A Model for Competency-based Simulation Training in Cardiac Surgery Utilizing Dimensional Fidelity

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Abstract

Introduction: Simulation-based training has been increasingly utilized in cardiac surgery to train surgeons over the last two decades. The recent transition to competency-based surgical education has brought more challenges to train surgeons in less time amidst work-hour constraints and complex clinical environments. Educators strive to enhance their pedagogical strategies and theory-based methodologies to design better simulation experiences. In order to further advance cardiac surgery simulation design and conduct, I aim to expand and analyze surgical simulation fidelity concepts in this thesis and apply them to a competency-based simulation model.

Methods: A keyword-based literature review was conducted to retrieve published cardiac surgical simulation literature using MEDLINE and EMBASE from January 2000 up to February 2020. The search was limited by date of publication but not type. Included articles were thematically analyzed using deductive and inductive coding to identify fidelity meanings within predetermined dimensions.

Results: Twenty-six articles were included in the thematic literature review after duplicate removal, screening, and eligibility assessment according to inclusion and exclusion criteria. Within a physical, surgical field, and interactional dimension, seven themes were identified. They were derived from environmental, equipment, anatomical, physiological, procedural, perceptual, and psychological simulation components. Subthemes for three levels of realism were generated for each theme through an iterative process. These findings were developed from already existing simulation fidelity concepts to create a fidelity framework specific to cardiac surgical simulation. The development of a purposeful, goal-oriented cardiac

surgery simulation model was made possible by the alignment of surgical competencies, fidelity themes, and intended outcomes.

Conclusion: Seven major dimensional themes for cardiac surgical simulation fidelity were mapped from published literature. For each theme, the review outlined what low, moderate, and high levels of realism represented as subthemes. This enhanced fidelity framework can help create a competency-based simulation model that adjusts to training objectives by creating cost-effective simulations to complement contemporary cardiac surgical training.

Résumé

Introduction: La formation chirurgicale par simulation est de plus en plus utilisée en chirurgie cardiaque afin de former des chirurgiens, et ce, depuis les deux dernières décennies. La récente transition vers une formation chirurgicale axée sur les compétences (approche par compétences ou APC) a entraîné certains défis. En effet, il est maintenant nécessaire de former des chirurgiens en moins de temps dans un contexte de contraintes d'heures de travail et d'environnements cliniques complexes. Les éducateurs s'efforcent d'améliorer leurs stratégies pédagogiques et leurs méthodologies fondées sur les données probantes afin de concevoir de meilleures expériences de simulation. Afin de faire progresser la conception et la conduite de simulations en chirurgie cardiaque, je vise à élargir et à analyser les concepts de fidélité de simulation chirurgicale dans cette thèse et à les appliquer à un modèle de simulation basé sur les compétences.

Méthodologie: Une revue de la littérature basée sur des mots clés a été menée pour récupérer la littérature de simulation en chirurgie cardiaque publiée à l'aide de MEDLINE et EMBASE de janvier 2000 à février 2020. La recherche était limitée par la date de publication, mais elle n'était pas limitée par type. Les articles inclus ont été analysés thématiquement à l'aide d'un codage déductif et inductif pour identifier les significations de fidélité dans des dimensions prédéterminées.

Résultats: Vingt-six articles ont été inclus pour la revue de la littérature thématique après suppression des doublons, présélection et évaluation de l'admissibilité selon les critères d'inclusion et d'exclusion. Sept thèmes ont été identifiés dans les dimensions physiques, chirurgicales et interactionnelles. Ils ont été dérivés de composants de simulation environnementale, matérielle, anatomique, physiologique, procédurale, perceptuelle et

psychologique. Des sous-thèmes pour trois niveaux de réalisme ont été générés pour chaque thème au moyen d'un processus itératif. Ces résultats ont été développés à partir de concepts de fidélité de simulation déjà existants pour créer un cadre de fidélité spécifique à la simulation en chirurgie cardiaque. Le développement d'un modèle de simulation en chirurgie cardiaque ciblé et axé sur ces objectifs a été rendu possible par l'harmonisation des compétences chirurgicales, des thèmes de fidélité et des résultats escomptés.

Conclusion: Sept grands thèmes dimensionnels pour la fidélité de la simulation en chirurgie cardiaque ont été cartographiés à partir de la littérature publiée. Pour chaque thème, l'examen a souligné ce que les niveaux de réalisme faibles, modérés et élevés représentaient comme sous-thèmes. Ce cadre de fidélité amélioré peut aider à créer un modèle de simulation basé sur les compétences qui s'ajuste aux objectifs de formation en créant des simulations rentables dans le but de compléter la formation contemporaine en chirurgie cardiaque.

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Conflict of Interest

I declare no conflict of interest

Authors Contributions

Dr. Mohammed Abdullah Alharbi:

- Conceptual design of this thesis and manuscript
- Data collection and interpretation of the manuscript
- Preparation of this thesis and manuscript

Dr. Hellmuth Muller Moran and Ms. Meagane Maurice-Ventouris:

- Support with conceptual design, literature review, editing and approval of the manuscript

Dr. Kevin Lachapelle and Dr. Jason M. Harley:

- Supervision of all work related to this thesis
- Support and guidance with conceptual design and data interpretation of the manuscript
- Editing and approval of this thesis and manuscript

List of Abbreviations

RCPSC: Royal college of physicians and surgeons of Canada.

CBD: Competence by design

CBME: Competency-based medical education

HFS: High fidelity simulation

EPA: Entrustable professional activity

MEDLINE: Medical literature analysis and retrieval system online

EMBASE: Excerpta medica database

PICo: Population, Interest, Context

OPCAB: Off-pump coronary artery bypass

COVID-19: Coronavirus disease 2019

OR: Operating room

ICU: Intensive care unit

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Chapter 1: Introduction

Background and rationale

Cardiac surgery is one of the most demanding and challenging surgical disciplines to be trained in. Over the years, cardiac surgery education had evolved from subspecialty training as combined cardio-vascular-thoracic training to direct-entry programs.[1] In Canada, medical graduates match in cardiac surgery directly after medical school since 1994. It is a challenge for programs to transform young physicians with no surgical experience into highly qualified cardiac surgeons in six years. Additionally, work-hour restrictions policies and the introduction of minimally invasive techniques have limited trainees' classical surgical exposure. The advancements in percutaneous interventions have led to more cardiac surgery patients with highly complex diseases.[2] Moreover, cardiac surgeons are required to report their outcomes and train residents safely which puts them under immense pressure.[3] Recently, generational gaps between veteran cardiac surgeons and young trainees emerged as a modern educational concern.[4] With a growing demand for more cardiac surgeons, programs must find creative ways to prepare trainees for the transition to the workforce.[5] This is a problem that calls for evaluating classical operative teaching and moving toward effective utilization of surgical simulation-based training.

