8-3-2022

The use of objective assessments in the evaluation of technical skills in cardiothoracic surgery: A systematic review

Nabil Hussein

Jef Van den Eynde

Connor Callahan

Alvise Guariento

Can Gollmann-Tepeköylü

See next page for additional authors

Authors

Nabil Hussein, Jef Van den Eynde, Connor Callahan, Alvise Guariento, Can Gollmann-Tepeköylü, Malak Elbatarny, and Mahmoud Loubani

Interactive CardioVascular and Thoracic Surgery 2022, 35(3), ivac194
https://doi.org/10.1093/icvts/ivac194 Advance Access publication 28 July 2022

META-ANALYSIS

Cite this article as: Hussein N, Van den Eynde J, Callahan C, Guariento A, Gollmann-Tepeköylü C, Elbatarny M *et al.* The use of objective assessments in the evaluation of technical skills in cardiothoracic surgery: a systematic review. Interact CardioVasc Thorac Surg 2022; doi:10.1093/icvts/ivac194.

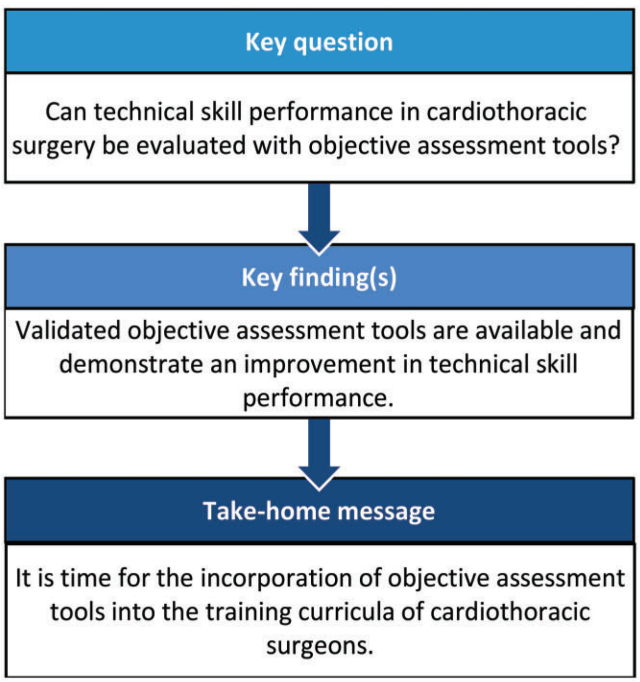
The use of objective assessments in the evaluation of technical skills in cardiothoracic surgery: a systematic review

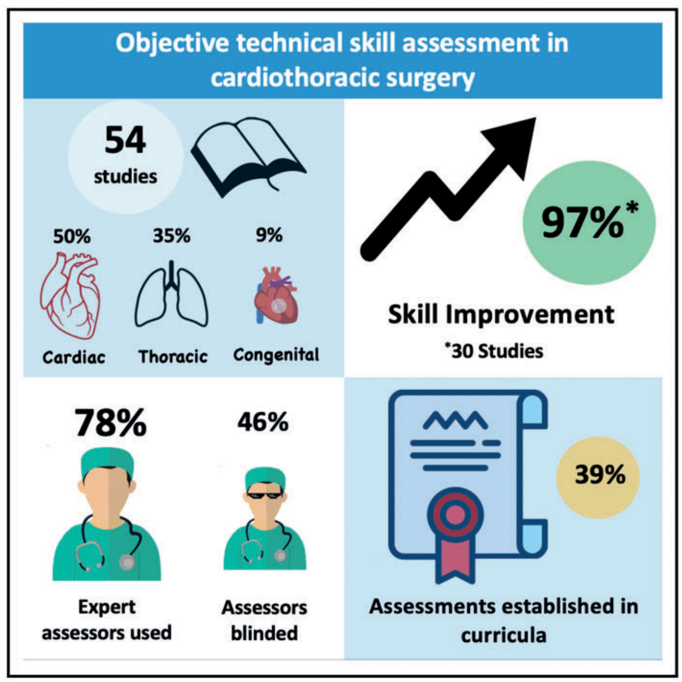
Nabil Hussein [a,b,*], Jef Van den Eynde [c], Connor Callahan [d], Alvise Guariento [e], Can Gollmann-Tepeköylü [f], Malak Elbatarny [g] and Mahmoud Loubani [a,b]

[a] Hull-York-Medical-School, University of York, York, UK
[b] Department of Cardiothoracic Surgery, Castle Hill Hospital, Cottingham, UK
[c] Department of Cardiovascular Sciences, KU Leuven, Leuven, Belgium
[d] Department of Surgery, Washington University School of Medicine, St. Louis, MO, USA
[e] Pediatric and Congenital Cardiac Surgery Unit, Department of Cardiac, Thoracic, Vascular Sciences and Public Health, University of Padua, Padua, Italy
[f] Department of Cardiac Surgery, Medical University of Innsbruck, Innsbruck, Austria
[g] Department of Cardiac Surgery, University of Toronto, Toronto, ON, Canada

* Corresponding author. Department of Cardiothoracic Surgery, Castle Hill Hospital, Castle Road, Cottingham HU165JQ, UK. Tel: +44-7825548925; e-mail: nh1033@york.ac.uk; nabil.hussein1@nhs.net; nabil.hussein18@gmail.com (N. Hussein).

Received 9 June 2022; accepted 21 July 2022





Abstract

OBJECTIVES: With reductions in training time and intraoperative exposure, there is a need for objective assessments to measure trainee progression. This systematic review focuses on the evaluation of trainee technical skill performance using objective assessments in cardiothoracic surgery and its incorporation into training curricula.

METHODS: Databases (EBSCOHOST, Scopus and Web of Science) and reference lists of relevant articles for studies that incorporated objective assessment of technical skills of trainees/residents in cardiothoracic surgery were included. Data extraction included task performed; assessment setting and tool used; number/level of assessors; study outcome and whether the assessments were incorporated into training curricula. The methodological rigour of the studies was scored using the Medical Education Research Study Quality Instrument (MERSQI).

RESULTS: Fifty-four studies were included for quantitative synthesis. Six were randomized-controlled trials. Cardiac surgery was the most common speciality utilizing objective assessment methods with coronary anastomosis the most frequently tested task. Likert-based assessment tools were most commonly used (61%). Eighty-five per cent of studies were simulation-based with the rest being intraoperative. Expert surgeons were primarily used for objective assessments (78%) with 46% using blinding. Thirty (56%) studies explored objective changes in technical performance with 97% demonstrating improvement. The other studies were primarily validating assessment tools. Thirty-nine per cent of studies had established these assessment tools into training curricula. The mean ± standard deviation MERSQI score for all studies was 13.6 ± 1.5 demonstrating high validity.

CONCLUSIONS: Despite validated technical skill assessment tools being available and demonstrating trainee improvement, their regular adoption into training curricula is lacking. There is a need to incorporate these assessments to increase the efficiency and transparency of training programmes for cardiothoracic surgeons.

Keywords: Objective assessment • Technical skills • Cardiothoracic surgery • Simulation • Resident training

ABBREVIATIONS

CTS	Cardiothoracic surgery
MERSQI	Medical Education Research Study Quality Instrument
OSATS	Objective Structured Assessment of Technical Skills

INTRODUCTION

Technical skill development in cardiothoracic surgery (CTS) training has been primarily via direct experience in the operation room. The growth of simulation-based training has provided an adjunct to training with programmes successfully incorporating these methods into their curricula [1–5]. However, with the reduction in training time and intraoperative exposure, there is a greater need for the incorporation of objective assessments to facilitate trainee progression [1, 6–10]. This systematic review focuses solely on the use of objective assessments in the evaluation of technical skill performance for surgical trainees/residents in CTS. Furthermore, it will explore whether such assessment methods have been successfully incorporated into training programmes.

METHODS

Ethics statement

Institutional Review Board review was not required for this review as patient data were not used and participant data was anonymous.

Eligibility criteria, databases and search strategy

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) reporting guideline [11]. Inclusion criteria included original research studies (i.e. randomized controlled trials, observation, cohort, case control and cross-sectional studies) published in English-peer reviewed journals and related to adult and paediatric CTS. Only studies that incorporated objective assessment of technical skills in CTS were included. The following definitions were used for clarity: (i) 'technical skill'—any hands-on action by a surgeon/trainee in the operating room or simulated operating environment (including benchtop, wet-lab or virtual reality simulation); (ii) 'assessment'—the reporting of a surgeon/trainees' technical proficiency/performance of the specified task; (iii) 'objective'—predefined, structured scoring criteria that is used to evaluate performance. Furthermore, only studies that included the technical skill assessment of trainee/resident surgeons were included (i.e. studies looking at only medical students or established/expert surgeons were excluded). Validation studies were also included if the above inclusion criteria were satisfied.

Exclusion criteria included unpublished abstracts, posters, opinions, case reports, reviews, letters to editors and editorials. Papers were also excluded if they reported on non-technical skills training or skills that are not directly CTS related. The latter comprised skills that are not routinely included in CTS training curricula, such as echocardiography, cardiac catheterization and endovascular skills.

