperative navigation effectiveness ($P = 0.014$), practicality ($P = 0.006$), and overall satisfaction ($P = 0.036$). It was also superior to the CAD-3DP group in terms of intraoperative navigation practicality.

3.3.2. Comparison of patients' subjective evaluations

There was no statistically significant difference between

Table 1. Comparison of general information among three groups of patients (cases/±s)

Clinical data	3DV group (n = 9)	DP group (n = 6)	CAD-3DP group (n = 7)	χ^2 value/F value	P value
Age (years)	60.56 ± 12.89	51.67 ± 11.67	56.71 ± 12.66	0.911	0.419
Gender				0.477	1.000
Male	2	1	2		
Female	7	5	5		
Tumor diameter (cm)	1.13 ± 0.59	1.08 ± 0.19	0.97 ± 0.26	0.295	0.748
Comorbidities					
Hypertension	5	0	2	4.869	0.080
Diabetes	0	1	1	1.876	0.494
Coronary heart disease	2	0	2	1.831	0.509
Stroke	2	0	1	1.379	0.755
Histological type				1.374	0.727
Adenocarcinoma	8	5	7		
Others	1	1	0		
Pleural invasion	1	0	0	1.543	1.000
Smoking history	2	1	3	1.295	0.588

Table 2. Surgical sites of patients in three groups (cases)

Surgical site	3DV group (n = 9)	DP group (n = 6)	CAD-3DP group (n = 7)
Right lung			
S^1	1	0	0
S^2	2	0	0
S^3	0	1	0
S^1+S^3	0	0	1
S^6	2	2	2
S^8	0	1	0
Left lung			
S^{1+2}	1	2	2
$S^{1+2b}+S^{1+2c}$	0	0	1
S^{4+5}	1	0	0
S^6	2	0	1

Table 3. Comparison of perioperative indicators among three groups of patients (cases/mean ± SD)

Clinical data	3DV group (n = 9)	DP group (n = 6)	CAD-3DP group (n = 7)	χ^2 value/F value	P value
Operation time (min)	190.00 ± 95.75	161.17 ± 76.64	185.00 ± 41.43	0.269	0.767
Intraoperative blood loss (mL)	42.00 ± 31.40	72.50 ± 113.13	70.71 ± 30.61	0.570	0.575
Drainage volume on the first day after surgery (mL)	297.22 ± 173.41	145.83 ± 29.23	199.29 ± 119.39	2.564	0.103
Total drainage volume (mL)	776.11 ± 570.26	384.17 ± 192.75	557.14 ± 353.20	1.535	0.241
Indwelling time of chest drainage tube (d)	5.33 ± 4.09	3.50 ± 1.38	5.14 ± 2.73	0.681	0.518
Length of hospital stay (d)	6.33 ± 4.18	4.83 ± 1.47	6.00 ± 2.65	0.416	0.666
Postoperative complications	2	2	2	0.484	1.000

the three groups in terms of helping patients understand the location of the tumor (P = 0.762). The comparison between the 3DP group and the 3DV group showed that the 3DV group was better in terms of helping patients understand the surrounding vasculature of the tumor (P = 0.012) and postoperative complications (P = 0.004), but the 3DP group was better in terms of helping patients understand the size of the tumor (P = 0.035). The comparison between the 3DP group and the CAD-3DP group showed that the CAD-3DP group was superior to the 3DP group in terms of helping patients understand the surrounding vasculature of the tumor (P = 0.005), surgical steps (P = 0.007), treatment options (P = 0.010), and overall satisfaction. The comparison between the 3DV group and the CAD-3DP group showed that the CAD-3DP group was superior to the 3DV group in terms of helping patients understand the size of the tumor (P = 0.013) and overall satisfaction (P = 0.033).

4. Discussion

The standard surgical procedure for early-stage lung cancer has traditionally been lobectomy with lymph node dissection [10]. However, recent studies [11-13] have shown that for non-small cell lung cancer (NSCLC) with a nodule diameter of less than 2 cm, there is no statistically significant difference in overall survival rate and postoperative complication rate between sublobar resection and lobectomy. As a result, more and more patients with early-stage lung cancer are opting for VATS sublobar resection.