Simulation-based training gained popularity during the early days of cardiac surgery when surgeons simulated procedures on cadavers and explanted animal hearts and vessels before performing them on humans. Modern simulation-based training has flourished over the past two decades using animal-based and artificial simulators. The majority of simulators were used to practice coronary anastomoses and cardiopulmonary bypass skills. Recently, highly technological simulations were created to mimic real cardiac operating rooms. These simulators have been used by many programs as adjuncts to skill training, with a current emphasis on the creation of efficient instructional design and advancements in assessment and metrics.[6] Furthermore, these programs started adopting innovative simulation curricula to train their residents and fellows. After running bootcamps or rigorous simulation courses, they started publishing their simulation training results, as well as providing data on statistics and limitations. According to results from published cardiac surgical simulation literature, skill training improved over the last ten years, with junior trainees as the major beneficiaries. The majority were low fidelity simulators with no detrimental effects on training outcomes. Lastly, surgical educators needed to apply educational theories while designing simulation programs since they were lacking.[7]

The Royal College of Physicians and Surgeons of Canada (RCPSC) has adopted competence by design (CBD) as a model for competency-based medical education (CBME) in Canada. The model was implemented as a step away from classical medical training paradigms. Residency programs must define clear learning objectives, focus on feedback, and use coaching strategies, especially in surgical training. The trainees would have more control over their learning which makes it possible to fill in any knowledge or skill gaps. Cardiac surgery residency programs launched their CBD which brought a major change in residents' training and assessment. It uses a stage-based approach for training levels where trainees move up based on their performance.[8] Additionally, this raised challenges unique to the nature of surgical training, the chief of which was the limitation to hands-on surgical exposure. The CBD model implementation can be supported by simulation-based training that uses the same competency-based curriculum to establish competency-based simulations.

Although the value of simulation-based training in medical education is widely recognized, educators continue to scrutinize its outcomes, utilization, and cost. In fact, without systematic incorporation in training programs, simulation was used as an auxiliary tool to hone basic skills and teach new techniques in traditional cardiac surgery. Even with the current paradigm shift with CBME, which advocate for competency-based training and assessment, programs still use the same classical and direct encounters to assess trainees' competence. While not always used, some programs required the use of simulation-based encounters to assess certain surgical competencies, but this was not systematically embedded. A recent needs assessment of simulation in cardiac surgery training in Canada revealed that it is not being used to its full potential. Furthermore, structured instructional design and simulation-based competency assessment were lacking.[9]

Optimization of simulation-based training requires equal efforts from cardiac surgical educators and leaders. The necessity for a structured simulation curriculum that is competency-based, driven by cost-effective design, and based on educational theory cannot be overstated, given the growing need for cardiac surgeons and the current challenges in cardiac surgical training. To design better simulations, educators need a simulation model that provides them with versatile instructional design options. The primary objective of this thesis is to seek and expand simulation concepts to be used for a competency-based simulation model for cardiac surgical training.

Fidelity in surgical simulation-based training

Fidelity is a critical concept in simulation design, the degree of resemblance in physical, functional, and social aspects of a simulated task is undoubtedly an appealing feature. The definition of simulation fidelity is debated in medical education. An outdated definition of fidelity limits it to the mere functional resemblance a simulator has to the actual task it simulates.[10] Contemporary definitions of fidelity in medical education are based on how learners perceive simulations from various aspects. With the learner placed at the center of a simulation experience, fidelity can be defined as the various features of a simulation that, when combined, mimic certain reality that is needed for training.[11]

High fidelity simulation (HFS) is a term used in medical simulation literature which refers to the advanced technological or functional complexity of simulators.[12] Over the years, educators have been striving for the highest fidelity possible to promote better learning. On the other hand, many of these very sophisticated simulators are inherently costly and their running cost is even higher. With even more hype with HFS, fidelity as a concept lost its clarity since it was linked to a functional- and engineering-driven definition. Since then, many educators have questioned the effectiveness of HFS and contrasted its outcomes with low fidelity simulation.[13-15] Evidently, reports demonstrated good educational outcomes with low fidelity simulation and questioned the need for HFS or higher simulator functions.[15] It is also evident that there are many misconceptions about fidelity in medical education. While some consider the type of simulator modality as a synonym for fidelity (i.e., bench-top, task-trainers, manikin or virtual reality assisted), others think of it only from a technological standpoint. Due to a lack of consistency, fidelity definitions differ among disciplines and clear common terminology is lacking. As a result, it is difficult to interpret fidelity in the heterogenous medical simulation literature.[16] Furthermore, this has prompted calls from medical educators to abandon fidelity as a simulation concept and shift focus to functionality-driven design by advocating functional-task alignment.[17] However, educators have also argued for defining a range of fidelity features or dimensions and employing them to design authentic simulation experiences.[18,19]

In surgical simulation, fidelity is ultimately crucial to carry meaningful surgically derived reproductions of actual procedures. Surgical simulators must reflect specific functions, demonstrate correct anatomy, or adhere to procedural correctness to be able to train specific surgical skills. Importantly, surgical trainee engagement is essential to be able to create a reproducible simulation environment that is appealing and has believable authentic elements. Fidelity adjustments are unquestionably a powerful instrument for replicating various surgical scenarios for different trainee levels.[20] If defined appropriately within a surgical context, modifications to simulation fidelity can deconstruct a complex procedure to multiple tasks and vice versa. Fidelity in surgical simulation can be a multidimensional entity originating from the operating room functions, physical properties, and social interactions. In this case, high overall fidelity refers to the maximum available realities replicated of an actual surgical procedure. Whereas, low overall fidelity is the bare minimum and the intermediate level lies halfway between the two. In cardiac surgery, procedures are typically complex, and invasive and require highly advanced technical skills. Trainees usually graduate from simple tasks to advanced procedures throughout their training. Simulations for cardiac surgery must adapt to different teaching objectives, trainee levels and experiences through a flexible instructional design. Various learning objectives, skills, and eventually outcomes can be tackled by over- or underutilizing fidelity elements.

For surgical trainees, the ability to conduct the surgical procedure is the primary focus of their training. Their area of focus is unique as it entails handling organs and tissues and technically treating challenging diseases. Kneebone et al. illustrated the novel concept of circles of focus for surgical simulation.[21] The first or inner circle of focus, if applied to surgical trainees' perceived reality, would be the surgical field, where surgery is actively being performed. The second circle is beyond the inner circle, and it would stand for the context, the surrounding environment, and its different elements. This consists of the operating room, staff, and any physical elements related to the patient or the surgery. The third outermost circle is the bigger picture of the surgical environment, patient condition, surgical disease, and interactions outside the surgical act. The focus or awareness of the trainee decreases from the first to the third circle according to their level of training and experience. Consequently, certain simulations may replicate elements targeting the first circle of focus that is appropriate to the simulated task rather than the abstract reproduction of all three circles. As a result, educators can focus on specific perceived realities and control their level of realism according to the simulated task without including costly, out-of-focus reproductions. Thus, the experience will be more authentic, and trainee engagement will be higher.[22]

Traditionally, surgical simulations tend to have representations of the physical environment and elements around the surgical field where the simulation is taking place. They include sounds, smells, surgical devices, non-surgical team, and operative instruments which constitutes the perceived physical dimension. Secondly, they have reproductions of the surgical area and procedure being simulated, this constitutes a unique functional dimension. This represents anatomical features, physiological properties, procedural tasks, and surgical field functions (bleeding, exposure, angulation, dissection). Due to the fact that it is the area of training that educators and trainees are most focused on, this dimension is essential to surgical simulation training. It is where surgical training is manifesting, it is what makes a simulation experience purely technical and challenging. Finally, an interactional dimension where cognitive, perceptual, and affective processes resulting from the surgical simulation are displayed. This dimension represents perceptual (touch, smell, feedback, tissue feel) and affective (panic, stress, and anger) processes encountered during simulation training. It would certainly have a significant impact on trainees' learning experience and engagement because it replicates realistic interactions with the previous two dimensions.[23]

In this thesis, we argue that fidelity is a highly dynamic principle that can be manipulated according to different learner needs, clinical fields and learning objectives. Additionally, the idea of *fit-for-purpose* fidelity has demonstrated the ability to design cost-effective simulations and boost their educational impact.[24] We suggest expanding surgical fidelity meanings within a multidimensional model will enable us to design *fit-for-competency* simulations. Here, we will conduct a thematic literature review of published works on cardiac surgical simulation to develop a broadened fidelity framework specifically for a competency-based cardiac surgical simulation model.

