REVIEW

Technical skills simulation in transplant surgery: a systematic review

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Abstract

Purpose   Transplant surgery is a demanding field in which the technical skills of the surgeon correlates with patient outcomes. As such, there is potential for simulation-based training to play an important role in technical skill acquisition. This study provides a systematic assessment of the current literature regarding the use of simulation to improve surgeon technical skills in transplantation.

Methods   Data were collected by performing an electronic search of the PubMed and Scopus database for articles describing simulation in transplant surgery. The abstracts were screened using the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines. Three reviewers analyzed 172 abstracts and agreed upon articles that met the inclusion criteria for the systematic review.

Results   Simulators can be categorized into virtual reality simulators, cadaveric models, animal models (animate or inanimate) and synthetic physical models. No virtual reality simulators in transplant surgery are described in the literature. Three cadaveric models, seven animal models and eight synthetic physical models specific to transplant surgery are described. A total of 18 publications focusing on technical skills simulation in kidney, liver, lung, pancreas, and cardiac transplantation were found with the majority focusing on kidney transplantation.

Conclusions   This systematic review identifies currently reported simulation models in transplant surgery. This will serve as a reference for general surgery and transplant surgery professionals interested in using simulation to enhance their technical skills.

Keywords Simulation · Transplant surgery · Surgical education · Technical skills

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Introduction

Richard Satava described the first virtual abdominal simulator in 1993; since then, simulation-based training has steadily gained popularity in surgical education [1]. Simulation is defined as "a situation in which a particular set of conditions is artificially created to study or experience something that could exist in reality" [2]. In 1999, the US Army implemented simulation-based training as a core element for training combat medics; this led to a 10% decrease in pre-hospital deaths despite advancing weapons technology [3]. The increased use of simulation-based training allowed for faster skill acquisition, better retention, and standardization of skills among military personnel.

Patient outcomes in solid organ transplantation are impacted by surgical factors dependent on surgeon skill. In kidney transplantation, for example, prolonged warm ischemia time is typically the result of long vascular anastomotic time. Prolonged warm ischemic time has been

associated with longer hospitalizations, worse patient survival, and impaired long-term graft survival [4–6]. In bariatric surgery, Birkmeyer et al. reported that technical skills among practicing surgeons correlates with patient outcome [7]. Hence, simulation-based training to improve surgeon technical skills can have important implications in the improvement of care for surgical patients.

In the United States, transplant surgeons undergo rigorous training through dedicated residency programs in cardiothoracic surgery, general surgery, or urology prior to completing their abdominal or cardiothoracic transplant fellowships. The American Board of Surgery also mandates experience in solid organ transplantation for certification in surgery, but opportunities may be more limited in general surgery residencies [8]. Per the 2020–2021 national report by the Accreditation Council for Graduate Medical Education (ACGME), general surgery residents performed a limited number of abdominal transplant cases during their residency. Nationally the mean and standard deviation of cases logged was 1.5 ± 3 for liver transplants, 6.6 ± 8 for renal transplants, 2 ± 3 for donor nephrectomies and 1.7 ± 3 for donor hepatectomies [9]. Providing trainees with simulation opportunities allows them to practice surgical techniques in a low risk environment prior to performing in the high stress environment of the operating room [10].

Despite the technically demanding nature of transplant surgery, there is limited information in the literature regarding the use of simulation to improve transplant surgery specific technical skills, particularly for trainees. This systematic review aims to identify currently reported simulation models in transplant surgery that focus on technical skill acquisition. Training programs can use this review to select simulation models that meet their local needs and are within their budget, or to inform the development of new simulation models. This review will serve as a reference for general surgery and transplant surgery professionals interested in using simulation to enhance their technical skills.

Methods

Data were collected by scanning reference lists of articles manually and by performing an electronic search of the Pub-Med and Scopus database for articles describing simulation in transplant surgery. The databases were searched from their inception to April 28th, 2022. The Medical Subject Heading (MeSH) terms and keywords used to conduct this search are described in Table 1.