The following sources were searched with the assistance of a medical librarian, for articles that met our inclusion criteria and were published by October 2021: EBSCOHOST (MEDLINE, Academic Search Premier, CINAHL complete), Scopus, Web of Science Core Collection and reference lists of relevant articles. Terms used for the search included the (i) type of surgery (i.e. cardiothoracic, cardio*, cardiac, thoracic, congenital, heart, surgery), (ii) method of assessment (i.e. objective, competence*, technical, skill*, perform*, assess*, tool) and (iii) subject/participant (i.e. trainee, resident, registrar, fellow). The detailed search strategies are provided in Supplementary Material, Appendix SE1.

The following steps were taken for study selection: (i) identification of titles through database search, (ii) removal of duplicates, (iii) screening of abstracts, (iv) assessment of full-text articles for eligibility and (v) final inclusion into the study. Studies were selected by 2 independent reviewers (N.H. and J.V.D.E.) according to the inclusion/exclusion criteria. When there was any conflict a third reviewer (C.C.) made the decision to include or exclude the study.

Data collection

Data extraction was completed independently by 2 authors (N.H. and C.C.). Inconsistencies were resolved by consensus. Information was collected on the following 15 items: (i) study demographics, (ii) study type, (iii) CTS subspeciality, (iv) participant level (i.e. resident, consultant/attendee, medical student), (v) number of participants, (vi) task performed/assessed, (vi) type of

Table 1: Data extraction table of all studies included in the systematic review

Author	Year	Study Type (cohort number)	Speciality	Participant (*n*)	Task performed	Format of assessment	Time assessment	Setting of assessment	Level of assessor (*n*)	Video used	Assessor blinded	Retrospective/ prospective assessment	Outcome	Established in curriculum	Total MERSQI score
Bedetti [29]	2018	NR (2)	Thoracic	Trainee, surgeon (20)	Lobectomy	Likert	Y	Simulation VR	Simulator assessed	N	NA	P	Improvement	NS	11
Blum [30]	2004	R (3)	Thoracic	Trainee (13)	Bronchoscopy	Time + cues	Y	Intraoperative, simulation	Expert (1)	N	N	P	Improvement	Y	13.5
Bohnen [31]	2018	NR (2)	Thoracic	Trainee, surgeon (14)	Emergency thoracotomy	Likert	Y	Simulation-synthetic	Expert (2)	Y	Y	R	Validation only	N	13.5
Brandao [32]	2021	NR (1)	Cardiac	Trainee (16)	CABG, AVR, MVR	Likert	Y	Simulation-animal	NS	N	NS	P	Other trainees better prepared	NS	10.5
Duffy [33]	2019	NR (1)	Cardiac	Trainee, student, surgeon (14)	SVG harvesting	Likert	N	Simulation-synthetic	Expert + low experience (2)	Y	Y	R	Validation only	N	14.5
Fann [34]	2010	NR (1)	Cardiac	Trainee (33)	Coronary-anastomosis	Likert	N	Simulation-animal + synthetic	Expert (3)	Y	Y	R	Improvement	Y	13
Fouilloux [35]	2015	R (2)	Cardiac	Trainee (9)	CPB-management	Likert	N	Simulation-animal	Expert (2)	Y	Y	R	Improvement	NS	15.5
Ghazy [36]	2019	NR (2)	Thoracic	Trainee (10)	Flexible bronchoscopy	Time	Y	Simulation-synthetic	NA	N	N	P	Improvement	NS	13.5
Greenhouse [37]	2013	NR (3)	Cardiac	Trainee, surgeon (19)	MVR	Likert	Y	Simulation-synthetic	Expert (2)	Y	Y	R	Validation only	Y	13.5
Hance [6]	2005	NR (3)	Cardiac	Trainee, surgeon (40)	Coronary-anastomosis	Likert	N	Simulation-animal + synthetic	Expert (4)	Y	Y	R	Validation only	Y	15.5
Hermsen [26]	2020	NR (2)	Cardiac	Trainee, surgeon (6)	CPB	Checklist	Y	Simulation-animal	Expert (1)	N	N	P	Validation only	NS	13.5
Hicks [27]	2011	NR (1)	Cardiac	Trainee (32)	CPB	Hybrid	N	Simulation-animal	Expert (1)	N	N	P	No-comparison	Y	12
Hussein [38]	2020	NR (2)	Congenital	Trainee, surgeon (10)	Arterial switch operation	Hybrid	N	Simulation-synthetic	Expert + low experience(9)	Y	Y	R	Validation only	Y	14.5
Hussein [39]	2020	NR (1)	Congenital	Trainee, surgeon (30)	Arterial switch operation	Hybrid	Y	Simulation-synthetic	Expert (1)	Y	Y	R	Improvement	Y	14
Hussein [22]	2021	NR (2)	Congenital	Trainee, surgeon (30)	Norwood operation	Hybrid	Y	Simulation-synthetic	Expert + Low experience(10)	Y	Y	R	Improvement	Y	15.5
Hussein [4]	2020	NR (1)	Congenital	Trainee (7)	Congenital-operations	Hybrid	Y	Simulation-synthetic	Expert (1)	Y	Y	R	Improvement	Y	13
Iwasaki [40]	2008	NR (2)	Thoracic	Trainee, surgeon (8)	VATS-Lobectomy	Likert	Y	Simulation-synthetic	NS	Y	NS	R	Validation only	Y	12.5
Jebran [41]	2019	NR (2)	Cardiac	Trainee, student (20)	MI-MV surgery	Likert	Y	Simulation-synthetic	Expert (1)	N	N	P	Improvement	N	13.5
Jensen [42]	2017	NR (3)	Thoracic	Trainee, student, surgeon (53)	VATS-Lobectomy	VR-simulator score	Y	Simulation-VR	Simulator-assessed	Y	NA	P	Improvement	NS	15.5
Jensen [18]	2019	NR (3)	Thoracic	Trainee, student, surgeon (53)	VATS-Lobectomy	Likert	N	Simulation-VR	Expert (3)	Y	Y	R	Validation-only	NS	15.5
Joyce [43]	2011	NR (1)	Cardiac	Trainee (11)	MV-repair	Likert	Y	Simulation-animal + synthetic	Expert (1)	Y	Y	R	Improvement	NS	13
Joyce [44]	2018	NR (1)	Cardiac	Trainee (12)	CPB	Likert	Y	Simulation-synthetic	Expert (4)	Y	N	P	Validation-only	Y	12.5
Karim [45]	2017	NR (1)	Cardiothoracic	Trainee (33)	Cardiothoracic-cases	Qualitative-feedback	N	Intra-operative	Expert (48)	N	N	P	Validation-only	NS	10
Kenny [46]	2018	NR (1)	Cardiothoracic	Trainee (20)	CPB, Wedge resection	Likert	N	Simulation-animal	Expert (1)	N	N	P	Improvement	Y	13
Konge [19]	2012	NR (3)	Thoracic	Trainee, Surgeon (14)	Wedge-resection	Likert	N	Intra-operative	Expert (2)	Y	Y	P	Validation-only	NS	15
Korte [47]	2020	NR (3)	Cardiac	Trainee, student (19)	Coronary-anastomosis	Likert	Y	Simulation-animal+synthetic	Expert (NS)	Y	NS	P	Improvement	Y	13.5
Lee [48]	2013	NR (4)	Cardiac	Trainee, student, surgeon (5)	Coronary-anastomosis	Likert	N	Simulation-animal+synthetic	Expert (10)	Y	Y	R	Validation only	Y	14.5
Li [49]	2020	NR (2)	Cardiac	Trainee (12)		Likert	N	Simulation-animal	Expert (2)	Y	Y	R	Improvement	NS	13.5