Competence by Design (CBD) curriculum in cardiac surgery

The apprenticeship model was the only educational and training paradigm for surgical residency training. Five to six years would pass before trainees would be evaluated based on their overall body of knowledge and skills. Competency-based medical education (CBME) has been recently adopted by the Royal College of Physicians and Surgeons of Canada (RCPSC), which went into effect in 2017. This decision meant that trainees in surgical specialties will get trained using the CBD model. According to this model, residents go through four phases of training and are advanced to each stage based on a thorough evaluation of their acquisition of the necessary fundamental and core competencies. The main reason CBD was launched was to move away from the deficiencies of the Halstedian apprenticeship model. As a result, residency education and training underwent a significant paradigm shift in Canada. In 2019, cardiac surgery residency programs launched their CBD-based training. The program's four levels of training—transition to discipline, foundations of discipline, core of discipline, and transition to practice—each with its own set of competencies, were organized into the program's structure.[8] Numerous entrustable professional activities (EPAs) were created to demonstrate competence based on these predefined competencies. A trainee must pass the EPAs by demonstrating all the deconstructed tasks or milestones listed in them. These recordings are based on both direct and indirect observations from staff and senior team members during the trainee clinical rotations. For some milestones, simulation-based observations were included, but EPAs that are based on simulation observations solely were lacking. Therefore, the majority of the time, trainees are required to be observed in a clinical setting to demonstrate competency.

Simulation-based training provides surgical educators with a strong platform to demonstrate competency in a safe and controlled setting. Junior-level competencies, for instance, can be evaluated effectively in a simulated environment before they are observed in a clinical setting. To create *competency-based simulations*, the design for such simulated experiences might be based on the set milestones from EPAs. Additionally, the simulation-based assessment can be improved and informed by the extremely effective EPA-style assessment. Moreover, senior-level trainees can demonstrate their leadership and non-technical skills in complex team-oriented simulated scenarios. They can simulate the management of emergent and difficult cardiac surgery cases in a dedicated setting. Surgical educators will be able to offer technical guidance and appropriate feedback to trainees in a controlled environment.

In this work, we will link the simulation design to the CBD model-required competencies to create an instructional model that targets different milestones with the appropriate levels of fidelity.

Cardiac surgery discipline competencies

Since cardiac surgery programs adapted the CBD model, training committees have mapped and defined the competencies required for residency training.[25] These key competencies are presented within a framework consisting of the CanMEDS roles and CBD stages of competence.[8,26] Each CanMEDS role has a set of main key competencies, which branch into several enabling competencies. A trainee must successfully achieve milestones that are indicators of skill or knowledge development in order to achieve an enabling competency. A milestone is specific to the competence stage the trainee is at, a trainee who is transitioning from medical school to a discipline would have entry-level or fundamental milestones while a trainee who is at the core of discipline would be required to pass complex and advanced milestones. Attainment of milestones and their enabling competencies is assessed by EPAs, which are formal reports that detail the assessment plan, the targeted milestones, and the actual observation of skill by the educator or observer. Each encounter or observation was given context, quantity, and complexity level when developing these EPAs. There are 55 EPAs published by RCPSC for cardiac surgery residency, for example (see Cardiac Surgery EPA in Appendix).

The CanMEDS roles specify that in addition to medical expertise (knowledge and technical skills), communication, leadership, and collaborative abilities should also be demonstrated. A significant number of non-technical milestones were included, even if the majority of EPAs were focused on skillfulness milestones, procedures performance, disease diagnosis, and appropriate knowledge. Additionally, the competence by design model outlines realistic educational outcomes for each training stage while taking the principle of graded responsibility into account. Although simulation-based training was not incorporated systematically, the CBD framework has the potential to adapt simulation-based sessions for technical and non-technical skills. Certainly, the effective EPAs platform has clear objectives and assessment plans which could guide simulation-based training. To give an example, simulation-based observations for the EPA system can be introduced as competency milestones for junior and senior trainees (i.e., observing placing valve sutures in surgery and simulation setting to attain a valve suturing EPA). Moreover, developing a simulation-based EPA to evaluate and guarantee the integration of simulation-based training within CBD (i.e., constructing a whole EPA to demonstrate acquiring skill from simulation exercises so it becomes an attainable competency to proceed for further training).

The CBD model is considered a good resource to identify various competencies and milestones for competency-based simulation, but it is not the only source. A needs assessment can provide educators with the competencies they need to build simulation-based curricula. This has already been demonstrated with success in a cardiothoracic training program in the past.[27] With needs assessment is considered to be the first step in curricular development, a residency program might utilize it to identify underrepresented competencies. Adding to that, using data from continuous trainee evaluation, certain deficiencies can be targeted by competency-based simulation. There is no doubt that not every training program offers the same level of clinical exposure, but this may be overcome by developing objective simulation-based training. This may actually encourage institutions and programs to create their own competence frameworks.

In this work, we will take into account enabling competencies and their milestones as competence indicators to develop the model for competency-based simulation. Since this work would primarily serve Canadian cardiac surgical programs, we shall abide by the RCPSC's established competencies.

Educational theories in surgical simulation-based training

Instructional design, teaching strategies, and assessment can be influenced by educational theories in simulation-based training. These theories are generalizable principles, and some are acquired through experimental research. Generally, they aid educators to learn about learners' characteristics, learning environments and the interactional aspect of learning. We will discuss theories that are pertinent to surgical simulation-based training, to inform the competency-based simulation model.

Adult learning theory or *andragogy* was introduced by Knowles et al., who described the features of the adult learner. According to his theory, adult learning is driven intrinsically and independently. Major traits like confidence in self, curiosity-based learning style, and high level of responsibility and dedication to their training may inform simulation-based learning. Adult learners can analyze their knowledge and skill level, identify any gaps and plan strategies for improvement. Their reflections on their performance and self-feedback are paramount to their learning process and especially the practical aspect of their training. Since adult learners are involved in every component of their learning, this might pose a challenge for educators to prevent them from formulating their own learning objectives in a simulation setting. Alternatively, educators might give adult learners some authority gradually to enhance their learning experience.[28]

The premise of *Constructivist learning theory* is that learners build on their knowledge and skill from past learning or experience. Learners actively construct and form new concepts based on their decision on how, when, and why they learn. This should be guided by educators who facilitate the dissemination of new knowledge and skills. In surgical simulation, teachers should work to design meaningful experiences where learners are presented with new skills.