After removing the duplicates, abstracts of the 172 remaining full-text, English language articles were screened for relevance using the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines (Fig. 1). The website Rayyan was used to keep the systematic review organized [11].
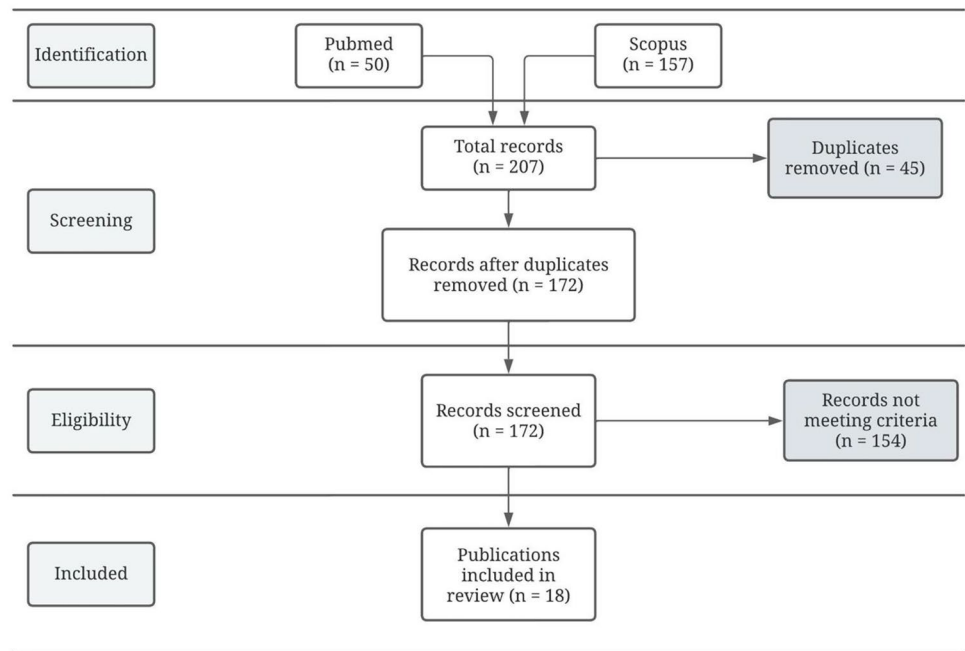
Our inclusion criteria were articles in English, those that focused on transplant surgery education, and studies involving improvement of technical skills. Only articles in the field of kidney, liver, pancreas, lung and cardiac transplantation were considered. Small bowel transplantation was intentionally excluded due to lack of any published simulation models. Articles focusing on simulation beyond technical skills were also excluded and out of the scope of this review. Three reviewers analyzed all 172 abstracts and individually determined their eligibility. In cases of conflict, all reviewers discussed the merits of the article for this review and voted on inclusion or exclusion, leading to a team consensus.

Simulators can be categorized into virtual reality simulators, cadaveric models, animal models (animate vs inanimate) and synthetic physical models [12, 13]. Furthermore, some models are whole task simulators, since they allow the entire procedure to be replicated, like performing an entire kidney transplant implantation or an entire nephrectomy [14]. Others are part-task simulators as they emphasize one aspect of the entire procedure, such as focusing on an anastomosis [14]. Cadaveric models utilize human derived tissues or the entire cadaver. Animal models can use animate subjects such as living animals or inanimate animal tissue. Synthetic physical models, also known as bench-top or task

Table 1 MeSH (Medical Subject Headings) and keywords used during the literature review

Concepts	Transplant	Education	Simulation
MeSH Keywords	Transplantation/education	Internship, residency and fellowship	Computer simulation
	Renal transplant	Surgical education	Simulation
	Kidney transplant	Surgical training	Surgical simulation
	Transplant	Resident	Virtual reality simulation
	Cardiac transplant	Fellow	Simulation-training
	Heart-transplant	General Surgery/education	
	Liver-transplant		
	Lung-transplant		
	Transplant surgery		

Fig. 1 PRISMA flow diagram

trainer models, represent a part of the body and are made from synthetic materials.

Results

Based on our inclusion criteria, 18 articles were selected for this systematic review. Tables were compiled summarizing the studies with columns reporting their publication date, type of simulator, and cost of the simulation session (if reported). As of now, no virtual reality-based transplant simulators exist.