Continued

Table 1: Continued

Author	Year	Study Type (cohort number)	Speciality	Participant (*n*)	Task performed	Format of assessment	Time assessment	Setting of assessment	Level of assessor (*n*)	Video used	Assessor blinded	Retrospective/ prospective assessment	Outcome	Established in curriculum	Total MERSQI score
					Coronary-anastomosis										
Liu [50]	2019	NR (1)	Cardiac	Trainee (5)	CPB	Checklist	Y	Simulation-synthetic	Expert (1)	N	N	P	Validation only	NS	11.5
Llado-Grove [51]	2015	NR (1)	Cardiac	Trainee (83)	Coronary-anastomosis	Likert	Y	Simulation-synthetic	NS (2)	N	N	P	Improvement	Y	14
Lou [16]	2014	NR (2)	Cardiac	Trainee, student (4)	Coronary-anastomosis	Likert	N	Simulation-synthetic	Low experience(9)	Y	Y	R	Validation only	NS	12.5
Macfie [20]	2014	NR (1)	Thoracic	Trainee (64)	Hilar-dissection	Likert	N	Simulation-animal	Expert (NS)	N	N	P	Improvement	Y	13
Malas [52]	2018	R (2)	Cardiac	Trainee (32)	Coronary-anastomosis	Likert	Y	Simulation-synthetic	Expert (2)	Y	Y	P	Improvement	NS	15.5
Maluf [53]	2015	NR (1)	Cardiac	Trainee (10)	Coronary-anastomosis	Likert	N	Simulation-animal + synthetic	Expert (NS)	Y	N	P	Improvement	Y	10
Maricic [54]	2016	NR (3)	Thoracic	Trainee, surgeon (39)	VATS-oesophageal atresia	Checklist	Y	Simulation-synthetic	NS	N	N	P	Validation only	Y	14.5
Marshall [55]	2012	NR (1)	Thoracic	Trainee (13)	Chest wall-resection	Hybrid	Y	Simulation-animal	Expert (1)	N	N	P	Improvement	Y	13
Miura [56]	2021	NR (1)	Thoracic	Trainee (3)	Lobectomy	Hybrid	N	Intra-operative	Expert (NS)	N	N	P	Validation only	NS	12
Nam [57]	2021	NR (1)	Congenital	Trainee (6)	ToF-repair	Time+ subjective-score	Y	Simulation-synthetic	Expert (1)	Y	NS	R	Improvement	NS	12
Nesbitt [17]	2013	NR (2)	Cardiac	Trainee, students (21)	Coronary-anastomosis	Likert	Y	Simulation-animal	Expert (3)	Y	Y	R	Improvement	NS	14.5
Ortiz [58]	2021	NR (1)	Cardiothoracic	Trainee (16)	CTS-trauma	Likert	Y	Simulation-animal	Expert (NS)	Y	Y	R	Improvement	NS	15.5
Petersen [59]	2018	NR (3)	Thoracic	Trainee, surgeon (18)	VATS-Lobectomy	Likert	N	Intraoperative	Expert (2)	Y	Y	R	Validation only	NS	16
Price [60]	2011	R (2)	Cardiac	Trainee (39)	Coronary-anastomosis	Likert	Y	Simulation-animal+synthetic	Expert (2)	Y	Y	R	Improvement	NS	15.5
Sardari-Nia [61]	2020	NR (3)	Cardiac	Trainee, surgeon (102)	MI-MV surgery	Suture-accuracy	Y	Simulation-synthetic	NS	Y	NS	R	Improvement	Y	13
Spratt [62]	2019	R (2)	Cardiac	Trainee (29)	Coronary-anastomosis	Likert	N	Simulation-synthetic	Expert (1)	Y	Y	R	No change	NS	13.5
Tanaka [63]	2021	NR (3)	Thoracic	Trainee, surgeon (29)	VATS-Lobectomy	Time	Y	Simulation-synthetic	NS	N	N	P	Validation only	NS	13.5
Tavlasoglu [64]	2013	NR (2)	Cardiac	Trainee (10)	MV-repair	Test of repair	N	Simulation-animal	Expert (3)	Y	Y	R	Improvement	NS	12
Tong [65]	2012	NR (3)	Thoracic	Trainee (13)	VATS-Lobectomy	Checklist	Y	Simulation-animal	Expert (NS)	Y	N	P	Validation only	NS	12.5
Turner [66]	2019	NR (1)	Thoracic	Trainee (5)	Mediastinal-staging	Likert	N	Intra-operative	Expert (NS)	Y	N	P	Validation only	Y	13.5
Turner [67]	2020	NR (1)	Thoracic	Trainee (7)	Lung-resection	Likert	N	Intra-operative	Expert (NS)	N	N	P	Improvement	NS	16
Valdis [68]	2016	R (4)	Cardiac	Trainee (40)	Robotic ITA+MV-repair	VR-simulator score	Y	Simulation-animal+synthetic	Expert (2)	Y	Y	R	Improvement	NS	15.5
Voduc [69]	2016	NR (2)	Thoracic	Trainees (19)	Flexible-Bronchoscopy	Likert	N	Intra-operative	Expert (NS)	N	N	P	Validation only	NS	14
Whittaker [70]	2019	NR (3)	Thoracic	Trainee, student, surgeon (30)	Robotic-lobectomy	VR-simulator score	Y	Simulation-VR	Simulator-assessed	N	NA	P	Validation only	NS	14.5
Wu [71]	2020	NR (1)	Cardiac	Trainee (26)	Coronary-anastomosis	Likert	Y	Simulation-animal	Expert (3)	Y	Y	R	Improvement	NS	13.5
Yasuda [72]	2021	NR (2)	Cardiac	Trainee, student (10)	Coronary-anastomosis	Likert	Y	Simulation-synthetic	Low experience (1)	N	N	P	Improvement	NS	13.5

AVR: aortic valve replacement; CABG: coronary artery bypass grafts; CPB: cardiopulmonary bypass; CTS: cardiothoracic surgery; ITA: internal thoracic artery; MI: minimally invasive; MVR: mitral valve replacement; NA: not applicable; NR: non-randomized; NS: not specified; R: randomized; SVG: saphenous vein graft; ToF: tetralogy of Fallot; VATS: video-assisted thorocoscopic surgery; VR: virtual reality.

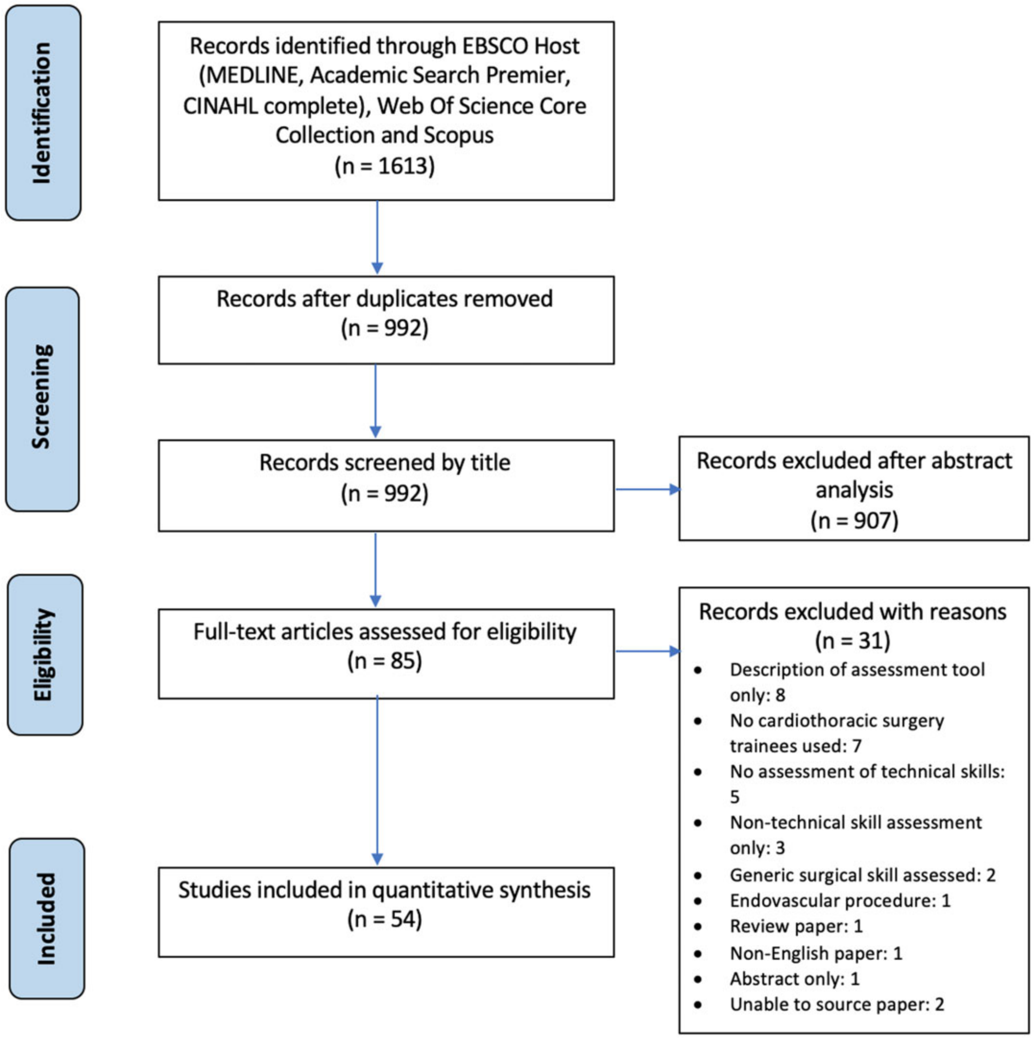


Figure 1: PRISMA flow diagram of studies include in data search. PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analyses.

assessment tool (i.e. Likert scale, checklist, hybrid), (vii) time assessment, (viii) setting of assessment [i.e. intraoperative, simulation (animal, synthetic, hybrid, cadaveric)], (ix) number of assessor(s), (x) level of assessor(s), (xi) use of video assessment, (xii) blinding of assessor (i.e. participant identification or attempt number removed), (xiii) retrospective versus prospective assessment, (xiv) outcome of study (i.e. improvement in performance, validation only) and (xv) if the assessment method was established into the training curriculum (Table 1).