Constructivist learners often take their time to explore and learn, therefore educators must be patient and provide them with ample time.[29] Vygotsky et al. proposed the concept of the zone of proximal development where learning is most optimal. This zone is useful in simulation-based training when trainees are presented with skills just above their level and guided to advance their learning. This zone can be introduced automatically if senior trainees joined their junior colleagues in a social learning simulation environment.[30] This scaffolding concept was introduced by Wood et al. and is closely related to the zone of proximal development idea. Scaffolding refers to the supportive tools that an educator provides to guide a learner to gain new knowledge and acquire complex tasks. Once a learner masters a certain task, the scaffoldings can then be removed from the learning zone. An educator can deconstruct tasks into simpler parts and use cues to solve problems. Controlling the learner's engagement and affective reactions is also essential to facilitate learning. In simulation, removing scaffolding can be difficult at first, but it will fade away with time as educators transfer the process of guidance from them to trainees and provide it when needed only.[31]

Experiential learning theory by Kolb et al. focused on a four-stage learning process that forms a circle where learning can begin at any stage. The stages are concrete experiences, reflective observation, abstract conceptualization, and active experimentation. This cycle could represent everyday medical learning experiences from patient encounters to problem-solving. This is highly applicable to the simulation setting because reproductions of these experiences are aimed to enhance learning. With the proper coaching and focused guidance, learners may engage at any stage to formulate new knowledge or skill.[32]

Educational theories and concepts can help educators plan, design, develop and implement better simulation experiences. The use of these conceptualizations to augment learning activities and enhance skill training is an engaging process not only for learners but for educators too. Surely, educators who are aware of how trainees learn are better able to facilitate their learning.

Models of skill acquisition and mastery

Honing and mastering operative skills is the ultimate professional goal of any surgical trainee and represent their identity as surgeons. A substantial amount of time and energy is devoted by educators and trainees to shaping and refining fundamental and advanced surgical skills. Certainly, cardiac surgical training confronts trainees with a steeper learning curve compared to other surgical programs. Consequently, programs with effective skill-training methods are highly sought after, as they simply train better surgeons. One of these tools is simulation-based training which can supplement skill training in the actual operating room. In fact, a simulation instructional design that takes into account many skill acquisition models would likely produce superior training outcomes.[33] In order to reflect this on our suggested competency-based simulation model, we will address theories and advances in skill acquisition and mastery research.

Classical models of skill acquisition supported the theory of gradual motor skill development through multiple stages. For instance, Fitts and Posner proposed a model in which the acquisition of a motor skill starts with a cognitive phase where performance is not organized and is primarily led by an educator. This transitions to an associative phase in which performance improvement is evident based on repetitive practice and directed feedback. The last phase consists of autonomous performance that is effortless and refined, this results only from sustained practice. As a result, cognitive processing of skill declines with each phase as less thinking is needed to perform a task.[34] Similarly, Dreyfus et al. suggested five stages of experience which include novice, beginner, competent, proficient and expert. Transitioning from one phase to the next requires time and experience, which leads to enhances performance and automaticity. This means rules-guided behaviour decreases at the competent level with an increase in situational awareness. At the expert level, intuition-guided behaviour and effortless motor skills predominate.[35] This has led to a deep understanding of motor skill development which made educators assess their trainees' performance and better identify their learning deficiencies.

Advancements in simulation education shifted the focus to high fidelity simulators with abundant audiovisual stimuli and busy simulation environments. As a result, the sensory and cognitive processing needed by trainees has increased dramatically. According to cognitive load theory, this might hinder acquisition of new skills or learning in novice trainees.[36] With high fidelity, the visual, perceptual, auditory and cognitive load are optimized, as opposed to lower fidelity simulators in which novice trainees tend to perform better.[7] This also applies to the current model of competence by design, as the focus on graded responsibility supports the incremental cognitive load. Hence, trainee level, knowledge, experience, and complexity of tasks should be taken into consideration when designing simulations. This is supported by Miller's pyramid of assessment of clinical competence informs a hierarchical approach to skill acquisition.[37] A trainee begins with acquiring factual and procedural knowledge (knows), then moves to the ability to explain that knowledge (knows how). The subsequent step is to apply it in a simulated or actual scenario (shows how). Finally, the trainee would integrate the acquired knowledge, skill, and experience to address real-life surgical situations (does). Consequently, the progression of surgical simulation training can start from deconstructed simple tasks then add complexities in skill, and context or integrate multiple tasks, resulting in a graded simulation that is consistent with the graded responsibility paradigm.

Once trainees achieve the ability to perform a procedure or a complex skill in a simulation setting, equal to the (shows how) stage on Miller's pyramid, advanced practice strategies can augment their learning. For instance, Ericsson et al. first introduced deliberate practice as goal-directed, repetitive, and focused skill practice for motivated learners.[38] The model was conceptualized for real-life performers but the author demonstrated its efficacy in simulated environments also which must be supported by critical feedback and guidance.[39] The purpose of this concentrated practice is to refine skill and introduce skill mastery. The learner can engage and concentrate purposefully on a measurable outcome (e.g., time, smoothness, accuracy, or dexterity). Moreover, McGaghie et al. demonstrated a positive correlation between the amount of deliberate practice and performance.[40] To apply this model, once a trainee demonstrates skill competency, educators can adjust simulated experiences to refine critical skills. The context should involve primarily technical skills and establish their mastery or refinement standards (i.e., performance metrics). In addition, deliberate practice necessitates ample time for the trainee to practice on simulators, and educators exert effort to provide feedback and monitor performance. This requires a dynamic, efficient, and cost-effective simulation curriculum.

Skill acquisition is the primary learning objective of early and contemporary surgical simulations, and it will always be the most effective motivator for trainees and educators. Models of skill acquisition enable educators to design evidence-based simulation experiences. An instructional design based on graded fidelity can achieve the gradual introduction of simulated skills to trainees, keeping in mind the desired competency.

Chapter 2: Objectives and Aim

The main objectives of this thesis are:

1. To search and map the cardiac surgical simulation literature for expanded meanings and dimensions of surgical simulation fidelity
2. To establish a cardiac surgery simulation model using surgical competencies and simulation fidelity association for cost-efficient simulation-based training

The aim of this thesis is to offer an adapted simulation model that is based on sound educational theory and evidence-based skill acquisition models. It seeks to align various cardiac surgical competencies and objective milestones with a multidimensional, operational concept of surgical fidelity.

Chapter 3: Thematic Literature Review

Despite the fact that fidelity is a contested issue, contemporary research advocates harnessing its potential in simulation-based training to create engaging experiences.[18] In simulation education, the notion of fidelity dimensions has been described previously by Beaubien et al. who recommended three dimensions to train teamwork skills in healthcare (equipment, environment and psychological fidelity).[41] Additionally, Tun et al. suggested a dimensional framework for fidelity in simulation in healthcare education. His model incorporated three levels for realistic representation (low, intermediate and high) and three dimensions of fidelity (the patient, the clinical scenario and the healthcare facilities).[42] Herein, as a first step to establish the simulation model, we seek to broaden our knowledge about fidelity in cardiac surgery simulation within a multidimensional notion, and we shall continue to explore dimensional meanings from the literature.

There has, to our knowledge, been no previous description of fidelity dimensions in surgical simulation. Hence, we proposed three overarching dimensions that originate from the operating room using Kneebone's concept of circles of focus and Rystedt's definition of interactional fidelity.[21,23] The surgical fidelity dimensions will comprise a physical dimension representing the physical elements around the trainee from the operating room. Importantly, a surgical field dimension in which the representation of the surgical procedure occurs. Finally, an interactional dimension that reproduces the trainees' perceptions and affective responses. In this literature review, a thematic analysis will map the literature according to these dimensions using appropriate qualitative techniques aiming to extract relevant themes for cardiac surgical fidelity.