Cadaveric models

We identified three published cadaveric models (Table 2). Cabello et al. described a method of training in renal transplant surgery with cadaveric models preserved using Thiel's embalming method (TEM) [15]. TEM preserves the real-life qualities of fresh frozen cadavers while also offering a way to store them for months at room temperature and at a moderate cost compared to other methods. Coloma et al. reported using this method to implement a curriculum to simulate kidney transplantation with 149 surgical residents [16]. They utilized 39 TEM preserved bodies from which 75 viable renal grafts were obtained. In each cadaver, bilateral kidneys were recovered en block with the aorta and vena cava, then separated and prepared on the back table as for transplantation. Anatomically suitable kidneys were then transplanted into the iliac fossa. Post-intervention surveys from participants noted that the tissue quality was very realistic, the simulation was very similar to clinical training and that the session improved their surgical technique.

Rice et al. reported on a 2 day workshop with 36 abdominal transplant surgery fellows which consisted of observing laparoscopic living donor nephrectomies with discussion of

Table 2 Cadaveric models in transplant surgery education

Organ	Author	Year	Description	Type of simulator	Cost	Benefits
Kidney	Cabello et al.	2015	Cadaveric kidney procurement followed by implantation. Validation of technique	Whole task	Cost of Thiel's Embalming Method—$1300	Maintains realistic tissue quality
Kidney	Coloma et al.	2020	Implementation of the Cabello et al. technique into a curriculum	Whole task	Not reported	Maintains realistic tissue quality. Curriculum provides mentored guidance
Kidney	Rice et al.	2020	A laparoscopic living donor nephrectomy workshop that includes a cadaver lab	Whole task	Not reported	Didactics, mentored cadaveric sessions, and realistic anatomy

the technique, a cadaver lab and didactic sessions [17]. The cadaver lab included 3.5 h of hands-on skills training. This simulation workshop resulted in an increased confidence in the trainees' operative skills, improved their ability to assess kidneys prior to donation, and enhanced their capacity to risk stratify donors. This workshop was noted to be valuable in improving trainee peri-operative and technical skills in the setting of a living donor nephrectomy on a healthy patient.

Animal models

This review identified seven articles regarding the use of animal models in transplant surgery education. The articles ranged from model validation to specific procedural skills training to implementation of entire curricula (Table 3). Gladden et al. described the use of an inanimate low-fidelity bovine carotid artery model to perform an end-to-end and end-to-side anastomosis with feedback from a transplant surgeon proctor after each attempt [18]. A total of 27 residents participated in this experience during their transplant rotation with all participants reporting "neutral" to "strongly agree" to the educational value, fidelity, and efficacy of this simulation.

Golriz et al. described their hands-on course, where a total of 61 participants (fellows and attending surgeons) performed multi-organ procurement and solid organ transplantation during a 2 day course, on an animate porcine model [19]. Participants were oriented with a theoretical introduction of the anatomy of the porcine model and then divided into groups. Each participant performed on average 1.8 multiorgan procurements (1.8 liver, 3.6 kidneys, and 1.8 pancreas), 2.3 kidney implantations, 1.5 liver implantations, and 0.7 pancreas implantations. Each participant performed on average 4.8 arterial anastomoses, 8.6 venous anastomoses, 1.9 urethral anastomosis, and 1.2 bile duct anastomosis. All participants reported improvement in their surgical skills. Golriz et al. also published a guide on how to perform porcine kidney transplants [20].

Tiong et al. demonstrated the construct validity of an animate porcine model that involved a robotic-assisted laparoscopic renal auto-transplantation [21]. The training procedure involved performing ipsilateral iliac vessel dissection, followed by robotic-assisted laparoscopic donor nephrectomy and finally an auto-transplantation involving an intracorporeal vascular anastomosis and evaluation of vascular patency. The perfusion of the graft was assessed using intraoperative indocyanine green imaging and monitoring urine output. The authors reported face and content validity with usefulness as a training tool for robotic-assisted intracorporeal vascular anastomosis.

Kassam et al. described a faculty-led lab experience for six residents returning to clinical rotations from a research sabbatical [22]. The curriculum included instructional videos, followed by transplant specific dry labs allowing the participants to practice arterial and venous anastomoses and finally a wet lab component, where residents performed renal auto-transplants in animate porcine models. This lab was well received by residents and faculty and increased confidence in residents.