Preoperative planning is crucial for the success of surgery, as it can help reduce risks and operating room time [14]. A recent meta-analysis [15] revealed that preoperative 3D lung simulation leads to better intraoperative and postoperative results in terms of blood loss, operative time, postoperative hospital stay, and complications. Additionally, a study by Liu *et al.* [16] demonstrated that for experienced surgeons, 3D printing technology is effective in developing preoperative plans for VATS segmentectomy. Preoperative 3D printed simulation to evaluate lung vasculature and bronchial branching patterns facilitates safe and efficient VATS segmentectomy. Therefore, in this study, we utilized 3DV models, 3DP models, and redesigned CAD-3DP models to aid in preoperative planning. We collected subjective evaluations from surgeons on the three models to assess their effectiveness in preoperative planning and observe the enhanced surgical outcomes achieved through the optimized 3D printed models.

The results indicated that the CAD-3DP group excelled in preoperative planning difficulty and efficiency compared to the 3DP group. Moreover, the CAD-3DP group surpassed the 3DV group in terms of preoperative planning efficiency and intuitiveness. Through participation in the entire preoperative planning process, we discovered that the CAD-3DP group's advantages stemmed primarily from the model's sublobar segmentation structure with hollowed-out roots and intersegmental passing structures. This design allowed for direct visualization of the positional relationship between the tumor, its surrounding vasculature, and each sublobar segment. As a result, it was easier to identify which pulmonary arteries, veins, and tissues to resect and how to perform the resection, addressing the surgical challenges of determining arteriovenous, bronchial, and sublobar boundaries in sublobar resection. Simultaneously, the hollowed-out intersegmental separation structures designed through CAD facilitated convenient observation of the vascular structures that needed to be preserved in the adjacent lung tissue of the target area.

Furthermore, while the 3DV group did not fare poorly in terms of preoperative planning difficulty compared to the CAD-3DP group, we inferred that this could be due to the 3DV model's ability to highlight the anatomical structure of the sublobar segment containing the tumor through a series of operations such as hiding, enlarging, and adjusting transparency. However, these manipulations in the 3DV model can be challenging and require step-by-step demonstration by an assistant, thus explaining the higher preoperative planning efficiency of the CAD-3DP model. Additionally, the CAD-3DP model, as a physical model, offers better intuitiveness during planning compared to the 3DV model, which relies on a two-dimensional screen display.

Locating and precisely resecting pulmonary nodules during VATS can be challenging. Traditional localization methods include CT-guided hookwire puncture and CT-guided percutaneous injection of staining agents, which require careful control of the injected dose to avoid either excessive fluorescence dispersal affecting localization or insufficient staining leading to failed localization [17]. According to Chen *et al.* [18], three-dimensional reconstruction and 3DP technology for lung tumors and anatomical lung models can assist surgeons in more accurate nodule localization, improving both accuracy and safety. Therefore, in this study, we applied 3DV and 3DP technologies to intraoperative navigation to aid in nodule localization.

We found that the 3DV group excelled in intraoperative navigation practicality compared to the 3DP and CAD-3DP groups. Upon further analysis of intraoperative situations, we believed that although both the CAD-3DP model and the 3DV model could highlight the surgical resection site, the surgeon, focused on the procedure, did not have time to examine the CAD-3DP physical model through touch to aid in intraoperative navigation. Consequently, the unique advantage of tactile feedback from the physical model could not be utilized. On the other hand, the 3DV model, directly displayed on a large two-dimensional screen in front of the operating table, made it easier for surgeons to accurately identify target vascular and bronchial branches during the surgery, thus being more favored by surgeons.

Despite the high overall evaluation of the CAD-3DP model in assisting preoperative planning and intraoperative navigation by surgeons, there were no statistically significant differences in perioperative indicators such as operative time, intraoperative blood loss, drainage volume on the first day after surgery, total drainage volume, chest tube indwelling time (P = 0.518), and hospital stay (P = 0.666) among the three groups (P > 0.05). We attributed this to the fact that most of the 22 surgeries were simple segmentectomies (e.g., S^6 segment, left lung S^{1+2} segments) that did not require excessive planning and skill, making it difficult to distinguish the advantages and disadvantages of the three models. Additionally, the small number of cases in each group may have affected the reliability of the comparison results. We plan to continue collecting case data that meet the inclusion criteria. However, the results of this study indicate that due to the assistance of the models, the incidence of conversion to thoracotomy due to intraoperative vascular injury and the incidence of extended resection or lobectomy due to insufficient resection margins were both 0.0% in all three groups. This suggests that 3D technology can indeed reduce or avoid accidental damage to blood vessels or tissues and accurately plan the surgical scope.

