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Simulation-Based Training in Cardiology Education: A Systematic Review of Educational Outcomes, Procedural Skills, and Clinical Translation

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Abstract **Original Research Article**

Background: Simulation-based education has emerged as an important adjunct to traditional cardiology training by providing a safe environment for acquiring technical, cognitive, and non-technical skills. Its applications now include echocardiography, transesophageal echocardiography (TEE), cardiac catheterization, coronary angiography, acute cardiovascular care, and crisis management. ***Objective:*** To synthesize current evidence regarding the educational impact of simulation-based training in cardiology. ***Methods:*** A structured literature review was conducted according to PRISMA 2020 principles. PubMed/MEDLINE, Embase, Scopus, Web of Science, Cochrane Library, ERIC, and Google Scholar were searched for studies evaluating simulation-based educational interventions in cardiology or cardiovascular medicine. Eligible studies included randomized controlled trials, quasi-experimental studies, cohort studies, and pre-post educational studies reporting learner-, performance-, or patient-related outcomes. ***Results:*** Simulation-based training was consistently associated with improved knowledge, procedural skills, learner confidence, and objective performance metrics. The strongest evidence concerned echocardiography, TEE, coronary angiography, and cardiac catheterization training. Several randomized and controlled studies demonstrated improvements in theoretical knowledge, image acquisition, catheter manipulation, and procedural performance. However, the literature remains limited by small sample sizes, heterogeneous assessment methods, short follow-up periods, and scarce evaluation of patient-related outcomes. ***Conclusion:*** Simulation-based education is a valuable adjunct to conventional cardiology training, particularly for procedural and emergency-based learning. Further multicenter studies using standardized assessment tools and long-term clinical outcomes are needed to better define its role in cardiology curricula.

Keywords: cardiology; simulation-based education; medical education; echocardiography; cardiac catheterization; interventional cardiology; procedural training; systematic review.

INTRODUCTION

Cardiology is a technically demanding and cognitively complex specialty. Training requires mastery of clinical reasoning, image interpretation, procedural skills, communication, teamwork, and rapid decision-making in high-risk situations [1–3]. Traditional cardiology education has historically relied on an apprenticeship model, in which trainees acquire skills through bedside exposure, supervised clinical practice, and progressive procedural responsibility. Although this approach remains essential, it is increasingly challenged by concerns regarding patient safety, variability in clinical exposure, reduced working hours, limited procedural opportunities, and the growing emphasis on competency-based assessment [1,2].

Simulation-based education has emerged as a major educational tool in healthcare [1–3]. It allows learners to practice clinical and procedural tasks in a controlled environment without exposing patients to unnecessary risk. Simulation also permits deliberate practice, immediate feedback, repetition, objective assessment, and exposure to rare but critical events [1,2]. McGaghie *et al.,* demonstrated that simulation-based medical education with deliberate practice is superior to traditional clinical education for specific skill acquisition outcomes [2].

In cardiology, simulation has been applied across multiple domains, including cardiac auscultation, electrocardiography, transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), point-of-care ultrasound (POCUS), coronary angiography, cardiac catheterization, electrophysiology, structural heart interventions, advanced cardiovascular life support, and crisis resource management [3–8]. These applications are particularly relevant because many cardiology procedures are technically complex and associated with potential complications such as vascular injury, coronary dissection, perforation, tamponade, arrhythmias, hemodynamic collapse, and radiation exposure [7,8].

Several reviews have suggested that simulation may improve cardiology training, but the literature remains heterogeneous [3–6]. Studies vary widely in simulation modality, target population, training duration, comparator group, assessment method, and outcome level. Many studies report improved learner satisfaction or confidence, but fewer evaluate objective performance, skill retention, clinical transfer, or patient outcomes [4–6].

More recently, simulation has expanded into hybrid and virtual-reality learning environments, integrating immersive three-dimensional imaging and competency-based procedural teaching [8–10]. The emergence of competency-based medical education has further reinforced the need for reproducible and measurable training strategies in procedural cardiology [9,10].

Simulation has also been increasingly incorporated into procedural competency assessment and mastery learning models in cardiovascular education [24,25]. Several studies from invasive cardiology and critical care have suggested that structured simulation curricula may shorten learning curves, improve procedural consistency, and enhance trainee preparedness before real-world patient exposure [26,27].

The aim of this systematic review was therefore to synthesize the available evidence on simulation-based training in cardiology education, focusing on educational outcomes, procedural proficiency, clinical translation, and implementation challenges.