MERSQI assessment

The methodological rigour of the included studies was scored using the Medical Education Research Study Quality Instrument (MERSQI). This is a validated assessment tool for quantitative appraisal of medical education across 8 domains including (i) study design, (ii) institution samples, (iii) response rate (i.e. percentage of participants who were objective assessed), (iv) type of data, (v) validity of evidence for evaluation of instrument scores, (vi) sophistication of data analysis, (vii) appropriateness of data analysis and (viii) assessment outcome [12, 13]. Descriptive statistics were used.

RESULTS

Study selection and characteristics

The literature search identified 1613 potentially relevant papers (Fig. 1). Following the removal of duplicates, records were screened by title and abstract leaving 85 full-text articles to be assessed for eligibility. A further 31 papers were excluded following full-text review leaving a total of 54 to be included in the quantitative synthesis. Reasons for exclusion are given in Fig. 1. Six of the studies (11%) were randomized controlled trials. A single cohort was used in 37% of studies (20/54), with 2 cohorts being the next most common at 33% (18/54). Three and 4 cohort studies comprised 24% (13/54) and 6% of the sample, respectively (3/54; Fig. 2). Cardiac surgery was the most common subspeciality utilizing objective assessment methods at 50% (27/54), followed by thoracic surgery (35%, 19/54), congenital surgery (9%, 5/54) and CTS in general (6%, 3/54). There were no studies in cardiothoracic transplantation (Fig. 3A).

Participant characteristics

Fifty-six per cent (30/54) of studies included only trainees/residents, while 28% (15/54) assessed trainees/residents + expert surgeons,

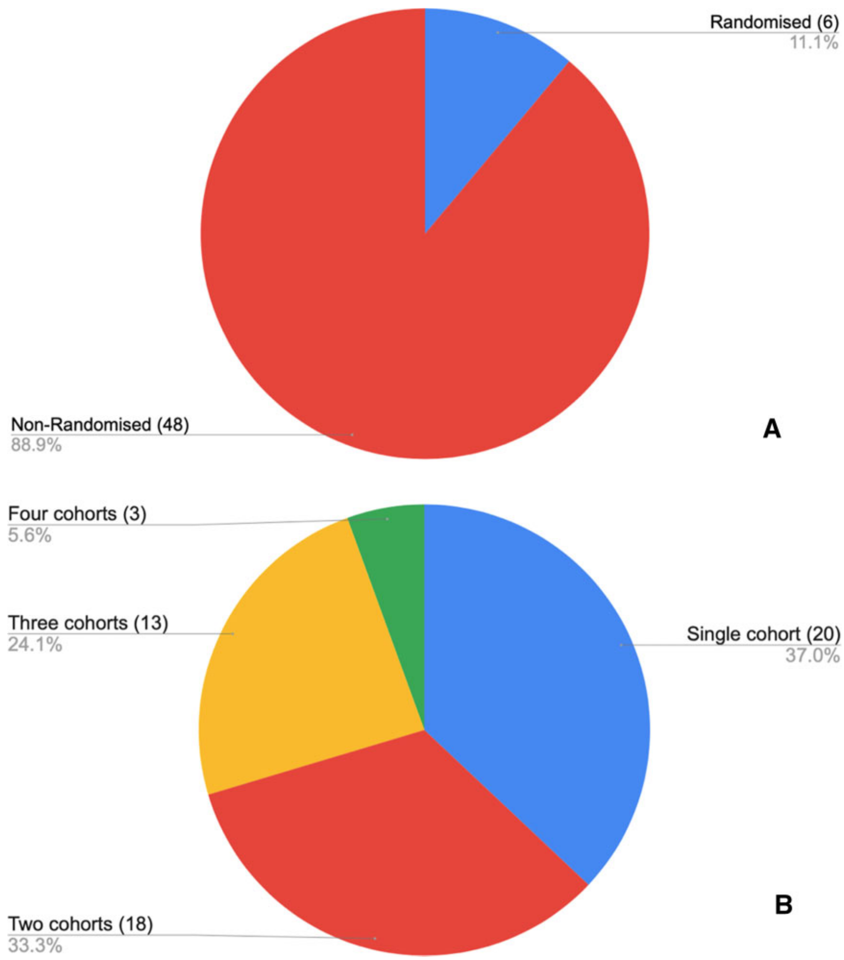


Figure 2: Chart demonstrating the number of studies which were randomized versus non-randomized (**A**) and number of cohorts that were included in the studies (**B**).

7% (4/54) used trainees/residents + medical students and 11% (6/54) used trainees/residents + medical students + experts. The average number of participants across all studies was 23 ranging from 1 to 5 participants (5/54) to >51 participants (5/54; Fig. 3B).

Assessment characteristics

The most common task assessed was coronary anastomosis at 28% (15/54), followed by pulmonary lobectomy (19%, 10/54), cardiopulmonary bypass and mitral valve surgery (both 11% [6/54]). Table 2 demonstrates the full list of tasks included in all studies.

The objective assessment of technical skills was present in all studies. The Likert scale [i.e. Objective Structured Assessment of Technical Skills (OSATS tool)] was the most commonly used assessment tool at 61% (33/54), while a checklist-based assessment was used in only 7% (4/54) of studies. A hybrid assessment combining both the Likert and checklist assessment methods was used in 13% (7/54) of studies. Other objective assessments included: time only (7%, 4/54), automated virtual reality simulator score (6%, 3/54), suture accuracy, test of repair and qualitative feedback (2% each, 1/54). Time assessments were used in 60% of all studies (Fig. 4A).

Eighty-five per cent (46/54) of assessments were made in the setting of simulation with only 15% being intraoperative assessments (8/54). Synthetic simulators were the most common at 39% (21/54) of all assessments, followed by animal (26%, 14/54) and hybrid simulation comprising both synthetic and animal simulators (13%, 7/54). Virtual reality simulator assessments were present in 7% (4/54) of studies (Fig. 4B).

Twenty-six per cent (14/54) of studies did not specify the number of assessors/evaluators used for the objective assessments. Of the remaining studies (40), 35%(14) used a single evaluator, with 28% (11) using 2 evaluators. Three (5) and >4 (7) evaluators were used in 13% and 18% of studies, respectively. In 3 studies, the simulator was able to perform an automated assessment. Expert surgeons were primarily used to perform the objective assessments with 69% (37/54) of studies using only expert assessors. Nine per cent (5/54) of studies used an expert surgeon + other less-experienced evaluators. Studies using only less-experienced evaluators were present in 4% (2/54) of studies. Seven studies either did not specify the level of evaluator or this was not applicable (i.e. time only assessment). Assessors were blinded in 46% (25/54) of studies (Fig. 5) and video recordings were used in 63% (34/54). The number of assessments performed either prospectively (i.e. at the time of task) or retrospective (i.e. following task) were almost equal (52% vs 48%).

Outcomes

Thirty (56%) studies explored objective changes in technical performance (i.e. minimum of 2 sessions/attempts) with 29 (97%)

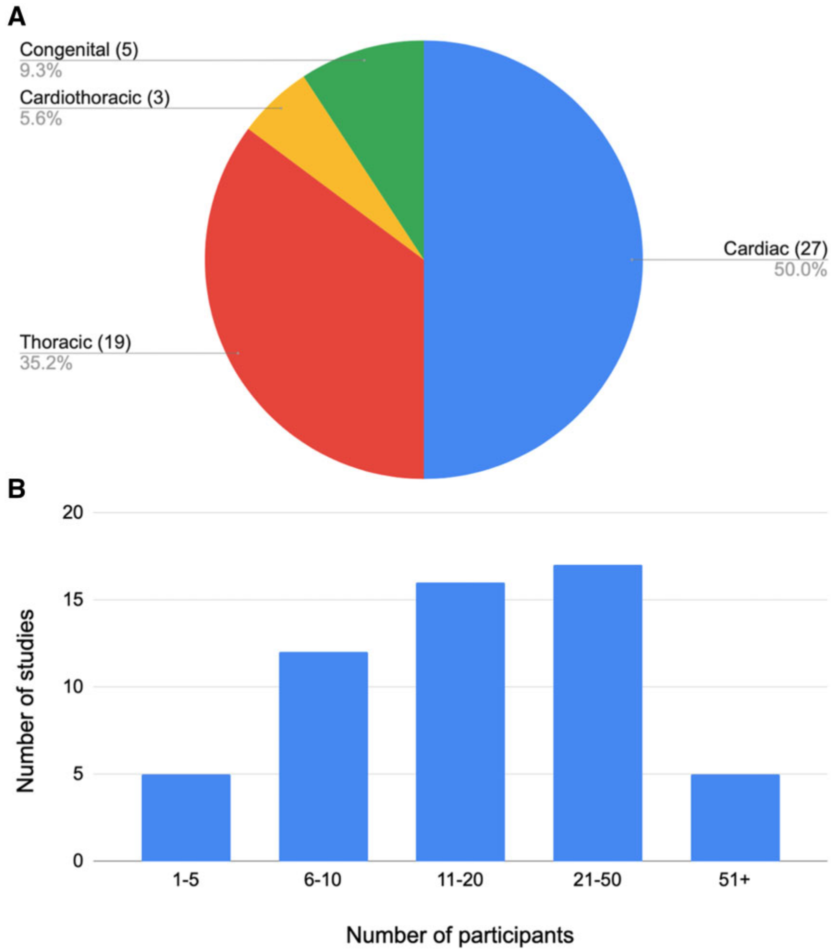


Figure 3: Studies broken down by subspeciality in cardiothoracic surgery (**A**). Number of participants included in studies (**B**).