Mapping simulation fidelity in cardiac surgery using a multidimensional framework: a thematic literature review

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STRUCTURED ABSTRACT

Introduction: Simulation-based training is increasingly being adopted in cardiac surgery to train future surgeons. Despite the fact that low and high-fidelity cardiac surgical simulation has been described in the past, the idea of simulation fidelity is poorly defined and not well established. This paper examines the literature in search for meanings and themes of fidelity.

Methods: A keyword-based literature review was conducted to retrieve published cardiac surgical simulation studies using MEDLINE and EMBASE from January 2000 up to February 2020. The search was limited by date of publication but not type. Within predefined dimensions, included articles were thematically analyzed using a hybrid coding approach to identify fidelity meanings.

Results: Twenty-six articles were included for the thematic analysis after duplicate removal, screening, and eligibility assessment according to inclusion and exclusion criteria. Seven themes were identified within a physical, surgical field and interactional dimension. They were derived from environmental, equipment, anatomical, physiological, procedural, perceptual, and psychological simulation components. Subthemes for three levels of realism were generated for each theme through an iterative process.

Conclusions: Seven major dimensional themes for cardiac surgical simulation fidelity were mapped from published literature. We also identified subthemes for low, intermediate, and high realism for each theme. This fidelity framework may inform cost-effective cardiac surgical simulation design within competency-based education.

INTRODUCTION

Simulation-based cardiac surgery training is a valuable tool for teaching complex, invasive and high-stake procedures in a safe environment. Since the beginning, cardiac surgeons used simulation to practice procedures on animals or cadavers before performing them on humans.[1] Recent advances in surgical simulation have motivated training bodies to adapt simulation in resident training. Considering that surgical education is transforming into competency-based training rather than the Halstedian apprenticeship model, simulation-based training certainly could be advantageous.[2] Such transition puts pressure on surgical educators to advance simulation-based training curricular and instructional design and call for further funding in simulation research.

The literature on cardiac surgical simulation is rich with several publications documenting significant efforts to design and validate simulators, build simulation experiences, and assess their educational value. Notably, the literature presented a multitude of simulation experimentation, from bench-top, low-cost, and do-it-yourself simulators to sophisticated complex simulation programs by major academic centers.[1,3,4] Frequently, researchers described their simulators as having low or high fidelity based on their complexity and technical abilities.[5] It is indisputable that increasing simulator functions would increase the cost to design, and operate them. As a result, without financial backing, access to so-called "high fidelity" simulators would become limited.

Since simulation operational cost has become a challenge to simulation-based training, many medical educators have questioned the concept of fidelity.[6-8] This prompted educators to study fidelity as a construct and add further controversy.[9,10] In surgical simulation, the relationship between the trainee and the simulator is unique and essential. This relationship cannot be characterized exclusively in terms of engineering or simulator functions and capabilities. In fact, surgical simulation fidelity emerges from several reality aspects around the trainee, including physical elements, procedures, and simulation interactions. Here, the concept of dimensional simulation fidelity by Beaubien et al. becomes more relevant and dynamic in surgical simulation design.[11] In fact, surgical educators can design simulation experiences with fit-for-purpose fidelity and cost efficiency in mind.[12] This thematic literature review intends to expand the dimensional fidelity concept by mapping and identifying its patterns in cardiac surgical simulation.

DIMENSIONAL FRAMEWORK

Pragmatically, overarching fidelity dimensions may be derived from real surgical practice. In fact, Kneebone et al. demonstrated this in their circles of focus simulation concept.[13] The innermost circle encompasses the surgical field in which surgery is actively been performed, so establishing a surgical field dimension. Lies outside that circle, the surrounding environment, and its elements, hence a physical dimension was added. Finally, the outermost, least-focused circle is the general context of the disease. Additionally, the trainee's interaction with the simulation itself could be a major modifier to enhance simulation authenticity. Rystedt et al. advocated considering this interaction as an indication of simulation fidelity; hence, we included an interactional dimension[14]

AIM

The aim of this thematic review is to identify fidelity themes according to a multidimensional framework expanded from Kneebone et al. and Rystedt et al. work and generate subthemes that determine the level of realism (low, intermediate, and high) for each theme within cardiac surgical simulation. The research questions were as follows: (1) What are the fidelity themes in cardiac surgical simulation according to predefined fidelity dimensions? (2) What subthemes determine their level of realism?

METHODS

Study design and search strategy

A literature review was conducted using MEDLINE (January 2000 to February 2020) and EMBASE (January 2000 to February 2020). Medical Subject Heading (MeSH) terms and keywords are identified using Population, Interest and Context (PICo) framework for qualitative research. The search strategy was formulated using population (cardiac surgery trainees), interest (surgical simulation) and context (training), (see Table in the appendix). The search covered simulation publication in English language and a search was conducted on retrieved studies for cited references. Duplicates were removed using MEDLINE and EMBASE database advanced tools.

Screening

Our initial search identified 880 sources of evidence, after removing duplicates, 425 articles abstracts were retrieved. Screening of titles and abstracts yielded 99 articles for full-text analysis. Of these, 76 articles did not match the inclusion/exclusion criteria. Subsequently, 23 articles were included, and three further were added from references search for a total of 26. A PRISMA flowchart depicts screening and assessment process, see Figure 1.

The full-text review of 99 articles determined eligibility according to predetermined criteria which included 1) simulation-based training with a defined outcome 2) involving cardiovascular training 3) trainees include residents, fellows or attendings 4) including cardiac surgical procedures 5) all simulator modalities 6) including a description of simulation design. Articles offering a technical description of simulation technology were excluded.

Analysis

A thematic analysis was conducted to identify themes and subthemes based on a hybrid approach with deductive and inductive coding. One author (M.A.) examined the articles' text, photographs, and video-based data. This process was accomplished by following established steps; familiarization by reading and viewing data from articles, generating initial codes manually using an iterative process. After that, identification of themes and subthemes, reviewing the initial results with authors (K.L., J.H., H.M, and M.M.), and creating a thematic map. After final analysis by authors (M.A., K.L. and J.H), themes were organized, renamed, and defined to generate a final report.

The coding process included an initial deductive coding where three overarching dimensions (physical, surgical field and interactional dimension) were examined within the data. This resulted in identifying initial codes manually and inductive coding followed by consolidating the extracted codes into thirteen initial themes and extensive search for subthemes. The retrieved subthemes were aimed to find patterns of gradual simulation realism within the data. The review process involved analyzing and testing the final themes and subthemes.

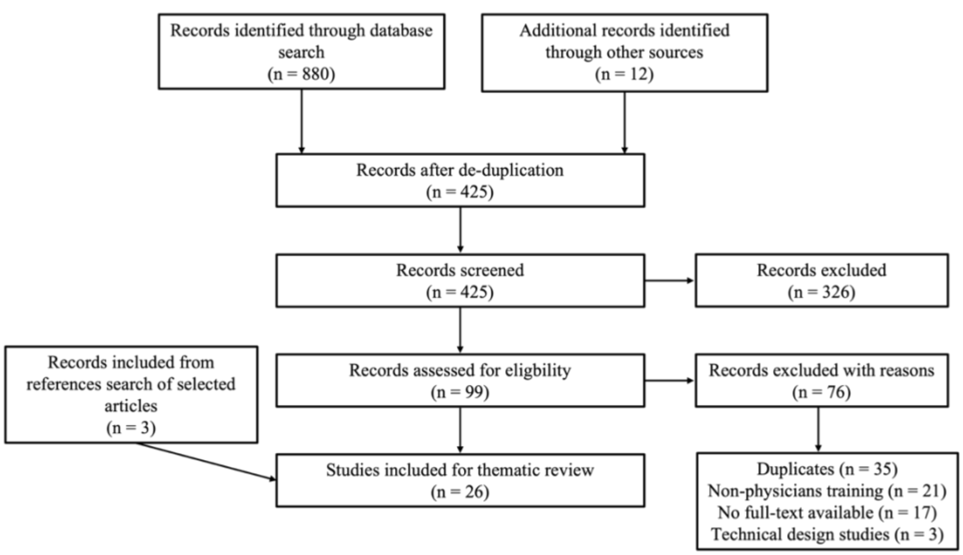

Figure 1. PRISMA flowchart of screening and assessment process.

