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REVIEW

Simulation in cardiac surgery: current evidence

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Abstract

Simulation permeated healthcare curricula and has become a powerful teaching tool to improve manual and cognitive skills in medicine today. Amongst other skill sets, cardiothoracic anaesthetists are expected to make safe life-saving decisions to improve patient outcome during rare critical events. These stressful situations require leadership and problem solving skills from all medical personnel, which traditional learning by "apprenticeship" may not cover. This narrative review looks at current simulation modalities used in cardiothoracic anaesthesia, which include critical scenarios for the placement of arterial and central venous lines, as well as the interpretation of the pulmonary artery catheter derived data. Simulation in transthoracic and transoesophageal echocardiography has proven to be very useful. Of particular importance in cardiothoracic clinical practice is simulation for cardiopulmonary bypass, veno-arterial and veno-venous extracorporeal membrane oxygenation. Trainees' working hour regulations may affect patient safety, because of decreased exposure to real life patient-related scenarios. The complexity of patient interventions in a high-stakes discipline like cardiothoracic anaesthesia may necessitate the development of further simulation-enhanced educational processes.

Keywords

Simulation; Cardiothoracic anaesthesia; Hemodynamic monitoring; ECMO; Debriefing

1. Introduction

Simulation aims to facilitate learning in the cognitive, psychomotor or affective domains [1–3]. Simulation-based medical education includes any educational activity that uses simulative tools and methods to create learning opportunities for participants of all levels, from novices to the experts [3–5]. One of its primary underlying advantages is improved patient safety, as patients are not directly involved in the learning process. Simulation aims to create a supportive, encouraging learning environment, which facilitates changes in the behaviour of the individual and the team [4]. By definition, simulation is a technology to replace or amplify real patient experiences with guided experiences, which artificially replicate aspects of the natural world in an interactive manner [2]. Real-time training and learning is achieved using low and high-fidelity mannequins, and simulated patients in hybrid simulation.

Over the past 50 years, the development of simulation has increased exponentially (Fig. 1). Patients increasingly question their care process and want to participate in the decisions made about their own healthcare management [6, 7], which has relevant consequences for healthcare education. Nowadays, learners and healthcare practitioners are expected to be prepared for clinical practice before their first patient contact [8]. This has led to significant medical education changes globally [9–11]. Furthermore, the current highly legislated working time restrictions limit opportunities for the traditional learning of medical skills by "apprenticeship" [12]. Simulation offers a feasible alternative to learning procedural skills, provides the opportunity to rehearse performance in complex integrated scenarios in a safe, protected, learner-centred simulated clinical setting. The setting is mostly time-independent, and specifically allows practising rare events, for example resuscitation of a patient with a cardiac arrest. The general public may assume that each healthcare provider can and should be able to manage such critical situations [1, 4, 13]. On the other hand, it is well known that skills degrade over time if not regularly practiced [14–16]. The simulation-based practice has little impact if healthcare providers are exposed to singular events and evidence shows interval training improves retention of skills and knowledge. The success of simulation depends on an embedded educational strategy with regular revisiting and should be set in a curriculum favouring hybrid blended learning approaches [13, 16, 17].