Table 2: List of technical skill tasks performed during studies that were objectively assessed

Task performed	Number of studies, *n* (%)
Cardiac surgery	
Coronary anastomosis	15 (28)
Cardiopulmonary bypass	6 (11)
Mitral valve surgery	6 (11)
Conduit harvesting	2 (4)
Aortic valve surgery	1 (2)
Thoracic surgery	
Pulmonary lobectomy	10 (19)
Bronchoscopy	3 (6)
Wedge resection	2 (4)
Hilar dissection	1 (2)
VATS oesophageal surgery	1 (2)
Invasive mediastinal staging	1 (2)
Cardiothoracic surgery	
Emergency scenarios	3 (6)
Congenital cardiac surgery	
Arterial switch operation	2 (4)
Norwood operation	1 (2)
Tetralogy of Fallot repair	1 (2)
Multiple congenital procedures	1 (2)

demonstrating improvement. A large proportion of studies (39%, 21/54) were designed to validate the simulator or assessment tool (i.e. demonstrate construct validity) and were not focused on demonstrating objective improvement in performance (Fig. 6A). Thirty-nine per cent (21/54) of studies had established these objective assessment methods in the training curriculum of their respective training programmes (Fig. 6B).

METHODOLOGICAL QUALITY

The mean ± standard deviation MERSQI score for all studies was 13.6 ± 1.5 (maximum score: 18). Fifty-two per cent (28/54) of studies were performed by a single institution with the rest involving ≥2 institutions. Most studies had a very high response rate with 96% (52/54) reporting a >75% response. Over 68% (37/54) of assessment tools demonstrated either a moderate (48%, 26/54) or high validity (20%, 11/54) due to the inclusion of content/construct validity and internal structure in their development and evaluation. Ninety-one per cent (49/54) of studies used more than descriptive statistics, which was deemed appropriate on review. The majority of studies (87%, 47/54) assessed knowledge/skills with 13% (7/54) being performed on real-life patients. No study used patient outcomes as a measure of technical skill performance.

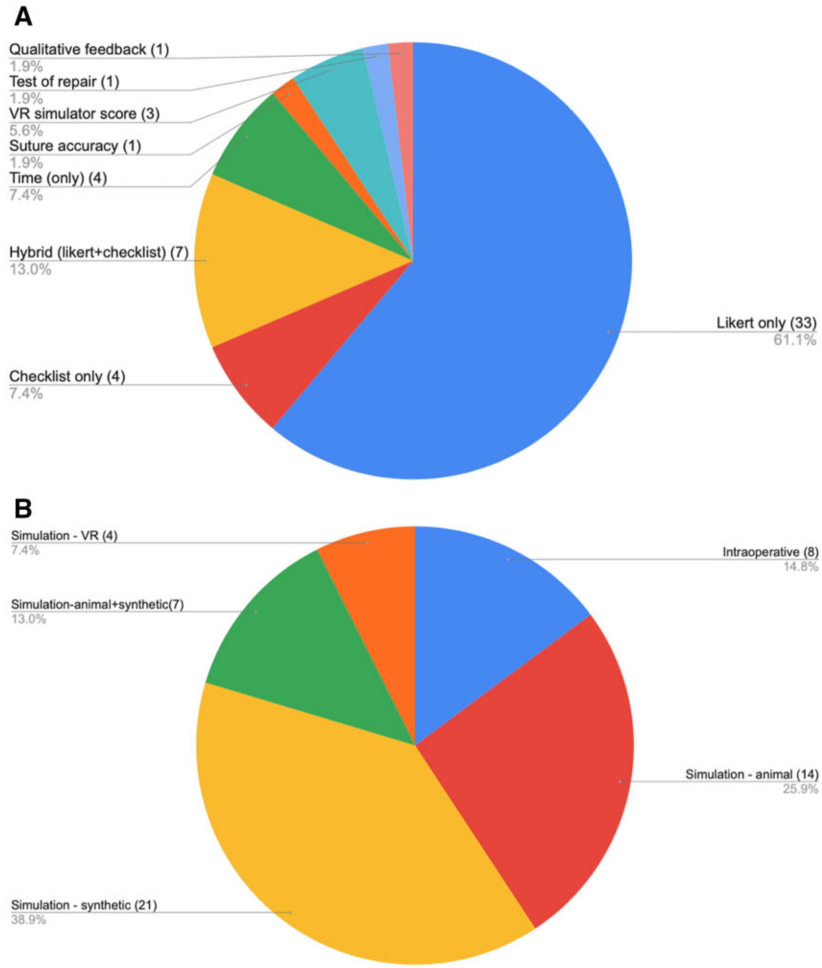


Figure 4: Chart demonstrating the types of objective assessment methods used to assess technical skill performance (**A**) and the setting of the assessment (**B**).

DISCUSSION

Within this review, 85% of assessments were made in the setting of simulation with 15% being in the intraoperative environment. Although simulation assessments are more readily available and can be performed outside of the operating environment, intraoperative assessments provide trainee surgeons with real-life experience and the associated pressures. In the ideal training curriculum, a trainee surgeon would initially train on simulators to refine their technical skills, fluency and operative sequencing. Once proficient they would transfer these learnt skills into the intraoperative environment, where further objective assessment is performed to focus on learning and progression.

The 2 most commonly assessed tasks were in coronary anastomosis (28%) and pulmonary lobectomy (19%), which are the fundamental index procedures. Surprisingly, there was only one study which included objective assessment in aortic valve surgery and none in cardiothoracic transplantation. Although validated aortic valve simulators exist, the lack of studies using objective assessments may be related to no assessment tool being available and/or validated, which may be a focus for future work [3, 5].

Improvement in objective assessment scores

One crucial aspect to simulation training is the demonstration of improvement and surgical skill progression. Not only does this allow simulators to be validated but it can also be used to identify when a trainee has gained competence in a particular skill and can progress to the next step in their training. Furthermore, the regular objective assessment will allow surgeons to focus their ongoing training needs which will potentially streamline the efficiency of technical skill acquisition. Fifty-six per cent of studies explored objective changes in technical performance with 97% of these (all except one) demonstrating improvement. The primary goal of the remaining studies was to validate the assessment tool rather than demonstrate the effects of objective assessment.

MERSQI score

The mean MERSQI score across all 54 studies was 13.6. Using a score of 14 as a cut-off for high-quality research 39% (21/54) of studies fell into this category [14]. Although the majority of studies were non-randomized, nearly half of the studies involved more than one institution with a high sampling rate (>75%). The majority of studies demonstrated both moderate or high validity

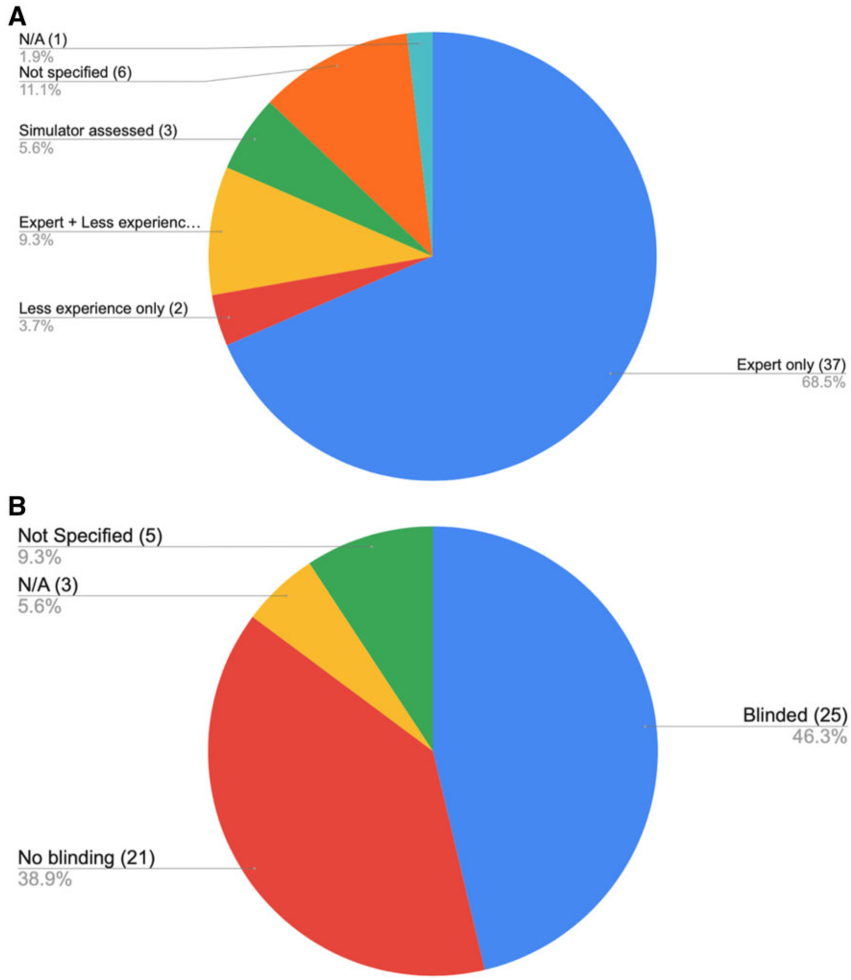


Figure 5: Chart demonstrating the level of assessors used in the studies (**A**) and whether assessors were blinded or not (**B**).