RESULTS

Studies characteristics

Of the final included studies, publication years spanned from 2008 to 2020. The studies were conducted in the United States (n=14), Canada (n=4), China (n=2), Turkey (n=2) and others (n=4), see Figure 2. Publications were empirical articles, with comparative studies being the prevalent (single group, pre-post test (n=9), single group, post-test (n=5), randomized controlled trials (n=4), observational studies (n=4), and others (n=4)). Table 1 summarizes other descriptive characteristics such as simulators utilized, simulator modality, targeted competencies or skills, and outcomes.

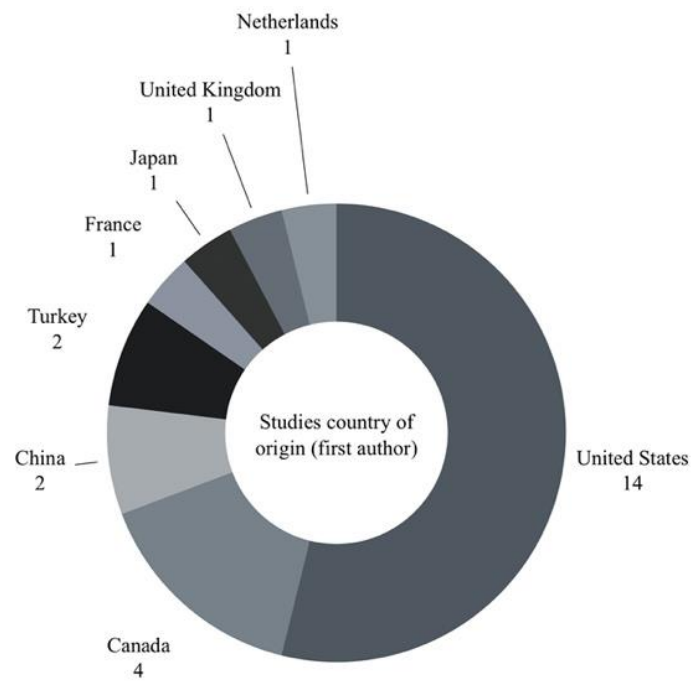

Figure 2. Included studies and country of origin for the first author.

The cardiac surgical competencies targeted included coronary artery bypass grafting competencies (n=8), aortic and venous cannulation and cardiopulmonary bypass or extracorporeal membrane oxygenation management (n=6), aortic or mitral valve procedures (n=4), multiple cardiac surgical procedures (n=3), heart transplant and left ventricular assist device insertion (n=2), congenital procedures (n=2) and aortic anastomosis (n=1), see Figure 3.

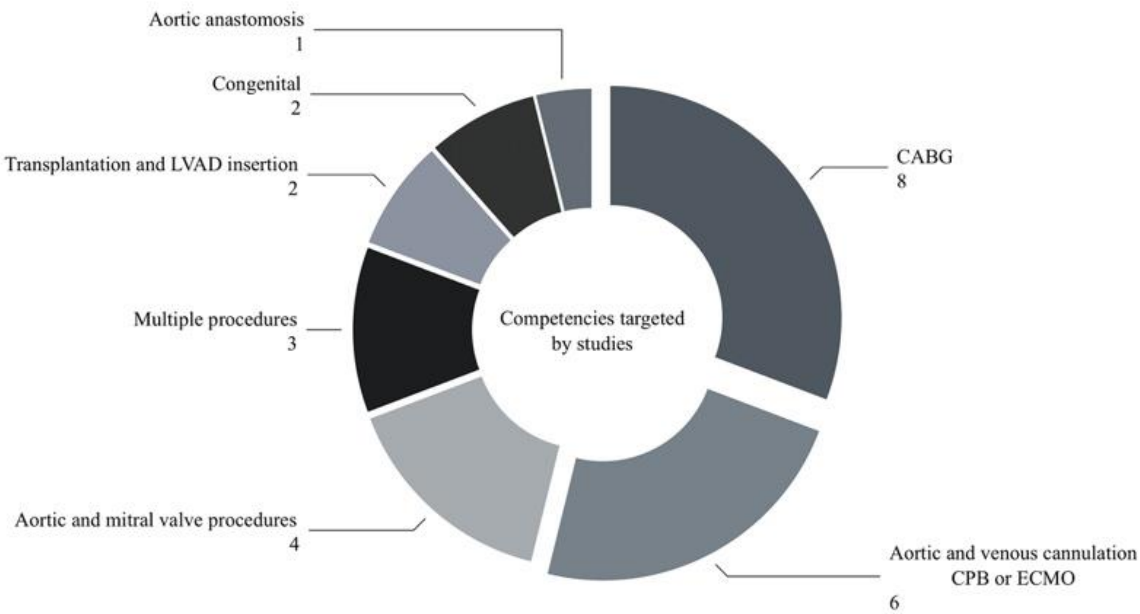

Figure 3. Surgical competencies or skills simulated in included articles.

Table 1: Characteristics of included studies.

#	Author	Year / Country	Publication type	Simulator(s)	Simulation modality	Surgical competency / Skill	Outcomes
1	Allan et al.[15]	2013 USA	Single group Pre-post test	ECMO skills trainer (vessel cannulation trainer with infant mannequin)	Integrated bench-top models in a simulated reality (resuscitation in intensive care unit)	Perform jugular and carotid cannulation and starting ECMO	Performance of ECMO cannulation technical skills and time from decision to actual ECMO run
2	Baker et al.[16]	2012 USA	Single group Mixed methods study	Synthetic vessels procedural trainer (Chamberlain group)	Bench-top	Coronary artery anastomosis	Performance of technical skills and knowledge assessment
				Inanimate aortic and mitral valve models (Chamberlain group)	Bench-top	AVR, MVR	
				Inanimate saphenous vein harvest model (Chamberlain group)	Bench-top	Saphenous vein harvest	
				Tissue cadaver	Simulated operative procedure	Redo sternotomy ITA harvest Aortic valve resuspension Total arch replacement Endoscopic vein harvest LVAD placement Minimally invasive MVR & AVR	
				Ramphal cardiac surgery simulator	High technology, porcine heart, complex simulator	Coronary artery anastomosis AVR, management of small aortic root MVR, atrial fibrillation surgical management MV and TV repair Root replacement, homograft Valve-sparing root replacement Weaning off CPB	