Recent systematic reviews show that simulation-based train-

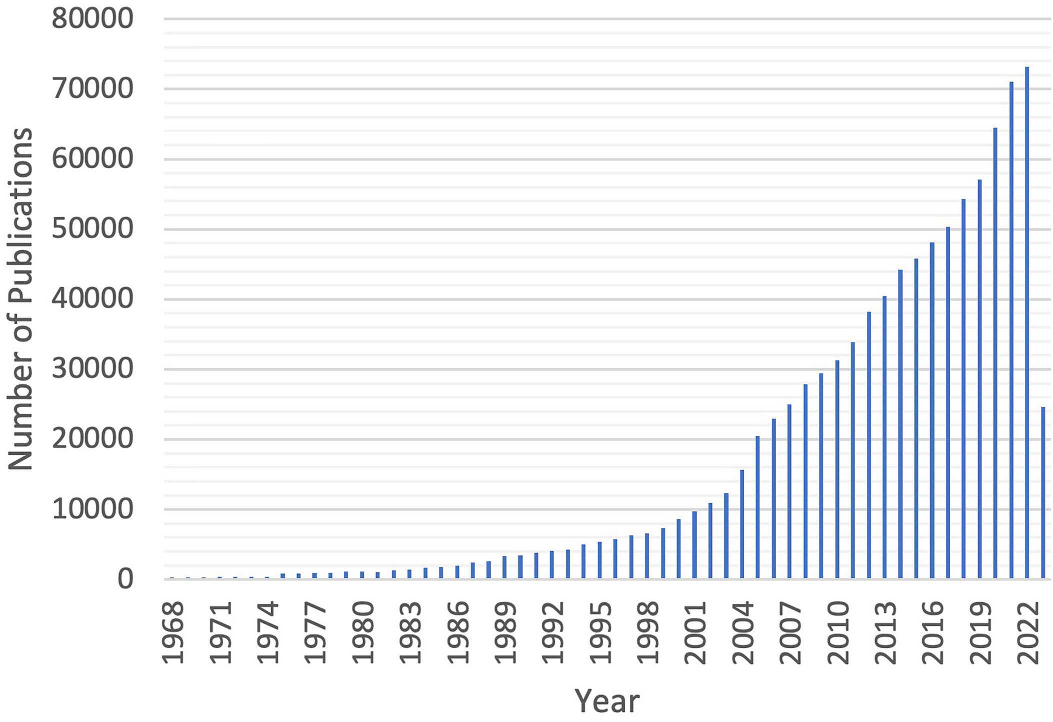

FIGURE 1. Number of publications relating to simulation in medicine. Results are per year over the last fifty years.

ing is associated with moderate to large effects for educational outcomes when compared with no intervention [18] and small to moderate effects when compared with other instructional approaches (*e.g.*, lectures) [19]. In anaesthesia, results from systematic reviews seem to show a similar pattern, despite the paucity of studies measuring either learner or patient effects [3].

In anaesthesia, healthcare professionals must make rapid and correct decisions in critical and emergency situations, often based on minimal information. These rare clinical events necessitate vital decisions often made with little clinical experience. While many practical skills can be acquired through low-fidelity manikin training, exposure leads to clinical expertise. In addition, the successful management of medical crisis depends not only on technical skills performance but also on non-technical behavioural skills like leadership, crisis management, communication, decision-making, situational awareness, and collaborative teamwork. Early acquisition of such competencies plays a vital role in improving patient safety. Simulation puts forward a way to achieve that.

Cardiothoracic anaesthesia requires the command of such complex skills. Therefore, novice learners can benefit from low-fidelity task trainers, which provide a promising alternative to patient bedside-teaching. Various simulation-based technologies are commercially available and relevant to cardiothoracic anaesthesia training, like anaesthesia management software [20], vascular access trainers [21, 22], bronchoscopy simulators [23], full-sized mannequins [24], cardiopulmonary bypass simulators [25] and many more.

2. Simulation in cardiac anaesthesia

A broad range of simulators are available to implement covering different components of cardiac anaesthesia training.

2.1 Simulation in vessel cannulation and hemodynamic monitoring

Cardiothoracic anaesthetists' skillset include placement of arterial lines, central venous and pulmonary catheters, and the interpretation of hemodynamic data derived from the measurements from these catheters. The competencies needed are manual dexterity and certain cognitive knowledge-based components. Dexterity includes all the steps, from finding the best puncture site to the insertion technique (*e.g.*, the "Seldinger" technique). An example is the placement of a pulmonary artery catheter, which needs additional steps. These steps include manipulating the pulmonary catheter through the introducer sheath to the wedge position in the pulmonary artery. That means the cognitive and dexterity components of this procedure include recognising anatomic landmarks, knowing the contents of a cannulation kit and the catheter, placing of the catheter efficiently, and recognising correct vessel cannulation: these steps need to be performed under sterile conditions, while observing and interpreting the pressure curve on a remote screen. Part-task trainers are devices that teach and enable mastery of technical, psychomotor, and procedural skills in educational settings. They range from low-fidelity trainers, like arterial puncture arms, to highly sophisticated computerised high-fidelity human-like simulators [26]. Various part-task trainers are commercially available to facilitate trainees in learning both dexterity and cognitive skills for vessel cannulation [23].