and reliability. Validity refers to whether a test measures what it intends to test, whereas reliability refers to the precision of the assessment (i.e. if the assessment was repeated would it produce the same result). Most studies included a combination of the following methods: (i) face ± content validity (i.e. assessment tool contents were reviewed by experts to deem if they assessed what they intended to ± appropriateness), (ii) internal structure (i.e. assessment of inter-rater reliability, or test–retest) and (iii) construct validity (i.e. demonstrating a difference in performance between expert and trainee/junior surgeons). Although no study demonstrated the actual effect on real patients, all studies assessed technical skill with 13% assessing performance on real patients. This is further evidence that the use of objective assessment methods in technical assessment evaluation renders itself to high-quality educational research, encouraging such methods to be incorporated into training programmes if feasible.

Ideal assessment tool for objective assessment in cardiothoracic surgery

The evaluation of technical skill is crucial for CTS; however, the ability to generate objective assessment from unbiased experts and create reproducible results remains challenging. Various methods have been described to address this. The Likert scale utilizing an OSATS format was the most commonly used assessment tool with checklist methods appearing infrequently. This is likely related to the Likert scale being a thoroughly validated tool and its general format makes it easier to be tailored to multiple surgical procedures [6, 16–20]. The disadvantage of this method is the limitation on feedback it may provide the trainee surgeon as it does not focus on the specific aspects of the technical skill the surgeon failed on.

The evaluator is an important factor to consider in establishing objective assessment. Within this review, the majority of studies (63%) used ≤2 evaluators and experts were primarily used (69%). Although the use of expert assessors is the most robust method of assessment their reliance adds an additional limitation to its regular use. Ideally, objective assessments should be validated to be performed automatically or by less-experienced personnel to increase use. A number of studies have demonstrated that objective improvement can occur without supervisor/expert supervision within CTS [16, 21, 22]. Crowd-sourced evaluations using lay persons may be a potential solution with studies demonstrating that as well as being cost-effective and efficient, can generate results comparable to experts [23]. Barriers to crowd-sourcing include cost as local experts usually provide feedback free of charge, albeit their availability may be limited [23]. However, if such methods are used to assess trainee progression, there must be input from experts, whose assessment is

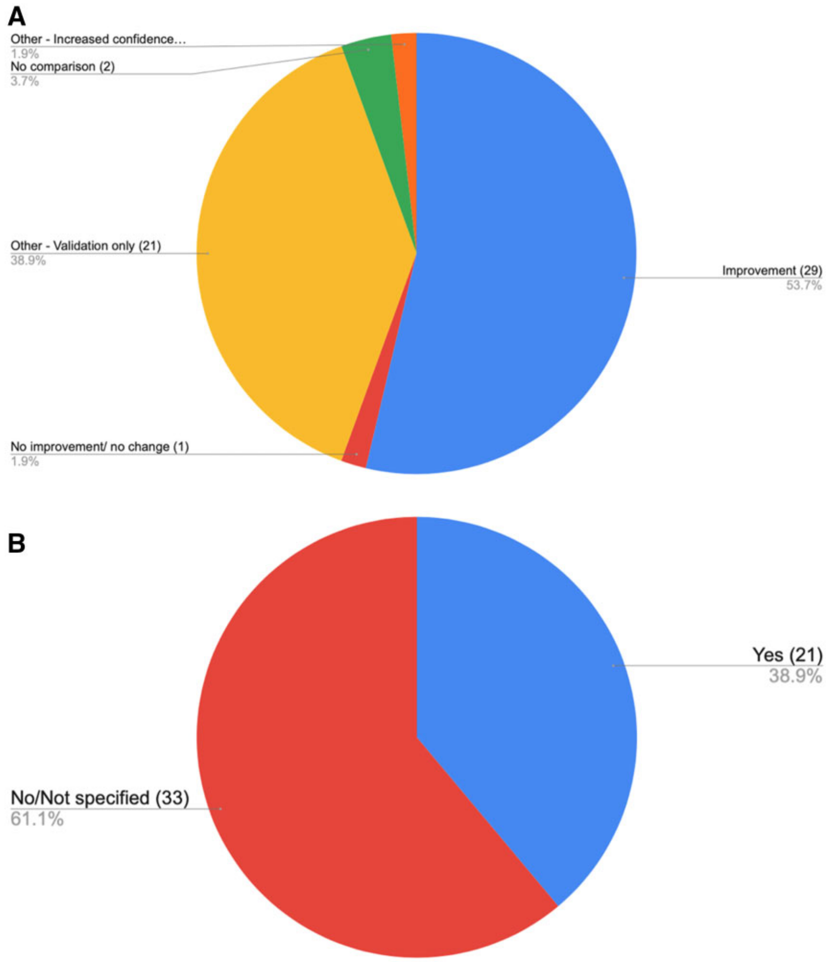


Figure 6: Chart demonstrating the outcome of the assessment (e.g. improvement in technical skill performance) (**A**) and whether the assessment method was incorporated into the training curricula (**B**).

crucial to assess the holistic aspects of performance and ensure continued assessment validity and reliability. Video recordings were used in most studies (63%), which maybe a potential solution to the above limitation as it allows retrospective, blinded assessment which was apparent in 46% of studies. If methods like crowd-sourcing are established it could potentially allow trainees to benefit from regular, unbiased, objective assessments in an efficient and cost-effective manner and promote better utilization of expert surgeon input [23–25].

In order for objective assessments to be successfully incorporated into training curricula, there is a need for the tool to be reproducible, easy to use and potentially have the ability to be assessed by less-experienced evaluators. There are a number of examples within this review which meet these criteria and are available for training programmes to adopt now. Lou *et al.* [16] describe the JCSTE (Joint Council on Thoracic Surgery Education) coronary anastomosis assessment tool, which utilizes the OSATS method. Hermsen *et al.* [26] and Hicks *et al.* [27] utilized the checklist method to assess the establishment of cardiopulmonary bypass and crisis management. Within thoracic surgery, the OSATS-based VATSAT (Video-Assisted Thoracoscopic Surgery Assessment tool) is a validated tool for pulmonary resection [18]. In congenital heart surgery, the HOST-CHS (Hands-On Surgical Training-in-Congenital Heart Surgery) assessment tool uses a hybrid checklist and Likert scale to objectively assess technical performance across the spectrum of congenital heart surgical procedures [4].

Objective assessments within cardiothoracic surgery curricula

Despite concerted efforts to incorporate objective technical skill assessment into CTS training curricula, its utilization worldwide is lacking. Although this study demonstrated that only 39% of studies had incorporated assessment methods into their local curricula, this may be under-represented as a large proportion of studies were for validation purposes only. However, when considering this number as a proportion of CTS institutions worldwide it is likely that is an overestimation due to selection bias. Institutions that are able to conduct such research and publish their experiences are more likely to be actively involved in incorporating assessments into their curricula. Conversely, poorly represented institutions/countries in the literature are unlikely to be involved in or utilize such methods and should be a focus of future research. Validated objective assessment methods will provide more granular evaluations of surgical performance, which can be provided through both simulation and intraoperative environments as demonstrated in this review.

Although this review sought to comprehensively evaluate the use of objective assessment in technical skill evaluation in CTS, it is not without its limitations. Firstly, there was an exclusion of non-English text which potentially leads to selection bias. Secondly, only published articles were reviewed which leads to potential publication bias. Due to the nature of the studies and lack of data incorporated made more detailed quantitative synthesis not feasible. This paper purposely focuses on the technical skill performance of trainee surgeons, which is only one aspect on becoming a competent cardiothoracic surgeon albeit an important one. Trainee surgeons must not only show technical perfection but also demonstrate competency in non-technical skills. This includes clinical judgement, critical thinking, academic scholarship/education and competency in emotional capabilities like empathy and emotional intelligence [28]. Not all of these skills can be trained in simulation environments or objectively assessed and can only be achieved during a surgeon's lifetime through experience. However, dedicated training alongside objective assessment is the key to perform technically on a high level. The validated evaluation methods included in this review are helpful to assess technical improvement after simulation training. However, questions remain regarding the predictive validity and the translation to real-patient performance [28]. The constructs of real-life operations are vastly different to the low-risk provided during simulation. There is a need to establish if improvements in simulation are translatable to intraoperative performance and should be the focus of future research.