3	Burkhart et al.[17]	2010 USA	Single group Pre-post test	Orpheus simulator (Ulco Technologies, Marrickville, New South Wales, Australia)	High technology, high complexity perfusion simulator	Cardiopulmonary bypass management	Ability to manage CPB and certain emergencies
4	Burkhart et al.[18]	2013 USA	Single group Pre-post test	Extracorporeal membrane oxygenation ECMO circuit Air Man mannequin	Simulated ECMO circuit	Identification and management of ECMO crisis scenarios	Confidence of residents in dealing with crisis scenarios Knowledge and management of ECMO
5	Cristancho et al.[19]	2012 Canada	Observational study	Knot-tying prototype with Penrose drains for suturing	Bench-top	Perform off-pump coronary artery bypass (knot tying, suture of anastomosis)	Performance of technical skills, non-technical skills, and interaction with the team in crisis in advanced levels
				Inanimate plastic heart with a plastic tube for vascular anastomosis	Bench-top	Perform off-pump coronary artery bypass (perform complete distal and proximal coronary anastomosis on still heart)	
				Mechanical model for beating heart surgery with a plastic tube for vascular anastomosis	High-technology complex simulator	Perform off-pump coronary artery bypass (distal anastomosis on beating heart, perform heart enucleation then perform distal anastomosis)	
6	Enter et al.[20]	2015 USA	Single group Pre-post test	Inanimate vessel anastomosis model	Bench-top	Perform end-side coronary anastomosis	Performance of technical skills

7	Fann et al.[21]	2008 USA	Single group Pre-post test	Synthetic vessels station	Bench-top	End-side coronary anastomosis	Practice anastomosis at home
				Chamberlain heart simulator	High technology, beating synthetic heart, complex simulator	End-side coronary anastomosis on beating heart model	Performance of technical skill of anastomoses on beating heart
8	Fann et al.[22]	2010 USA	Single group Pre-post test	Synthetic vessels station	Bench-top	End-side coronary anastomosis	Performance of full end-to-side anastomosis
				Porcine heart	Bench-top	Distal and proximal coronary graft anastomoses	
9	Fouilloux et al.[23]	2015 France	RCT	Animate sheep heart and aorta	Bench-top Pressurized heart and aorta	Practice aortic cannulation	Knowledge, technical, non-technical skills, and critical thinking skills
				Swine, live animals Cardiopulmonary bypass pump	Simulated operative procedure	Practice full CPB run with an operative team	
				Swine, live animals Cardiopulmonary bypass pump	Simulated operative procedure	Practice CPB run with an operative team Management of CPB crisis scenarios	
10	Greenhouse et al.[24]	2013 USA	Single group Post-test only	MVR skill training station	Bench-top	Perform MVR (suture placement, valve placement and knot tying)	Performance of technical aspects of MVR

11	Helder et al.[25]	2016 USA	Single group Post-test only	Animate porcine heart	Bench-top	Perform end-end aortic anastomosis	Performance of technical skills in aortic anastomosis
				Dacron graft	Bench-top	Perform end-end aortic anastomosis	
12	Hermsen et al.[26]	2018 USA	Single group Pre-post test	3D printed heart with real anatomical details	Simulated operative procedure	Perform septal myomectomy after identification of diseased part	Procedural steps and knowledge Technical and non-technical skills and anatomical identification of disease
13	Hicks et al.[27]	2011 USA	Single group Post-test only	Perfused non-beating porcine heart and aorta	Partial-task trainer, benchtop	Arterial and venous cannulation	Performance of technical skills of cannulation Communicating with perfusionist Management of CPB and emergency scenarios
				Orpheus simulator (Ulco Technologies, Marrickville, New South Wales, Australia)	High-technology complex simulator	Management of cardiopulmonary bypass Dealing with bypass crisis scenarios	
				Ramphal cardiac surgery simulator	High technology, beating porcine heart, complex simulator	Arterial and venous cannulation Management of CPB	
14	Ito et al.[28]	2013 Japan	Validation study Single group Post-test only	BEAT, YOUCAN simulator Inanimate synthetic arteries on a moving station	Bench-top, electrically driven	Perform end-side coronary anastomosis on beating heart (platform)	Performance of simulator to practice coronary anastomosis

15	Joyce et al.[29]	2011 USA	Single group Pre-post test	Inanimate mitral valve model (Chamberlain group)	Bench-top	Performing mitral annuloplasty	Open practice to perform annuloplasty
				Porcine heart	Bench-top	Assessment of mitral valve Performing mitral annuloplasty	Technical skill to perform annuloplasty
16	Joyce et al.[30]	2018 USA	Single group Post-test only	Simulated OR including Orpheus simulator, coronary bypass, AVR and mitral repair models and CPB pump	Advanced simulated OR	Coronary artery bypass, AVR, MV repair Cardiopulmonary bypass	Technical skills, knowledge, and management of CPB crisis Communication with perfusionists
17	Liu et al.[31]	2016 China	Observational study	Swine, live animals	Simulated operative procedure	Left internal thoracic harvest and off-pump coronary anastomosis training	Performance of off-pump coronary anastomosis
18	Mavroudis et al.[32]	2018 USA	Observational study	Neonatal piglets' hearts	Simulated operative procedure	Perform various congenital cardiac surgery procedures	Designed to teach congenital procedures to non-congenital cardiac surgery trainees
19	Price et al.[33]	2011 Canada	RCT	Synthetic arteries procedural trainer (Limbs & Things, Savannah, Ga)	Bench-top	End-side coronary anastomosis	Deliberate practice
				Porcine artery, live animal	Simulated operative procedure	End-side coronary anastomosis	Performance and completion of coronary anastomosis on live animal

20	Sardari et al.[34]	2020 Netherlands	Single group Pre-post test	3D printed mitral valve within a simulated torso with computerized monitoring	Simulated procedure Bench-top	Endoscopic mitral valve repair	Performance of technical skills for placing annuloplasty sutures and theoretical knowledge
21	Smelt et al.[35]	2016 UK	RCT	Orpheus simulator (Ulco Technologies, Marrickville, New South Wales, Australia)	High-technology complex simulator	Management of cardiopulmonary bypass Dealing with bypass crisis scenarios	Knowledge and management of CPB crisis scenarios
22	Spooner et al.[36]	2019 Canada	Observational study	Swine, live animals	Simulated operative procedure	Perform cardioectomy and heart transplantation	Designed to teach heart transplantation surgical skills to trainees
23	Tavlasoglu et al.[37]	2015 Turkey	Non-randomized Three groups	Animate bovine heart	Bench-top	Perform distal coronary anastomosis	Performance of technical skills, and anastomosis quality
24	Tavlasoglu et al.[38]	2013 Turkey	Non-randomized Two groups	Animate bovine heart	Simulated procedure Bench-top	Mitral valve repair	Performance of technical skill by measuring procedural success
25	Valdis et al.[39]	2016 Canada	RCT	da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA) with an animate porcine model	Surgical robot with an animal model	Perform ITA harvest and mitral annuloplasty	Performance of technical skills of ITA harvest and mitral annuloplasty

				da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA)	Surgical robot with inanimate models	Camera movement, peg transfer, intracorporeal knot tying	
				da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA)	Surgical robot with virtual reality simulation exercises	Robot simulation exercises (not resembling the primary surgical procedure)	
26	Zhang et al.[40]	2019 China	Single group Post-test only	Swine, live animals	Simulated operative procedure	Implant left ventricular assist device LVAD without cardiopulmonary bypass	Team performance, addressing emergency situations and success rate of the procedure