Most part-task trainers are intricate and anatomically correct. They are also cost-effective and can be used repeatedly with minor wear and tear. Using part-task trainers has produced significant medical care cost savings by reducing preventable complications such as catheter-related bloodstream infections [27]. Nonetheless, many models need concomitant monitoring software, making cognitive components such as dealing with data recognition and interpretation, which is impossible to be simulated. This limits implementation of such models for training purposes. The Louisville Central Venous Cannulation Simulator [28] (University of Louisville, USA) overcomes these cognitive learning limitations by connecting the device to a human patient simulator that can present the central venous, arterial, and pulmonary artery pressures, cardiac rhythms, and oxygen saturation on commercially compatible monitors. With this device, all the procedural steps performed on the patient can be learned and trained on the mannequin [23]. Similar principles were used to develop an arterial cannulation simulator [29].

Computer-based simulation systems lack the physical component of simulation manikins. These computer programs provide learners with interfaces that allow them to interact with materials related to either basic sciences or decision-making, which can be presented at the learner's own pace [30]. Currently, several computer-controlled screen-based pulmonary artery catheter simulators and apps are used to simulate pulmonary artery catheter (PAC) placement (Swan-Ganz Simulation App: Edwards Lifesciences; 2019) [23, 31, 32]. These programmes simulate the advancement of the PAC through the heart chambers and the inflation of the balloon to obtain wedge pressure. The advantages of this simulation software include low costs and the ability to practice without supervision. Some limitations include the inability to control complications and the absence of educational studies validating these simulators as educational tools. Such tools also do not control the learner's progress or give feedback.

At present, the closest to real-life simulation are high-fidelity whole- or part-body manikins coupled to a computer that models physiological responses, which mirror a desired output to "patient" monitors [30]. The vital signs can be displayed and altered in response to interventions and therapies initiated by the user interacting with the manikin. There are several such examples in anaesthesia, which can also be used to simulate cardiac emergencies (Table 1) [33].

Several hemodynamic and ventilation simulation software models may be incorporated into these human patient simulators [32, 34, 35]. These models are based on actual patient findings, which make all relevant hemodynamic values more realistic. The Simulation Interface Software Version 1.0 (AQAI GmbH, Mainz, Germany) is a flexible software system which synchronises the heart rate of the cardiac simulator and the artificial lung simulator lung mechanics, gas exchange, and heart-lung interactions with the heart rate of the mannequin. These models can also analyse drugs relevant for anesthesia, calculate drug interactions, and generate a simulated bispectral index.

2.2 Simulation with echocardiography

Anaesthetists, as the in-hospital peri-operative physicians, are often responsible for treating cardiac emergencies. Therefore, an increased training in transthoracic echocardiography (TTE) is also necessary. Traditional TTE training is limited by the availability of trainers and patients for TTE examinations, the episodic learning opportunities, and the absence of a graduated increase in exposure, from easy, normal to heavy abnormal cases. This precludes adequate and rigorous training [36]. Thus, TTE simulation in cardiac curricula can shorten the initial learning curve and shorten the training duration.

Commercially available transesophageal echocardiogram (TEE) simulators consistently showed improvement of psychomotor skills [37, 38] (Table 2). TEE simulators also offer visualisation of pathological heart conditions and image interpretation [39], which in turn improves the ability to perform and interpret a focused cardiovascular ultrasound examination [40, 41]. However, the acquisition of such a TEE simulator system represents a substantial financial burden for already stretched hospital budgets, and there are concerns that simulators may not teach exemplary machine handling [42]. Therefore, after initial training by simulation, continued learning should occur directly on human volunteers or patients, which may give an authentic feeling of probe holding and control, raising the learner's confidence [42].