CONCLUSION

The reductions in training time and intraoperative exposure for trainees in CTS has driven the growth in simulation-based training and the validation of objective assessment methods of technical skill. Although most studies were for validation purposes only, out of the studies that investigated performance outcomes all but one demonstrated an objective improvement in technical skill performance. Despite these assessment tools being available its adoption in training, curricula is still sparse. With the current and future challenges to training, there is a greater need to incorporate objective technical skill assessments. These will eventually help increase the efficiency and transparency of training programmes and ensure the development of the next generation of cardiothoracic surgeons.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *ICVTS* online.

Conflict of interest: none declared.

Data availability

The data underlying this article are available in the article and in its online supplementary material.

Author contributions

Nabil Hussein: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing—original draft; Writing—review & editing. **Jef Van den Eynde:** Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing—original draft; Writing—review & editing. **Connor Callahan:** Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing—original draft. **Alvise Guariento:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing—original draft; Writing—review & editing. **Can Gollmann-Tepeköylü:** Investigation; Methodology; Validation; Visualization; Writing—original draft; Writing—review & editing. **Malak Elbatarny:** Investigation; Methodology; Validation; Visualization; Writing—original draft; Writing—review & editing. **Mahmoud Loubani:** Conceptualization; Formal analysis; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing.

Reviewer information

Interactive CardioVascular and Thoracic Surgery thanks Paul Kurlansky, Marco Moscarelli and the other anonymous reviewer(s) for their contribution to the peer review process of this article.

REFERENCES

[1] Shah R, Jahangiri M, Goodwin A, Barnard S, Moorjani N. Cardiothoracic surgery curriculum:Intercollegiate Surgical Curriculum Programme-General Medical Council (GMC). 2020. https://www.iscp.ac.uk/media/1108/cardiothoracic-surgery-curriculum-aug-2021-approved-oct-20.pdf.
[2] Moorjani N, Lewis M, Shah R, Barnard S, Graham T, Rathinam S. Implementation of a novel portfolio of structured, curriculum-aligned, simulation-based, cardiothoracic surgery training courses: evolving the delivery of surgical education. J Thorac Cardiovasc Surg 2017;154:2009–16.
[3] Trehan K, Kemp CD, Yang SC. Simulation in cardiothoracic surgical training: where do we stand? J Thorac Cardiovasc Surg 2014;147:18–24.
[4] Hussein N, Honjo O, Barron DJ, Haller C, Coles JG, Yoo SJ. The incorporation of hands-on surgical training in a congenital heart surgery training curriculum. Ann Thorac Surg 2021;112:1672–80.
[5] Whittaker G, Salmasi MY, Aydin A, Magouliotis D, Raja SG, Asimakopoulos G *et al.* Recommendations for the use of coronary and valve simulators in cardiac surgical training: a systematic review. Eur J Cardiothorac Surg 2021;61:1–10.
[6] Hance J, Aggarwal R, Stanbridge R, Blauth C, Munz Y, Darzi A *et al.* Objective assessment of technical skills in cardiac surgery. Eur J Cardiothorac Surg 2005;28:157–62.
[7] Lodge D, Grantcharov T. Training and assessment of technical skills and competency in cardiac surgery. Eur J Cardiothorac Surg 2011;39:287–93.
[8] Karl TR, Jacobs JP. Paediatric cardiac surgical education: which are the important elements? Cardiol Young 2016;26:1465–70.
[9] Tweddell JS. Commentary: the time has come to measure and examine technical skills. J Thorac Cardiovasc Surg 2020.
[10] Vaporciyan AA, Yang SC, Baker CJ, Fann JI, Verrier ED. Cardiothoracic surgery residency training: past, present, and future. J Thorac Cardiovasc Surg 2013;146:759–67.
[11] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD *et al.* The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71.
[12] Reed DA, Cook DA, Beckman TJ, Levine RB, Kern DE, Wright SM. Association between fundings and Quality of Published Medical Education Research. JAMA 2007;298:1002–9.
[13] Cook DA, Reed DA. Appraising the quality of medical education research methods: the medical education research study quality instrument and the Newcastle-Ottawa Scale-Education. Acad Med 2015;90:1067–76.
[14] Lin H, Lin E, Auditore S, Fanning J. A narrative review of high-quality literature on the effects of resident duty hours reforms. Acad Med 2016;91:140–50.

[15] Martin JA, Regehr G, Reznick R, Macrae H, Murnaghan J, Hutchison C et al Objective structured assessment of technical skill (OSATS) for surgical residents. Br J Surg 1997;84:273–8.

[16] Lou X, Lee R, Feins RH, Enter D, Hicks GL, Verrier ED *et al.* Training less-experienced faculty improves reliability of skills assessment in cardiac surgery. J Thorac Cardiovasc Surg 2014;148:2491–6.e1–2.

[17] Nesbitt JC, St Julien J, Absi TS, Ahmad RM, Grogan EL, Balaguer JM *et al.* Tissue-based coronary surgery simulation:medical student deliberate practice can achieve equivalency to senior surgery residents. J Thorac Cardiovasc Surg 2013;145:1453–8; discussion 1458–9.

[18] Jensen K, Hansen HJ, Petersen RH, Neckelmann K, Vad H, Møller LB *et al.* Evaluating competency in video-assisted thoracoscopic surgery (VATS) lobectomy performance using a novel assessment tool and virtual reality simulation. Surg Endosc 2019;33:1465–73.

[19] Konge L, Lehnert P, Hansen HJ, Petersen RH, Ringsted C. Reliable and valid assessment of performance in thoracoscopy. Surg Endosc 2012;26: 1624–8.

[20] Macfie RCL, Webel AD, Nesbitt JC, Fann JI, Hicks GL, Feins RH. 'Boot camp' simulator training in open hilar dissection in early cardiothoracic surgical residency. Ann Thorac Surg 2014;97:161–6.

[21] Enter DH, Lou X, Hui DS, Andrei A-C, Barner HB, Sheen L *et al.* Practice improves performance on a coronary anastomosis simulator, attending surgeon supervision does not. J Thorac Cardiovasc Surg 2015;149:12–6.

[22] Hussein N, Honjo O, Barron DJ, Haller C, Coles JG, Van Arsdell G *et al.* Assessment tool validation and technical skill improvement in the simulation of the Norwood operation using three-dimensional-printed heart models. Eur J Cardiothorac Surg 2021;59:316–24.

[23] Dai JC, Lendvay TS, Sorensen MD. Crowdsourcing in surgical skills acquisition: a developing technology in surgical education. J Grad Med Educ 2017;9:697–705.

[24] Deal SB, Scully RE, Wnuk G, George BC, Alseidi AA. Crowd-sourced and attending assessment of general surgery resident operative performance using global ratings scales. J Surg Educ 2020;77:e214–9.

[25] Powers MK, Boonjindasup A, Pinsky M, Dorsey P, Maddox M, Su L-M *et al.* Crowdsourcing assessment of surgeon dissection of renal artery and vein during robotic partial nephrectomy: a novel approach for quantitative assessment of surgical performance. J Endourol 2016;30:447–52.

[26] Hermsen JL *et al.* Multimodal cardiopulmonary bypass skills assessment within a high-fidelity simulation environment. Ann Thorac Surg 2021; 112:652–60.

[27] Hicks GL, Gangemi J, Angona RE, Ramphal PS, Feins RH, Fann JI. Cardiopulmonary bypass simulation at the Boot Camp. J Thorac Cardiovasc Surg 2011;141:284–92.

[28] Stephens EH, Dearani JA. Commentary: surgical skill assessment: time to examine? J Thorac Cardiovasc Surg 2020;160:242–43.

[29] Bedetti B, Bertolaccini L, Patrini D, Schmidt J, Scarci M. Virtual simulation and learning new skills in video-assisted thoracic surgery. Video-Assist Thorac Surg 2018;3:35.

[30] Blum MG, Powers TW, Sundaresan S. Bronchoscopy simulator effectively prepares junior residents to competently perform basic clinical bronchoscopy. Ann Thorac Surg 2004;78:287–91.

[31] Bohnen JD, Demetri L, Fuentes E, Butler K, Askari R, Anand RJ *et al.* High-fidelity emergency department thoracotomy simulator with beating-heart technology and OSATS tool improves trainee confidence and distinguishes level of skill. J Surg Educ 2018;75:1357–66.

[32] Brandao CMA, Dallan LRP, Dinato FJ, Monteiro R, Fiorelli AI, Jatene FB. Evaluation method of training simulation on biological models for cardiovascular surgery residents. J Card Surg 2021;36:2247–52.

[33] Duffy MC, Ibrahim M, Lachapelle K. Development of a saphenous vein harvest model for simulation-based assessment. J Thorac Cardiovasc Surg 2019;157:1082–9.

[34] Fann JI, Calhoon JH, Carpenter AJ, Merrill WH, Brown JW, Poston RS *et al.* Simulation in coronary artery anastomosis early in cardiothoracic surgical residency training: the Boot Camp experience. J Thorac Cardiovasc Surg 2010;139:1275–81.

[35] Fouilloux V, Doguet F, Kotsakis A, Dubrowski A, Berdah S. A model of cardiopulmonary bypass staged training integrating technical and non-technical skills dedicated to cardiac trainees. Perfusion 2015;30:132–9.