METHODS

Design and reporting framework

This review was designed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [11]. Given the heterogeneity of the available literature, a narrative synthesis was planned.

Research question

The review addressed the following question:

Among learners and healthcare professionals involved in cardiology or cardiovascular care, what is the impact of simulation-based training on knowledge, procedural skills, non-technical skills, confidence, clinical performance, and patient-related outcomes?

PICO Framework

Element	Definition
Population	Medical students, residents, cardiology fellows, cardiologists, nurses, technicians, or multidisciplinary cardiovascular teams
Intervention	Any simulation-based educational intervention related to cardiology or cardiovascular medicine
Comparator	Traditional teaching, didactic teaching, no intervention, usual training, alternative educational intervention, or pre-intervention performance
Outcomes	Knowledge, technical skills, procedural performance, confidence, satisfaction, non-technical skills, clinical behavior, patient outcomes

Eligibility criteria

Inclusion criteria

1. Studies were considered eligible if they:
2. Evaluated a simulation-based educational intervention in cardiology or cardiovascular medicine.
3. Included learners or healthcare professionals involved in cardiovascular care.
4. Reported at least one educational, performance, behavioral, or patient-related outcome.
5. Used an original study design, including randomized controlled trials, controlled trials, pre-post studies, cohort studies, or mixed-methods studies.
6. Were published in English or French.

Exclusion criteria

Studies were excluded if they:

1. Used simulation exclusively for engineering, device testing, or computational modeling without an educational objective.
2. Were unrelated to cardiology or cardiovascular medicine.
3. Were editorials, opinion papers, letters, or conference abstracts without usable data.
4. Did not report measurable outcomes.
5. Focused only on animal models without learner assessment.

Information sources and search strategy

The following databases were searched: PubMed/MEDLINE, Embase, Scopus, Web of Science, Cochrane Library, ERIC, and Google Scholar.

Search terms included combinations of:

- "simulation"
- "simulation-based education"
- "cardiology"
- "cardiovascular medicine"
- "echocardiography"
- "transesophageal echocardiography"
- "cardiac catheterization"
- "coronary angiography"
- "interventional cardiology"
- "medical education"
- "virtual reality"
- "procedural training"

Study selection

Retrieved records were screened by title and abstract, followed by full-text assessment of potentially eligible studies.

Data extraction

Data extracted included:

- First author and year
- Country and setting
- Study design
- Sample size
- Learner population
- Cardiology domain
- Simulation modality
- Intervention characteristics
- Comparator
- Outcome measures
- Assessment tools
- Main findings
- Follow-up duration
- Limitations

Outcome classification

Outcomes were classified according to an educational hierarchy adapted from Kirkpatrick's model [12].

Level	Outcome type	Example
Level 1	Reaction	Satisfaction, perceived usefulness
Level 2	Learning	Knowledge, technical skills, confidence
Level 3	Behavior	Transfer to clinical practice
Level 4	Results	Patient safety, complications, clinical outcomes

Risk of bias assessment

Randomized studies were interpreted according to the Cochrane Risk of Bias framework, while non-randomized studies were interpreted according to commonly accepted methodological standards in medical education research [13].

Data synthesis

Given the heterogeneity of interventions and outcomes, a narrative synthesis was considered most appropriate.

Results

Overview of the evidence

The literature supports the feasibility and educational value of simulation-based training in cardiology [3–6]. Most studies report improvements in learner knowledge, practical skills, confidence, or objective procedural performance. The strongest evidence concerns echocardiography and catheterization-based training, where simulation can reproduce technical tasks and allow repetitive practice before patient contact [4–8].

A recent systematic review in cardiovascular medicine concluded that simulation-based interventions generally improved learner outcomes, although the available evidence remained heterogeneous and frequently limited to short-term educational endpoints [4].

Echocardiography and transesophageal echocardiography

Echocardiography is one of the best-studied areas for simulation-based cardiology education [5–8]. Simulation allows learners to practice probe manipulation, image acquisition, standard views, anatomical recognition, and pathology interpretation.

Cook *et al.,* reviewed echocardiography simulation studies and found that most demonstrated positive educational outcomes [5]. TEE simulation has received particular attention because it requires integration of spatial anatomy, probe manipulation, image interpretation, and procedural safety [6–8].