Live 3D heart animation combined with 2D transthoracic echocardiography images can now be created, due to the advancement of echocardiography simulators. Doppler measurements for quantitative assessment of cardiac function are also possible, which allows replication of different pathologies [48].

2.3 Simulation of extracorporeal circulation devices

2.3.1 Cardiopulmonary bypass (CPB)

Cardiopulmonary bypass (CPB) is a common procedure performed in the operating room to assist cardiothoracic surgeons while they work by maintaining systemic circulation of blood. It is a complex process with potential serious but unexpected consequences. Although, simulation improved technical skills in the application of extracorporeal circulation (ECC) for open heart surgery, no direct correlation was found with patient safety. Small studies have shown that simulation prepared perfusionists response to critical incidents [49]. For inexperienced anaesthetists in cardiac anaesthesia, it is often quite challenging to assimilate the concepts of managing CPB, as a thorough understanding of the steps involved in initiating and discontinuing CPB is needed. CPB is a unique process with many pathophysiologic consequences for the patient, therefore simulation prepares the novice cardiac anaesthetist for peri-operative problems that may arise [50, 51]. Interestingly, simulation experienced shortly before a cardiac anaesthesia rotation allows for a steeper learning curve during clinical practice [50].

Virtual patients and hybrid simulation for risk-management training are beneficial for perfusionists to improve their skills in this area [49, 52]. However, high-fidelity mannequin simu-

TABLE 1. Common human patient simulators (HPS) used in simulation practice.

	Advantages	Disadvantages
SimMan® (Laerdal, Stavanger, Norway)	Realistic weight and articulation, palpable skin and anatomical landmarks. Displays oxygen saturation, end-tidal carbon dioxide, cardiac rhythm, central venous pressure, arterial pressure. Simulates pulmonary and cardiac sounds and can be set to represent a variety of abnormal findings. It allows the use of the hospital's own equipment (compatible with other software and hardware) manikin's anatomy can be modified to show changes in the patient's condition or responses to intervention (1). Portable manikin (wireless) (2). It connects with a Cloud where it can choose from several scenarios made by experts in their fields. It is possible to modify scenarios to match local guidelines or training needs. Paediatric (Laerdal SimBaby®) versions available.	Expensive The operator must enter the changes in physiologic parameters manually (1) Some software is only available for specific modules, and has to be separately bought. Patient cases and scenarios also have to be separately bought (2) Battery dependent
METIman® (CAE Healthcare Inc, Sarasota, USA)	Combines operator-driven simulator and autonomous-driven Simulators. Paediatric and pregnant versions available (Lucina®, pediaSIM®).	Expensive
Hal S5301® (Gaumard, Miami, Florida, USA)	Conversational speech, lifelike motor movement (3), including English and Spanish responses and possibility to custom speech phrases in any language (4). Displays oxygen saturation, end-tidal carbon dioxide, cardiac rhythm, central venous pressure, arterial pressure. Simulates pulmonary and cardiac sounds and can be set to represent a variety of abnormal findings. Can simulate clonic seizures, sweating and tears (4). Has a specific cardiac damage model (UNI® 3D Myocardial Infarction Model) (4). Supports radial arterial access site catheterization and Train of Four monitoring devices (4). It allows the use of the hospital's own equipment (compatible with other software and hardware). Paediatric and pregnant versions available (Noelle Maternity Simulator and Noelle's Newborn Baby Hal®).	Battery dependent Learners reported difficulty hearing or interpreting mannequin heart sounds accurately (5)
Harvey® (University of Miami's Gordon Center for Research and Medical Education)	Simulates 50 different cardiac diseases exhibiting all their physical signs (1). Next-generation Harvey® has six breath sound areas and nine cardiac auscultation areas. Provides cardiopulmonary training for all healthcare providers (1). Notable simulator for cardiac pathology.	Next-Gen Harvey® still in production (1)
VitalSim^{TM} (Laerdal, Stavanger, Norway)	Cost-effective, easy-to-use manikin. Simulates ECG, heart sounds, breath sounds, bowel sounds, blood pressure and pulse. Simpler devices, less training to operate. Indicated for beginners and advanced learners alike (1).	Mid-level fidelity Human Patient Simulator (1) Learners sometimes find it difficult to hear or interpret mannequin heart sounds accurately (5)
MegaCode Kelly^{TM} (Laerdal, Stavanger, Norway)	Cost-effective, easy-to-use manikin. Indicated for beginners and advanced learners alike. Allow practicing skills as intubation, chest tube insertion and defibrillation.	Mid-level fidelity Human Patient Simulator

