Review Article

Surgical simulation in robot-assisted thoracic surgery: patient safety

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Abstract: Robot-assisted thoracic surgery (RATS) procedures have been increasingly performed at various centers worldwide. Considerable proficiency and thorough preoperative evaluations are required to fully take advantage of RATS. Surgical simulation could help fulfill these preconditions through surgical training, preoperative planning and intraoperative navigation. We reviewed current publications of surgical simulations in RATS and discuss their benefits in patient safety. Overall, the current studies demonstrated that surgical simulation experienced a potential benefit in RATS in terms of rationalization of surgical design, accurate preoperative and intraoperative confirmation of anatomical structure, and improvement of clinical performance, all of which improved the surgical outcome and patient safety. More multicenter prospective studies are required to further prove the benefits of surgical simulation in improving patient safety in RATS.

Keywords: Surgical simulation; robot-assisted thoracic surgery (RATS); patient safety; surgical training; preoperative planning

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Introduction

Since the first use of robot-assisted thoracic surgery (RATS) described by Melfi *et al.* in 2002 (1), RATS procedures have been increasingly performed at various centers worldwide. Different studies have demonstrated the safety of RATS and its equivalence of surgical outcomes compared with open surgery and video-assisted thoracic surgery (VATS) (2-4). Despite the merits of RATS such as increased dexterity with the EndoWrist technology, magnified three-dimensional (3D) view and tremor filtration, considerable proficiency and thorough preoperative evaluations are required to fully take advantage of RATS and to probably improve patient safety. These preconditions could be fulfilled with the assistance of surgical simulation.

Simulation is a technique to replace or amplify real experiences with guided experiences that evoke or replicate substantial aspects of the real world in a fully interactive manner (5). Generally, surgical simulation provides the knowledge and training on how to maneuver and use the robotic system before operating on a live patient. Besides, surgical simulation of a specific patient helps with preoperative planning and intraoperative navigation individually. Simulation-based training, preoperative planning and intraoperative navigation in RATS have been of growing interests recently (6,7). Herein, we review current publications of surgical simulations in RATS and discuss whether they involve in the promotion of patient safety.

Surgical simulation in RATS training

The traditional approach to surgical training is described as "see one, do one and teach one" (8). This does not apply to current surgical education because of the inevitable exposure of patients to inexperienced surgeons and associated dangers and harms. Instead, surgical simulation allows surgical skills development in a risk-free environment and leads to improvement of clinical performance and patient outcome (9).

Modern surgical simulation traces back as far as 1800s when cadavers and animals were used for surgical practice (10). The adoption of animate and cadaveric models is defined as wet laboratories (11). Cadavers are most anatomically accurate but lack of pulsatile organs while animals offer similar anatomical structures with pulsation. They are of high fidelity but incredibly expensive and of limited availability (12).

Over the past few decades, the advances of minimally invasive surgeries, including robotic surgeries, contribute to the evolution of dry laboratories for learning new techniques and practicing advanced instruments. Dry laboratories apply synthetic materials for artificial simulators such as virtual reality simulators and box trainers (11). In dry laboratories, repetitive practice is readily available without the need of a proficient proctor; in addition, its incorporation into a surgical curriculum is easy. The special computerized system of robotic surgeries makes virtual reality simulators the choice of surgical simulators in robotic surgeries, including RATS. Accordingly, different virtual reality simulators have been produced, such as the dV-Trainer (Mimic Technologies, Inc, Seattle, Wash), the Robotic Surgical Simulator (RoSS; Simulated Surgical Systems, Buffalo, NY, USA), and the SEP Robot (SimSurgery, Oslo, Norway) (13).