[36] Ghazy A, Chaban R, Vahl C-F, Dorweiler B. Development and evaluation of 3-dimensional printed models of the human tracheobronchial system for training in flexible bronchoscopy. Interact CardioVasc Thorac Surg 2019;28:137–43.

[37] Greenhouse DG, Grossi EA, Dellis S, Park J, Yaffee DW, DeAnda A *et al.* Assessment of a mitral valve replacement skills trainer: a simplified, low-cost approach. J Thorac Cardiovasc Surg 2013;145:54–9.

[38] Hussein N *et al.* Development and validation of a procedure-specific assessment tool for hands-on surgical training in congenital heart surgery. J Thorac Cardiovasc Surg 2020;160:229–40.

[39] Hussein N *et al.* Quantitative assessment of technical performance during hands-on surgical training of the arterial switch operation using 3-dimensional printed heart models. J Thorac Cardiovasc Surg 2020;160: 1035–42.

[40] Iwasaki A, Moriyama S, Shirakusa T. New trainer for video-assisted thoracic surgery lobectomy. Thorac Cardiovasc Surg 2008;56:32–6.

[41] Jebran A-F, Saha S, Waezi N, Al-Ahmad A, Niehaus H, Danner BC *et al.* Design and training effects of a physical reality simulator for minimally invasive mitral valve surgery. Interact CardioVasc Thorac Surg 2019;29: 409–15.

[42] Jensen K, Bjerrum F, Hansen HJ, Petersen RH, Pedersen JH, Konge L et al Using virtual reality simulation to assess competence in video-assisted thoracoscopic surgery (VATS)lobectomy. Surg Endosc 2017;31: 2520–8.

[43] Joyce DL, Dhillon TS, Caffarelli AD, Joyce DD, Tsirigotis DN, Burdon TA *et al.* Simulation and skills training in mitral valve surgery. J Thorac Cardiovasc Surg 2011;141:107–12.

[44] Joyce DL, Lahr BD, Maltais S, Said SM, Stulak JM, Nuttall GA *et al.* Integration of simulation components enhances team training in cardiac surgery. J Thorac Cardiovasc Surg 2018;155:2518–24.e5.

[45] Karim AS, Sternbach JM, Bender EM, Zwischenberger JB, Meyerson SL. Quality of operative performance feedback given to thoracic surgery residents using an app-based system. J Surg Educ 2017;74:e81–7.

[46] Kenny L, Booth K, Freystaetter K, Wood G, Reynolds G, Rathinam S *et al.* Training cardiothoracic surgeons of the future: the UK experience. J Thorac Cardiovasc Surg 2018;155:2526–38.e2.

[47] Korte W, Merz C, Kirchhoff F, Heimeshoff J, Goecke T, Beckmann E et al Train early and with deliberate practice: simple coronary surgery simulation platform results in fast increase in technical surgical skills in residents and students. Interact CardioVasc Thorac Surg 2020;30: 871–8.

[48] Lee R, Enter D, Lou X, Feins RH, Hicks GL, Gasparri M *et al.* The joint council on thoracic surgery education coronary artery assessment tool has high interrater reliability. Ann Thorac Surg 2013;95:2064–70.

[49] Li BB, Luo X, Qi L, Zhang D, Luo F, Li B, Tang Y. Comparison of the effects of coronary artery anastomosis training between senior and junior surgeons. Anatol J Cardiol 2020;24:153–9.

[50] Liu T, Qin Z, Luo M, Tan Z-X, Xiong J-Y, Gu G-J *et al.* Assessment of three methods for removing massive air in a cardiopulmonary bypass circuit: simulation-based multi-discipline training in West China Hospital. Perfusion 2019;34:203–10.

[51] Lladó Grove G, Langager Høgh A, Nielsen J, Sandermann J. The use of the 'objective structured assessment of technical skills' as an assessment tool among Danish vascular surgeons in training. J Surg Educ 2015;72: 1052–6.

[52] Malas T, Al-Atassi T, Brandys T, Naik V, Lapierre H, Lam B-K. Impact of visualization on simulation training for vascular anastomosis. J Thorac Cardiovasc Surg 2018;155:1686–93.e5.

[53] Maluf MA, Gomes WJ, Bras AM, Araújo TC, Mota AL, Cardoso CC, Coutinho RV. Cardiovascular surgery residency program: training coronary anastomosis using the arroyo simulator and UNIFESP models. Brazilian J Cardiovasc Surg 2015;30:562–70.

[54] Maricic MA, Bailez MM, Rodriguez SP. Validation of an inanimate low cost model for training minimal invasive surgery (MIS) of esophageal atresia with tracheoesophageal fistula (AE/TEF) repair. J Pediatr Surg 2016;51:1429–35.

[55] Marshall MB, Wilson BM, Carter YM. Thoracic surgery skill proficiency with chest wall tumor simulator. J Surg Res 2012;174:250–6.

[56] Miura N *et al.* "Mutual checking system for assessing trainee skills of thoracic surgery. Asian Cardiovasc Thorac Ann 2021;29:792–97.

[57] Nam JG, Lee W, Jeong B, Park EA, Lim JY, Kwak Y *et al.* Three-dimensional printing of congenital heart disease models for cardiac surgery simulation: evaluation of surgical skill improvement among inexperienced cardiothoracic surgeons. Korean J Radiol 2021;22:706–13.

[58] Ortiz C, Vela J, Contreras C, Ávila R, Inzunza M, Quezada J *et al.* Achievement of effective cardiopulmonary trauma surgical skills training throughout the incorporation of a low-cost and easy to implement pulsatile simulation model. Injury 2021;52:1215–20.

[59] Petersen RH, Gjeraa K, Jensen K, Møller LB, Hansen HJ, Konge L. Assessment of competence in video-assisted thoracoscopic surgery lobectomy: a Danish nationwide study. J Thorac Cardiovasc Surg 2018; 156:1717–22.

[60] Price J, Naik V, Boodhwani M, Brandys T, Hendry P, Lam B-KK. A randomized evaluation of simulation training on performance of vascular anastomosis on a high-fidelity *in vivo* model: the role of deliberate practice. J Thorac Cardiovasc Surg 2011;142:496–503.
[61] Sardari Nia P, Heuts S, Daemen JHT, Olsthoorn JR, Chitwood WR, Maessen JG *et al.* The EACTS simulation-based training course for endoscopic mitral valve repair: an air-pilot training concept in action. Interact CardioVasc Thorac Surg 2020;30:691–8.
[62] Sprott JR, Brunsvold M, Joyce D, Nguyen T, Antonoff M, Loor G. Prospective Trial of Low-Fidelity Deliberate Practice of Aortic and Coronary Anastomoses (TECoG 002). J Surg Educ 2019;76:844–55.
[63] Tanaka T, Shimada Y, Furumoto H, Makino Y, Kudo Y, Maehara S *et al.* Comparative analysis of the results of video-assisted thoracic surgery lobectomy simulation using the three-dimensional-printed Biotexture wet-lung model and surgeons' experience. Interact CardioVasc Thorac Surg 2021;32:284–90.
[64] Tavlasoglu M, Durukan AB, Arslan Z, Kurkluoglu M, Amrahov A, Jahollari A. Evaluation of skill-acquisition process in mitral valve repair techniques: a simulation-based study. J Surg Educ 2013;70:318–25.
[65] Tong BC, Gustafson MR, Balderson SS, D'Amico TA, Meyerson SL. Validation of a thoracoscopic lobectomy simulator. Eur J Cardiothorac Surg 2012;42:364–9.
[66] Turner SR, Nasir BS, Lai H, Yasufuku K, Schieman C, Louie BE *et al.* Development and pilot testing of an assessment tool for performance of invasive mediastinal staging. Ann Thorac Surg 2019;108:590–6.
[67] Turner SR, Lai H, Nasir BS, Yasufuku K, Schieman C, Huang J *et al.* Development and pilot testing of an assessment tool for performance of anatomic lung resection. Ann Thorac Surg 2020;109:1922–30.
[68] Valdis M, Chu MWA, Schlachta C, Kiaii B. Evaluation of robotic cardiac surgery simulation training: a randomized controlled trial. J Thorac Cardiovasc Surg 2016;151:1498–505.e2.
[69] Voduc N, Dudek N, Parker CM, Sharma KB, Wood TJ. Development and validation of a bronchoscopy competence assessment tool in a clinical setting. Ann Am Thorac Soc 2016;13:495–501.
[70] Whittaker G, Aydin A, Raveendran S, Dar F, Dasgupta P, Ahmed K. Validity assessment of a simulation module for robot-assisted thoracic lobectomy. Asian Cardiovasc Thorac Ann 2019;27:23–9.
[71] Wu S, Fu Y-H, Zhao H, Ling Y-P. Simulation training in minimally invasive direct coronary artery bypass grafting. Heart Surg Forum 2020;23:E774–80.
[72] Yasuda S, Van den Eynde J, Vandendriessche K, Masuda M, Meyns B, Oosterlinck W. Implementation of a beating heart system for training in off-pump and minimally invasive coronary artery bypass. BMC Surg 2021;21:1–8.