(1) https://www.healthysimulation.com/human-patient-simulator/; *(2)* https://laerdal.com/at/products/simulation-training/emergency-care-trauma/simman-als/; *(3)* https://www.gaumard.com/hal-s5301/; *(4)* https://gaumard-downloads.s3.amazonaws.com/brochures/11190158A-HAL-S5301-2022-brochure.pdf; *(5)* https://aneskey.com/-mannequin-based-simulators/.

TABLE 2. Improvement of learning outcomes with echocardiography simulation.

• Allows repetitive practice [37, 42]
• Aids acquisition of proficiency in achieving quality of image [42, 43]
• Allows sufficient practice time with no negative consequences on patient safety [44]
• Allows better skills in access of images and anatomy identification [39, 45]
• Improves skill achievement [36, 46]
• Reduces the number of echocardiography examinations to reach competency [47]
• Allows standardisation and reproducibility in the early learning process [48]
• Provides a safe learning environment, allowing learning from mistakes [42]

lators in cardiac anaesthesia training lack the ability to simulate the CPB state [50, 53]. The integrate physiology model of human patient simulators usually does not allow the combination of adequate perfusion pressure in the presence of asystole or ventricular fibrillation. In a published simulator-based simulation scenario for cardiac anaesthesia, which included patient management during CPB, the authors reported keeping the actual scenario in "pause" mode for the period of CPB [54].

Unfortunately, the impact of training crisis management on CPB outcomes has been the subject of very few studies. Some small studies showed an improvement in the management of emergencies and adverse events after simulation [55–58], but their small sample size prevents generalization of conclusions.

2.3.2 Extracorporeal membrane oxygenation (ECMO)

ECMO, a form of long-term cardiopulmonary bypass, is one of the most invasive and complex methods to support patients with cardiac and respiratory failure [59]. Its use has increased exponentially over the last decade due to technological advancements, better outcomes and the coronavirus disease of 2019 (COVID-19) pandemic. Nevertheless, ECMO as a complex method requiring professionally trained medical personnel [60]. Simulation techniques in ECMO range from simple manikins that allow cannulation training to very sophisticated high-fidelity manikins that offer a realistic environment to facilitate a physiological, visual and engaging simulation experience [61].

Two recent US surveys reported that 46% of the ECMO centres have an ECMO simulation program and 73% of the centres have adopted simulation as part of their ECMO institutional accreditation [62, 63]. In 2017, ELSO (Extracorporeal Life Support Organization) included high-fidelity simulation into the training and continued medical education guidelines for ECMO physicians [64]. The guidelines clearly highlight the role of simulation in evaluating the knowledge and competencies of an ECMO physician managing routine and emergency ECMO interventions. It also underlines the role of simulation as an effective tool in training teamwork and communication skills [64]. ECMO-training, similar to CPB, should focus on recognising and managing rare but potentially fatal complications [65]. However, in most institutions, experience in ECMO is still acquired either by a period of apprenticeship or at the bedside in patients who are critically unwell [66].

The benefits of ECMO simulation training, such as acquiring technical and non-technical skills for the safe delivery of ECMO, have been reasonably demonstrated [67, 68]. Simulation has been shown to be superior to traditional training in reducing critical events on patients with ECMO treatment. These improvements were maintained over 12 months [69]. Despite this, simulation-based ECMO learning still needs to be standardised and evidence needs to be provided whether it is associated with better patient outcomes [60].