Surgical simulation in RATS training and patient safety

Consensus has been reached that surgical simulation is one of the essential sections of training curriculum for RATS, together with a baseline evaluation, an e-learning module and a robotic theatre observation (14). However, whether simulation-based training finally converts to enhanced patient safety? Seder *et al.* retrospectively collected and analyzed 79 cases of RATS, including pulmonary, mediastinal, benign esophageal and diaphragmatic operations (15). These surgeries were performed by one surgeon and three residents, who participated in a triphasic pathway for the development of robotic skills. Phase 1, individual preclinical learning, consisted of online training modules and dry laboratories. Cadaveric and animate models and robot simulators were provided for proctored preclinical training in phase 2. Phase 3 involved live surgery observation, bedside assistance and proctored operating. Surgical simulation played a major role in this training pathway. Results showed no perioperative mortality, with a 20% complication rate and a 3% readmission rate. Among eight patients converted to VATS or open lobectomy, only two cases were to control bleeding. Major perioperative complications were fewer in the later half of the experience. All residents performed RATS as part of their surgical practice. The clinical data above demonstrated an overall favorable result of patient safety. White *et al.* reviewed the first 100 RATS cases in the University of Michigan (16). Residents and attending surgeons participated in the 100 cases of the program, including lung, esophageal, mediastinal, diaphragm surgeries and sympathectomies. General surgery residents received didactic and simulator training during the training program. For thoracic fellows (also regarded as "residents" in the description of results), they participated in a simulator curriculum for the EndoWrist 2, energy dissection, and needle driving simulator exercises after online training and videos. Following this simulator training, they were required to complete two hours of simulator training per month for multiple skills evaluation or four surgical cases per month for manipulating camera and robotic arms as maintenance exercises. Residents participated more as the primary surgeons in the late periods (59%) than in the early periods (33%), though there was a shift in the patients to greater complexity indicated by increasing age and a trend toward increasing BMI (body mass index), ASA (American Society of Anesthesiologists) and comorbidities. A subset analysis of 20 lobectomies revealed similar clinical results between 7 attending surgeons and 13 residents as primary surgeons: Conversion to VATS or open (38% *vs.* 43%), operative time (260 *vs.* 249 min), estimated blood loss (187 *vs.* 203 mL) and length of stay (4.8 *vs.* 4.7 days). This study illustrated that experienced residents with simulator-based training could carry out RATS and ensure patient safety meanwhile. Baste *et al.* conducted a retrospective study of 30 patients from a RATS program (17). Two thoracic surgeons were trained during the entire period. The practical training phase consisted of visits of expert centers and surgical simulation, using virtual simulator and animal models. Thirty procedures included 9 thymectomies, 11 lobectomies, 4 segmentectomies, 3 lymphadenectomies, 2 bronchogenic cysts and 1 posterior mediastinal mass resection. There was no conversion to thoracotomy. Operating duration was 135 min and the amount of blood loss was 50 mL. Two intraoperative complications occurred early in the course of practice (7%) including a bronchial injury and a wound of a ganglionic arteriole, both of which were eventually repaired. Length of stay was 4 days with 6 grade 1 postoperative complications according to the Clavien-Dindo classification. A median 4-month follow-up revealed that all patients were alive and enjoyed a good quality of life. Cerfolio *et al.* reported a large cohort of RATS including 520 consecutive robot-assisted lobectomies completed by 35 general surgical residents and 7 cardiothoracic surgical residents in a prospective training program (18). RATS lobectomy is divided into 19 serial steps or surgical maneuvers. For every step that residents were not able to complete, simulation training, coaching techniques and surgical videos were used to facilitate their improvement. The operative duration, conversion to thoracotomy and major vascular injury reduced over the period. This study demonstrated the feasibility and effectiveness of simulation-based training in improving residents' performance and patient safety.

Surgical simulation in preoperative planning of RATS

Surgical simulation not only strengthens surgical training, but also plays an important role in preoperative planning in clinical practice. It helps surgeons identify individual anatomical characteristics of each patient preoperatively and make a comprehensive and strategic plan from different aspects.

Although the positions of port sites in robotic surgeries are highly standardized according to the type of surgery, even experienced teams sometimes would have trouble finding optimal incision positioning because of the anatomical variability (19). Appropriate incision positioning for robotic arm installation provides a better surgical view and cause less conflict among instruments, partly contributing to the success of robotic surgeries. However, the precise determination of port placements could be achieved by surgical simulation based on 3D image reconstruction (20). Another aspect that surgical simulation facilitates in robotic surgical planning is a thorough understanding of complicated anatomical structures before operation. Segmentectomy has been increasingly used for small, early non-small cell lung cancer. Compared to lobectomy, better postoperative lung function is preserved in segmentectomy with non-inferior oncological outcomes (21,22). But the complexity of pulmonary vessels and bronchi makes segmentectomy a challenge where accidents such as unexpected bleeding might occur (23). Therefore, surgical simulation is increasingly adopted for preoperative planning in segmentectomy, primarily using 3D reconstruction models. Three-dimensional computed tomography angiography and bronchography (3D-CTAB), reconstructed from contrast-enhanced CT scans, is able to identify the vascular and bronchial variations, illustrate the segmental structures and locate the tumor (24). Furthermore, reconstruction data could be printed into a model by rapid prototyping, which is also helpful for surgical simulation of segmentectomy (25,26).