The SIMULATOR randomized clinical trial compared simulation-based teaching with traditional didactic teaching for TEE among cardiology fellows and residents [7]. Simulation-based teaching significantly improved theoretical and practical performance and increased learner self-confidence.

Jujo *et al.,* also reported favorable outcomes in a systematic review and meta-analysis of TEE simulation, including improved image acquisition and procedural understanding [8].

Pediatric cardiology fellows may also benefit from simulation. Dayton *et al.,*demonstrated improved congenital heart disease knowledge and echocardiographic performance after simulator-based training [14].

Transthoracic echocardiography and point-of-care ultrasound

Simulation has also been applied to transthoracic echocardiography and focused cardiac ultrasound training [5,15]. Randomized and pilot studies suggest that structured simulation may improve image acquisition, practical skills, and learner confidence [15].

Cardiac catheterization and coronary angiography

Simulation-based training has been extensively studied in cardiac catheterization and coronary angiography [16–20]. These procedures are especially suited to simulation because they require psychomotor coordination, catheter manipulation, fluoroscopic orientation, radiation awareness, and rapid recognition of complications.

Bagai *et al.,* performed a randomized controlled pilot study showing that mentored simulation training improved procedural skills in cardiac catheterization among cardiology trainees [16].

Voelker *et al.,* reported that curriculum-based virtual reality simulation improved coronary angiography performance among cardiology fellows [17]. Similarly, Popovic *et al.,* demonstrated improved operator skills after simulation-based coronary angiography training compared with traditional catheterization laboratory teaching [18].

Joshi and Wragg emphasized the growing role of simulator training in interventional cardiology, particularly for reducing the early learning curve in invasive procedures [19]. Aggarwal *et al.,*also highlighted the utility of simulation in radiation management, procedural planning, and complication handling [20].

Additional studies have suggested that simulation may contribute to improved radiation safety awareness, reduction in technical errors, and optimization of procedural workflow during early invasive cardiology training [24,26–28].

Cardiac auscultation

Simulation has been used to improve cardiac auscultation skills through mannequins, heart sound simulators, and structured bedside-equivalent teaching [21]. McKinney *et al.,*concluded that simulation-based training improves cardiac physical examination skills, particularly when combined with deliberate practice and structured feedback [21].

Acute cardiovascular care and crisis resource management

High-fidelity simulation is particularly useful for acute cardiovascular scenarios, including cardiac arrest, acute coronary syndrome, cardiogenic shock, malignant arrhythmias, tamponade, peri-procedural complications, and post-procedural deterioration [3,22].

Non-technical skills

Simulation-based team training may improve communication, leadership, teamwork, and crisis resource management [3,22].

Patient-related outcomes

Patient-related outcomes remain insufficiently studied [4]. Most available studies focus on learner satisfaction, knowledge, confidence, or simulator performance rather than clinical endpoints.

Table 1: Key studies relevant to simulation-based training in cardiology

Study	Design / type	Domain	Population	Main contribution
Issenberg *et al.,* 2005 [1]	BEME systematic review	Medical simulation	Health professions education	Identified key features of effective simulation
McGaghie *et al.,* 2011 [2]	Meta-analysis	Deliberate practice	Medical learners	Simulation superior to traditional learning
Pezel *et al.,* 2021 [3]	Review	Cardiology simulation	Cardiology learners	Overview of cardiology simulation
Kweki *et al.,* 2023 [4]	Systematic review	Cardiovascular medicine	Cardiovascular learners	Positive learner outcomes
Cook *et al.,* 2019 [5]	Systematic review	Echocardiography	Health professionals	Positive outcomes in echo teaching
Pezel *et al.,* 2021 [6]	Study protocol	TEE	Residents	SIMULATOR study rationale
Pezel *et al.,* 2023 [7]	Randomized clinical trial	TEE	Fellows/residents	Improved theoretical and practical outcomes
Jujo *et al.,* 2021 [8]	Meta-analysis	TEE	Learners	Improved image acquisition
Dayton *et al.,* 2018 [14]	Educational intervention	Pediatric echo	Fellows	Improved CHD knowledge
Almonte *et al.,* 2022 [15]	Pilot study	Cardiac POCUS	Residents	Improved ultrasound learning
Bagai *et al.,* 2012 [16]	Randomized study	Cath lab	Trainees	Improved procedural skills
Voelker *et al.,* 2016 [17]	Pilot study	Coronary angiography	Fellows	Improved angiography performance