2.4 Simulation in resuscitation training

Simulation in resuscitation training is widely used and is a well-established educational strategy [70]. It facilitates contextualised learning relating to each learner's real-world setting and includes teaching technical skills and human factors. Advanced cardiac life support (ACLS) teaching includes simulation of acute cardiac arrest and peri-arrest situations.

Simulation training for advanced life support education encompasses both part-task trainers for basic life support teaching and complex high-fidelity technology equipment. The learning from a simulation experience is greatly enhanced during the cognitive, reflective debriefing of a simulated resuscitation scenario. Latest-generation manikins register learners' actions on the manikin, such as chest compression rate, depth and time without compression. They are able to display arterial blood gases, ECG waveforms and artefacts on monitors, and responses to various drug injections. These simulators also provide a lifelike patient experience for practising non-technical skills such as task-oriented teamwork, decision-making and situational awareness, leadership, and communication [34].

2.5 Debriefing for learning

Debriefing is a crucial part of simulation-based education and increases knowledge, skills and behavioural competences. Debriefing usually happens after a case-based simulation scenario, which in turn promotes reflective learning [71, 72]. In guided and facilitated debriefings by proper-trained debriefer, participants are encouraged to analyse their strengths and weaknesses, and develop and evaluate alternative courses of action [73]. Self-reflection occurs independently of the type of simulated scenario [74]. This is considered the most important factor initiating and facilitating the long-term learning experience. Several debriefing techniques were described, none better than another and if used appropriately by educators and facilitators have a significant impact on the quality of the simulation training [75]. Further discussion of debriefing techniques and its impact on learning is beyond the scope of this work.

3. Limitations

While simulation in cardiac surgery is now a widespread teaching method, additional scientific studies and research efforts are needed to validate this approach. Current literature provides us with few studies, small sample sizes and it is not uncommon to find unprecise methodology. Most studies compared simulation to traditional learning modalities, rather than comparing the different methods used in the various categories of cardiac simulation. Evidence to show better patient outcomes when simulation-based learning is used, is lacking. Studies on technical and non-technical performance in simulation require a larger number of cases and further investigation into the optimal timing of the evaluation in these replica scenarios.

Finally, despite being useful for summarizing the literature and providing guidance, this review also has methodological limitations. It does not meet the usual criteria of systematic reviews, which help mitigate bias. There were no explicit criteria for article selection and no evaluation of selected articles for risk of bias.

4. Conclusions

Simulation-based education has been in use for the last five decades, and its role in current healthcare curricula is expanding. Simulation is an essential educational tool in modern medical education. It represents an ideal platform for exposure to different situations and to improve skills, knowledge and behavioural competences in a psychological safe environment. In addition, it ameliorates teamwork and leadership. Simulation protects patients from unnecessary risks during learning and contributes to hospital safety. It permits the development of relevant clinical skills away from a clinical setting, where errors may contribute to mortality and morbidity. Moreover, it allows the rehearsal of either unusual or infrequent life-threatening critical incidents and also helps individuals to improve fundamental cognitive, technical and behavioural skills quicker, when compared to didactic teaching. It also improves personal skills such as confidence, proficiency and the ability to manage a crisis in medicine. Its primary disadvantage is the high personal resources needed associated with high costs.

Simulation is increasingly used in high-stake and challenging areas like cardiac anaesthesia. Learned competencies during simulation seem to be able to be translated to clinical environments and most likely improve patient outcomes. We welcome the further development of simulation as a tool to set standards in cardiavoascular anaesthesia in the near future.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

AUTHOR CONTRIBUTIONS

JBE, ABN and KG—made substantial contributions to the conception and first draft of the manuscript. DB and RG—critically reviewed the manuscript for important intellectual content. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

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CONFLICT OF INTEREST

JBE is an associate editor for BMC Medical Education and has received travel expenses from Medtronic® for the Save the Brain Initiative training. RG is the Board Director of Guidelines and ILCOR of the European Resuscitation Council, the Task Force Chair of Education, Implementation, and Team of ILCOR, and a member of the direction of the MME Programme of the University of Bern. The remaining authors have no conflicts of interest to disclose.

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