Surgical simulation in preoperative planning of RATS and patient safety

Some studies have shown the evidence of the benefits of preoperative simulation in VATS for patient safety (27,28). However, scarce publications were found discussing surgical simulation in preoperative planning of RATS and its role in improving patient safety. Kajiwara *et al.* reported a robot-assisted resection of a posterior mediastinal tumor, where they used 3D reconstruction to determine the optimal positioning of robotic arms and instruments preoperatively (29). The CT scan of the patient in the same position as operation was taken and processed by a high-speed 3D image analysis system. Based on the 3D image, which depicted the tumor and all surrounding structures, surgical simulation decided the best direction of robotic system, camera setting, and positioning of robotic arms. The whole operative time was 270 min and the robot set-up time was 21 min. The amount of blood loss was 167 mL and post-surgical drainage duration was 2 days. There were no complications only with slight pain. As a result, this patient had a generally safe outcome. In another study, Wen *et al.* reported a case series of four patients with thoracic masses including three mediastinal masses and one chest wall mass (20). All patients underwent RATS with incision selections by preoperative surgical simulation based on 3D image reconstruction. For each patient, various incision positions were designed and distances between incisions and from each incision to the mass were measured in the reconstruction model, ensuring that different instruments would work with considerable coordination and sufficient maneuvering room. The results showed an overall reduction of operation time (120 min on average) with a mean set-up time of 11 min. The average bleeding volume was

55 mL. The intraoperative data was relatively satisfying. Baste and colleagues undertook a pilot study of nine RATS segmentectomies using a 3D model for preoperative surgical simulation (7). All patients had contrast-enhanced CT scans and the raw imaging data were sent to a private company for 3D reconstruction. All 3D models met the expectations as anatomical accuracy, accurate delimitation of segments, margin resection, free space rotation, portability and time saving techniques. The anatomy of 3D models was highly coincident with that of surgical findings; 3D model rotation helps with the best positioning of patient and optimal port placements. The reconstruction model could also be used to measure the volume of each segment and lobe, which assists in the decision of best surgery between segmentectomy and lobectomy. The above advantages of surgical simulation in RATS provide potential improvement of patient safety.

Surgical simulation in intraoperative navigation of RATS

Besides preoperative planning, the 3D model could be applied for intraoperative navigation. The 3D image is integrated into the screen of the robot console during the surgery, allowing dynamic comparison of anatomy between the 3D model and surgical view.

Surgical simulation in intraoperative navigation of RATS and patient safety

In the previous study by Le Moal *et al.*'s group, the 3D models were also shown in the robot console for intraoperative navigation, which turned to be helpful (7). More recently, Baste's group reported a multimodal surgical navigation system for RATS segmentectomy (30). Based on 3D reconstruction, this multimodal system was used for preoperative simulation and intraoperative navigation. In addition, it was also used in complementary examinations such as endobronchial ultrasound and pleural dye marking. They gained the experience of more than 40 patients and found that the multimodal system provided a perfect anatomical accuracy, including precise localization of nodules and identification of anatomical variations. The study concluded that the multimodal system and a robotic platform could prevent intraoperative accidents and postoperative complications and thus contributes to the promotion of patient safety.

Conclusions

Surgical simulation was applied for its role not only in surgical training but also in preoperative planning and intraoperative navigation in RATS. The current evidence demonstrated that surgical simulation experienced a potential benefit in terms of rationalization of surgical design, accurate preoperative and intraoperative confirmation of anatomical structure, and improvement of clinical performance, all of which improved the surgical outcome and patient safety. However, the current researches are still scarce and have some limitations including the nature of retrospective studies, the small number of patients admitted in studies, and the lack of comparison groups. More multicenter prospective studies are required to further prove the benefits of surgical simulation in improving patient safety in RATS.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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