Popovic *et al.*, 2019 [18]	Educational study	Coronary angiography	Operators	Better cath-lab conduct
Joshi and Wragg, 2016 [19]	Review	Interventional cardiology	Trainees	Reduced learning curve
Aggarwal *et al.*, 2016 [20]	Review	Cath lab simulation	Trainees	Radiation awareness
McKinney *et al.*, 2013 [21]	Meta-analysis	Auscultation	Health professionals	Improved auscultation skills
Wayne *et al.*, 2005 [22]	Educational intervention	ACLS simulation	Residents	Better ACLS performance
Barsuk *et al.*, 2009 [24]	Mastery learning study	Invasive procedures	Residents	Simulation mastery learning improved procedural competence
Ericsson, 2008 [25]	Educational theory	Deliberate practice	Healthcare learners	Theoretical basis of expertise acquisition
Okuda *et al.*, 2009 [27]	Review	Medical simulation	Medical education	Evidence supporting simulation utility
Ma *et al.*, 2011 [28]	Meta-analysis	Procedural simulation	Medical trainees	Improved procedural outcomes
Motola *et al.*, 2013 [29]	Best evidence review	Healthcare simulation	Healthcare learners	Practical guide for simulation curricula
Rosen, 2008 [30]	Historical review	Medical simulation	Medical educators	Historical evolution of simulation

Discussion

Principal findings

This systematic review indicates that simulation-based training is a valuable adjunct in cardiology education. Across multiple domains, simulation is associated with improved knowledge, practical skills, procedural performance, learner confidence, and satisfaction [1–8,14–30]

The findings are consistent with broader medical education literature demonstrating that simulation is most effective when it includes deliberate practice, structured feedback, curriculum integration, progressive difficulty, and clearly defined learning outcomes [1,2,24,25].

Educational value in cardiology

Simulation addresses several limitations of traditional cardiology training. First, it allows early procedural practice without patient risk. Second, it permits repeated exposure to rare but critical complications. Third, it provides a standardized learning experience across trainees. Fourth, it enables objective assessment of technical and non-technical competencies. Finally, it may improve learner confidence before clinical exposure [2,3].

In interventional cardiology, simulation allows trainees to practice catheter handling, angiographic projections, procedural sequencing, and complication management before entering the catheterization laboratory [16–20].

Clinical translation

Despite positive educational outcomes, evidence for clinical translation remains limited [4]. Few studies evaluate whether simulation improves real-world procedural success, reduces complications, decreases fluoroscopy time, lowers radiation exposure, or improves patient outcomes.

Implementation challenges

Several barriers may limit the widespread adoption of simulation in cardiology:

- High simulator cost
- Need for trained faculty
- Limited access to simulation centers
- Lack of standardized curricula

Although cost remains an important limitation, simulation-based curricula may become increasingly cost-effective as technology becomes more accessible and reusable over time [27–29]. Emerging digital simulation platforms and remote-learning ecosystems may further facilitate dissemination of cardiovascular simulation training in low- and middle-income settings [29,30].

Strengths and limitations

The main strength of this review is its broad synthesis of simulation-based cardiology education across multiple domains.

However, several limitations should be acknowledged:

- Heterogeneity of included studies
- Variable methodological quality
- Predominance of single-center designs
- Short-term educational outcomes
- Scarcity of patient-related endpoints

Conclusion

Simulation-based training is a promising and increasingly relevant educational strategy in cardiology. Current evidence supports its role in improving knowledge, technical skills, procedural performance, and learner confidence, particularly in echocardiography, transesophageal echocardiography, cardiac catheterization, and coronary angiography

However, the literature remains heterogeneous and frequently limited to short-term learner outcomes. Further multicenter studies with standardized assessment tools, long-term follow-up, cost-effectiveness analyses, and patient-related endpoints are needed.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

- NL designed the study, performed the literature review, organized the data synthesis, and wrote the first draft of the manuscript.
- SS contributed to the literature screening, data interpretation, and manuscript revision.
- ZL contributed to methodological supervision and critical revision of the manuscript.
- AB supervised the study and contributed to the final scientific validation of the manuscript.
- All authors read and approved the final manuscript.

Consent

Not applicable. This study is a systematic review of previously published studies and did not involve direct patient participation or identifiable patient data. Therefore, informed consent was not required.

Ethical Approval

Ethical approval was not required for this study because it is a systematic review based exclusively on previously published data. The review was conducted in accordance with the principles of the Declaration of Helsinki and current recommendations for reporting systematic reviews.

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