Sanada et al. described the use of an inanimate ex vivo porcine model to train surgical residents on the key components of organ preparation for split liver transplantation—an extended right lobectomy and left lateral segmentectomy [23]. The authors describe porcine hepatic vascular and intra-hepatic biliary anatomy as analogous to human hepatic anatomy and provide additional detail regarding the appropriate plane of transection based upon external porcine landmarks. They found that cholangiography or the utilization of biliary contrast dye allowed for superior precision in dividing the left hepatic duct. Their model is proposed as a training opportunity for split liver transplantation. Further assessment of model performance was not reported.

Spooner et al. described a comprehensive curriculum on an animate porcine cardiac transplantation model. Four separate operating rooms were set up with nursing, anesthesia and perfusion support [24]. Two rooms were for cardiac procurement and two for implantation with full cardiopulmonary bypass perfusion setup. Their curriculum allowed residents to experience the full breadth of cardiac transplantation. The residents were expected to perform a midline sternotomy, expose the donor heart, and perform a cardiectomy. After this, the heart was transported across the hall to the implantation operating room, where the residents implanted the donor heart to the recipient pig on cardiopulmonary bypass.

Wilson et al. described a modification to the existing Ramphal Cardiac Surgery Simulator to accommodate cardiac transplantation training [25, 26]. The Ramphal cardiac surgery simulator uses an inanimate porcine heart that is prepared with an intraventricular balloon in each ventricle that simulates the beating heart in various pathologic states. This model has been used to teach various aspects of cardiac surgery since its invention in 2001. The modified model described by Wilson et al. involves a silicone pericardium with cuffs attached to the major blood vessels (aorta, pulmonary artery [PA], superior vena cava [SVC] and inferior vena cava [IVC]) procured from a porcine heart. This simulation included the following components of cardiac transplantation: (1) appropriate preparation of the donor organ before implantation, (2) anastomosis of the left atrium, (3) anastomosis of the IVC, (4) anastomosis of the SVC, (5) anastomosis of PA, (6) anastomosis of the aorta and (7) weaning from cardiopulmonary bypass. They validated its use by having an attending cardiac surgeon successfully perform the procedure.

Table 3 Animal models in transplant surgery education

Organ	Author	Year	Description	Type of simulator	Cost	Benefits
Kidney, liver	Gladden et al.	2018	Transplant surgeons guided residents through anastomoses using bovine carotid artery	Part task	Cost not reported	Mentored curriculum with realistic vascular tissue without the cost of an entire cadaver
Kidney, liver and pancreas	Golriz et al.	2013	Performed multi-organ procurement and solid organ transplantation	Whole task	Cost not reported	Mentored curriculum in a live porcine model
Kidney	Tiong et al.	2018	Robotic-assisted laparoscopic renal auto-transplantation for training of robotic. intracorporeal vascular anastomosis	Whole task	Cost—$6,557 per training session (included the cost of the pig and veterinary support, use of the training center, laparoscopic and robotic equipment)	One of the few RAKT models
Kidney	Kassam et al.	2019	Porcine renal auto-transplantation	Whole task	Total cost—$3,967.70 or $661.28 per resident	Structured curriculum with immediate feedback
Liver	Sanada et al.	2019	Simulation of split liver transplant in an ex-vivo porcine model	Part task	Cost not reported	Novel use of indo-carmine dye to identify biliary anatomy
Heart	Spooner et al.	2019	Utilized a porcine model to describe the viability of a cardiac surgical curriculum for trainees	Whole task	7100 CAD = $5572 USD—materials and personnel	Full spectrum experience with cardiac transplant
Heart	Wilson et al.	2020	Development of a donor heart model created from porcine tissue and silicone to use in cardiac transplant simulations	Whole task	Cost not reported	Novel modification of a well-established cardiac surgery simulator

CAD Canadian Dollars, *USD* US Dollars

Synthetic physical models

This review identified eight synthetic physical models to be used for transplantation (Table 4). Most of them focused on kidney transplantation, and one reported a lung transplant simulator. They ranged from expensive, 3D printed models to box models that can be built using items from local stores. Kusaka et al. reported on a system using pre-operative CT scans to print personalized donor grafts and recipient pelvic cavity replicas using a 3-D printer [27]. They described two cases in which surgeons used these models for pre-operative surgical simulation prior to operating on the patients. Peri et al. also developed a similar 3-D printed simulation platform with replicas of donor grafts and recipient pelvic cavities for kidney transplantation [28]. Two junior trainees practiced 30 anastomoses using this model.