In addition, a study [19] has shown that the use of 3D printed models during preoperative conversations can enhance patients' understanding of surgical procedures and risks, thereby contributing to a reduction in the risk of conflicts between doctors and patients. In our study, we found no statistically significant differences between the CAD-3DP group and the 3DP group, or between the 3DP group and the 3DV group. However, the CAD-3DP group was superior to the 3DV group. Simultaneously, the CAD-3DP group and the 3DP group had higher scores than the 3DV group. This suggests that surgeons perceive CAD-3DP and 3DP physical models as more effective communication tools compared to the 3DV digital model during preoperative discussions with patients and their families. We believe this is primarily due to the higher acceptability and ease of communication of physical CAD-3DP and 3DP models among patients and their families, who generally do not have medical expertise.

Further investigation into patients' and families' subjective evaluations of the models' assistance in understanding tumor details revealed some interesting findings. In terms of helping to understand tumor size, there was no statistically significant difference between the 3DP model and the CAD-3DP model, but both were superior to the 3DV model. When it comes to aiding in the understanding of the vasculature around the tumor, there was no statistically significant difference between the 3DV model and the CAD-3DP model, and both were better than the 3DP model. Although the tumor location was evident in all three models, the 3DP and CAD-3DP models, as physical models, provided a more intuitive representation of tumor size. For explaining the lung segment and surrounding vasculature to patients and their families, the CAD-3DP model with hollowed-out sublobar segmentation and the 3DV model capable of hiding other structures to highlight the surgical target area were significantly better than the regular 3DP model.

In terms of assisting patients and their families in understanding surgical information, there were no statistically significant differences in scores for surgical steps and treatment options between the CAD-3DP group and the 3DV group, or between the 3DV group and the

3DP group. However, the CAD-3DP group was superior to the 3DP group. Regarding help in understanding postoperative complications, there were no statistically significant differences between the 3DV group and the CAD-3DP group, or between the CAD-3DP group and the 3DP group, but the 3DV group was better than the 3DP group. Although most differences among these three surgical-related subjective evaluations were not significant, making it difficult to discern the superiority of the models, subjective evaluation scores revealed that patients and families were most satisfied with the CAD-3DP model's assistance in understanding surgical steps and treatment options, followed by the 3DV model, and lastly, the 3DP model. For understanding postoperative complications, the 3DV model was most preferred, followed by the CAD-3DP model, and the 3DP model was least preferred. We attribute this to the CAD-3DP model's combination of realism, which the 3DV model lacks, and clear sublobar boundaries, providing substantial help in locating the surgical target area and making it easier for patients and their families to understand what should be removed and how. The 3DV model, on the other hand, can demonstrate which complications may arise in different situations, such as hiding the bronchi and leaving only the pulmonary arteries and veins to show which vascular injuries could lead to postoperative hemoptysis.

Regarding the overall satisfaction of surgeons and patients with the auxiliary effects of these three models, surgeons believed that the CAD-3DP model and the 3DV model were better than the 3DP model. Since the CAD-3DP model had higher scores than the 3DV model, it can be inferred that the CAD-3DP model was the most satisfactory for surgeons, followed by the 3DV model, and the 3DP model was the least preferred. Similarly, patients and their families considered the CAD-3DP model superior to the 3DP and 3DV models, and the 3DV model had higher scores than the 3DP model. This aligns with the previous subjective evaluation results from both surgeons and patients, indicating that surgeons recognize the effectiveness of the CAD-3DP model in preoperative planning and intraoperative navigation, and patients and their families are also satisfied with the CAD-3DP model.

5. Conclusion

In conclusion, our study suggests that compared to the 3DV model and the regular 3DP model, the CAD-modified 3DP model has certain advantages in preoperative planning, intraoperative navigation, and doctor-patient communication for VATS sublobar resection. Therefore, using the CAD-modified 3DP model to assist in VATS sublobar resection is meaningful for both doctors and patients, demonstrating clinical application value.

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Disclosure statement

The authors declare no conflict of interest.

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