Building on this, Uwechue et al. proposed a hybrid simulation model combining rigid 3-D printed organs with cadaveric vascular grafts for practicing vascular anastomoses [29]. Claflin et al. reported on 12 surgical residents who practiced on a similar 3D printed model which used Penrose drains for vessels [30]. Their model was cheaper ($178 per model, not including the setup costs) and reusable [30]. More recently, Saba et al. combined 3D printing and hydrogel casting technologies to develop a high fidelity simulation platform for robotic assisted kidney transplantation (RAKT) that could be perfused with artificial blood [31]. This model allows the surgeon to mimic dissection, cauterization, and suturing while operating within a da Vinci abdominal trainer. They reported on a transplant surgeon using this model to complete a robotic training curriculum involving four RAKT simulations over a 2-month timeframe. The curriculum included procurement of the donor kidney from an abdominal model followed by implantation into a recipient pelvic model.

Melkonian et al. used a small plastic box to mimic the iliac fossa with several Penrose drains to mimic the external iliac vessels, the renal vessels, and the ureter [32]. Responses from 18 surgical residents indicated a favorable opinion of the model in terms of its realism, and its usefulness in improving technical skills. At $20.20 with a cost of $7.20 per use, this was the lowest cost simulator found in this review. Chan et al. described combining a 3-month virtual teaching course with a synthetic physical, lung-transplant model to help maintain the technical skills of seven senior surgical residents and fellows during the COVID-19 pandemic lock-down [33]. The trainees practiced and performed anastomosis on camera using the bench-top models and received faculty feedback. They reported that at the conclusion of their lock-down, the warm-ischemia time for the trainees did not change when comparing pre- and post-lock down cases. These are depicted in Table 4. Most recently, Patnaik et al. developed a portable, low-cost, low-fidelity

kidney transplant model with an adjustable depth of anastomosis and a confined space replicating the iliac fossa [34]. The model cost $29 and could be built from materials found at local stores. Per the authors, since the model to build and has cheap, replaceable parts, trainees can perform high volume repetitions for end-to-side vascular anastomoses.

Discussion

Graduating general surgery residents are exposed to a limited and varying number of transplant surgery cases, based on their institutional infrastructure, which makes it challenging to acquire transplant specific technical skills [10]. With continued sub-specialization in surgery, the expanding breadth of surgical knowledge and increasing complexity of surgical techniques, there is a need to implement efficient ways for trainees to practice and improve their technical skills outside the operating room. Simulation models can fill this need by facilitating the acquisition of skills specific to transplant surgery outside of the operating room. The previous literature on simulation in transplant surgery did not focused on technical skills acquisition [35]. In this systematic review, we addressed this gap in the literature and reported 18 full text publications describing a variety of simulation options that exist for surgical trainees interested in honing their transplant specific technical skills.

Traditionally, surgical training outside the operating room utilized cadaveric models to supplement training gaps. However, cadavers are expensive to store, procure, maintain, and dispose. Furthermore, they require embalming techniques or other forms of biohazardous preservation [36]. While many surgeons and trainees agree that cadaveric simulation remains "the gold standard" for realistic procedural simulation, some have also questioned the ethical implications [37–39]. Similarly, animal models provide very realistic simulation experiences. However, drawbacks to animal models include the high cost for specialized housing and personnel to look after animals, their limited availability, as well as ethical concerns [16].

Synthetic physical models offer a more affordable and less morally ambiguous simulation option [40]. In this review, the cost of synthetic physical simulators ranged broadly from $20.20 to $3027. In general, they are less expensive than cadaveric and animal models. The manner of implementation of synthetic physical models in training is important. Alessi et al. suggest that junior learners be introduced to concepts via simple simulation activities and as competence increases, more advanced levels of simulation be introduced to mimic the target environment [41, 42]. Hence, synthetic physical models provide a more profound benefit to junior trainees by providing high volume repetition outside the high stress environment of the operating room.

Table 4 Synthetic physical models in transplant surgery education

Organ	Author	Year	Description	Type of simulator	Cost	Benefits
Kidney	Kusaka et al.	2015	3D printed model of kidney transplant surgery	Part Task	Cost not reported. Requires a sophisticated 3D printer, labor, and CT imaging per patient	Personalized donor graft and pelvic anatomy ideal for case-specific simulation
Kidney	Uwechue et al.	2018	3D printed model based on patient CT scans with deceased donor vessels incorporated into the model to provide a tool to simulate RAKT	Part Task	Cost to print—1000 Euros ($1,130). Does not include cost of labor, machinery, etc.	Hybrid model combining a 3D printed model with cadaveric vascular grafts
Kidney	Claflin et al.	2020	Low-cost, reusable 3D printed model to simulate vascular anastomoses in kidney transplantation	Part Task	Cost—Setup—$20; Material—$137; Support material—$21; Total—$178; Does not include cost of printer	Reusable 3D printed model
Kidney	Saba et al.	2020	Combined 3D printing and hydrogel casting technologies to develop a HFM for RAKT. Prints the kidney and pelvis	Part Task	$95 (for material) with 8 h for labor and undisclosed cost for fabricating the model	Personalized model with artificial blood flow simulation
Kidney	Melkonian et al.	2020	Low-cost bench top kidney transplant surgery simulator	Part Task	Cost—$20.20; $134.30 w/sutures + instruments	Portable, low-cost model
Kidney	Peri et al.	2021	3D printed simulator for kidney transplant	Part Task	Cost—Platform—2665 Euros ($3027); only Kidney model—220 Euros ($250); does not include cost of printer	Personalized donor graft and pelvic anatomy ideal for case-specific simulation
Lung	Chan et al.	2021	Bench-top lung transplant model with virtual teaching	Part Task	Cost not shared	Portable model incorporating remote teaching
Kidney	Patnaik et al.	2022	Low-cost bench top kidney transplant surgery simulator with adjustable depths	Part Task	Cost—$29; (Cost of suture + instruments not shared)	Portable, low-cost, adjustable depth of anastomosis and confined operating space

Simulation models have been incorporated into a variety of surgical specialties. For example, in bariatric surgery and vascular surgery, trainees can use virtual reality along with cadaveric, animal, and synthetic physical models [43–46]. Many of these models have validity evidence and come with a mature training curriculum. These curricula define key skills to develop, provide appropriately timed feedback and report proficiency-based benchmarks for trainees to track their progress [10, 47].

Despite its increasing use, limited funding and resources pose a significant barrier for widespread adoption and standardization of simulation-based training in transplant surgery. It is our opinion that regular repetitions on any of the models described above are adequate to improve surgical skill acquisition. The best model for a training institution depends on the funding and resources available, as well as the target surgical skillset. The best model for a trainee depends on their level of training. We recommend starting on synthetic trainers and working up to more complex simulation models such as animal and cadaveric models. The next step in using simulation to improve technical skills in transplant surgery among trainees is implementing these simulation models in outcomes based or competency-based curricula [10, 47]. Ideally, these curricula must provide coaching and feedback, whether it's in person or video-based, to allow trainees to incrementally improve their technique and avoid imbibing poor technique [48, 49].

Future simulation models should report validity evidence using Messick's validity framework along with curriculum implementation strategies that showcase improved skill acquisition and retention [50]. During these validation studies, authors should report the number of participants, time spent training on the model, cost of building and implementing the model, an associated curriculum, and provide detailed descriptions so their model can be replicated for use at other institutions. As noted in this review, most technical skills simulation models in transplant surgery are focused on kidney transplantation. There is a dearth of models for liver, lung, cardiac and pancreas transplant simulation, and none for small bowel transplantation. Hence, this could be a ripe area for research and development. Moreover, with increasing utilization of virtual teaching methods in surgical education, simulation models can play a key role in tele-education [33]. Finally, virtual reality simulators could also be the next frontier of technical skills simulation in transplant surgery [51–53].

Limitations

This review was not without limitations. While some publications showcased validity data, others just provided proofs of concept. More work needs to be done to develop structured curricula around these simulation models to maximize their use in surgical training. Furthermore, many of the isolated skills in transplant surgery, such as exposure and vessel anastomoses, are taught through other specialties such as vascular surgery; however, we did not include vascular surgery specific simulation models, since they were out of the scope of our inclusion criteria.

Conclusions

This systematic review identifies currently reported simulation models in transplant surgery that focus on technical skill acquisition. It will serve as a reference for general surgery and transplant surgery professionals interested in using simulation to enhance their technical skills.

Declarations

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