ECMO = Extracorporeal Membrane Oxygenation; AVR = Aortic Valve Replacement; MVR = Mitral Valve Replacement; TV = Tricuspid valve, LVAD = Left Ventricular Assist Device; RCT = Randomized Controlled Trial; ITA = Internal Thoracic Artery; CPB = Cardiopulmonary Bypass; OR = Operating Room

Thematic analysis

The three predefined overarching fidelity dimensions, physical, surgical field, and interactional dimensions by Kneebone et al. and Rystedt et al., were the starting point of the analysis by the author (M.A.). The deductive coding process was started by reading the articles in search of patterns of meanings that might be coded. Initial codes were noted down manually, and they included features that fit under the predefined dimensions (e.g., physical elements: surgical lights, conversations, alarms, colors, and surgical instruments). This proceeded inductively as looking for themes that aggregate the codes yielding thirteen primary themes (e.g., Sounds and equipment under the physical dimension), (see Initial Thematic Map in appendix). After that, extracting subthemes that generated meanings of gradual increase or reduction in realism (low, intermediate, and high realism) commenced. This was followed by reviewing the themes and subthemes continuously to ensure their consistency across articles. As result, seven themes generated after the redefinition and renaming and subthemes were reviewed again within articles in order to refine and update them (see Figure 4 & Final Thematic Maps in appendix). Finally, two themes were identified and reported for the physical dimension: (1) simulation environment and (2) simulation equipment. Three themes were identified for the surgical field dimension: (3) surgical anatomy, (4) surgical physiology or pathology, and (5) procedural steps. Lastly, two themes for the interactional dimension: (6) perceptual interactions, and (7) psychological interactions. The results of the thematic analysis are presented in Table 2.

Physical dimension themes

S*imulation environment*, almost all the studies (n = 24) described the environment surrounding simulated activities in a variety of ways. The majority reported a detailed description of the physical space in which the activity is performed, also environmental

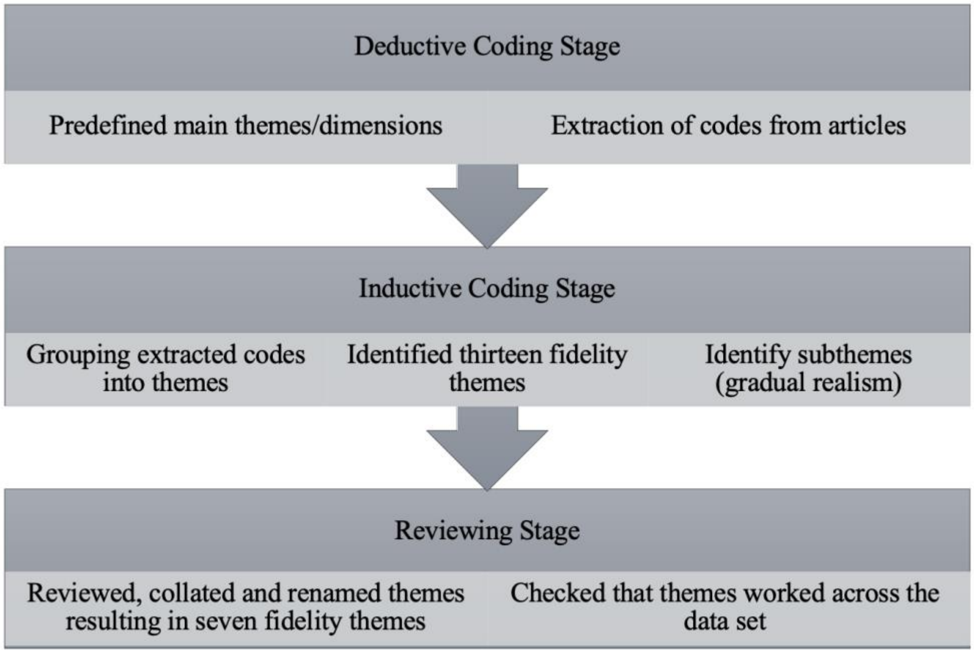

Figure 4. Hybrid thematic analysis stages.

elements like sounds, light, functions, and appearances. In fact, realism was closely related to those elements, for instance, low realism in a physical space would equal practicing at home or a basic simulation laboratory without operating room physical cues.[20,25,33] Advancing levels of realism would provide a greater resemblance to the real surgical zone around the trainee such as a simulated operating room or an actual operating room.[36,40]

S*imulation equipment,* the majority of the studies (n = 23) mentioned equipment used in their simulation exercises. Multiple studies emphasized the use of real surgical instruments to train skills, some studies described the use of specific devices that are crucial to the simulation context (e.g. use of a surgical robot, cardiopulmonary bypass pump, and prosthetic heart valves).[23,24,39] The level of realism was primarily determined by the degree of improvised items, the presence of devices or elements essential to context and most importantly the use of real surgical-grade instruments. Surgical equipment contributes significantly to the authenticity of the experience as it provides a specific surgical simulation theme.

Surgical field dimension themes

Surgical anatomy, all the studies addressed the anatomical features of the surgical field. Meanings were retrieved from descriptive simulation design or from attached photos and videos. Some articles referenced the usage of simulators with a previously published technical description. Such publications were retrieved for verification if needed. In regard to levels of realism of the simulated field, they ranged from lack of accurate anatomical details to absolute realism by using human cadavers.[16,29,33] Furthermore, the use of three-dimensional printing to create synthetic models with accurate pathological anatomy increased the level of realism significantly.[26,34]

Surgical physiology and pathology, each study (n = 26) was successfully mapped for physiological and pathological surgical field functions by extracting multiple codes from text, photos, and videos. The most coded physiological functions were simulating a beating heart to increase realism and inducing pathological reactions during surgical scenarios to add complexity.[21,27,28] Some simulations were created with just one needed physiological or pathological function, resulting in a higher level of realism.[19] Other simulators used complex technology to simulate multiple physiological functions, providing a realistic clinical scenario.[17,30]

S*urgical procedural steps*, all the studies (n = 26) included a description of the procedural tasks that were supposed to be simulated by trainees. Some studies were intended to teach non-technical cardiac surgical scenarios but did not address surgical skills.[18,19,23,35] As a result, trainees were evaluated based on their abilities to perform complete clinical assessments and provide a management plan. For these simulations, the ability to do complete assessments and management steps was considered for the degree of realism. For simulated technical procedures, the ability to perform all the tasks with minimal interruption was deemed high in realism. Incompleteness or frequent interruptions in performing these tasks conferred a lower level of realism. Additionally, following a chronological order was considered as higher realism and vice versa.

Table 2: Results of thematic analysis, main themes, and their levels of realism.

Dimension	Themes	Low realism	Intermediate realism	High realism
Physical dimension	Environmental fidelity	• Basic simulation laboratory • No physical elements of a real ICU or OR • At home practice • Dissection laboratory • No OR or ICU personnel	• Introduction of OR or ICU physical elements (lights, appearances, and sounds) • Introduction of OR or ICU personnel (limited, non-interactive, not in a realistic setting)	• Simulated operating room • Simulated intensive care unit • A fully interactive surgical or intensive care team • A real operating room or intensive care unit
	Equipment fidelity	• No realistic instruments or devices • All equipment is improvised • The surgical elements are not realistic or not appropriate (the suture is a different type, or the prosthetic valve is improvised)	• Presence of some improvised equipment • State when instruments needed for a specific task is real, but the setup is not (real needle holder but retractors are improvised) • Deficiency of an important device that is essential for context (valve seizer)	• Real surgical instruments, gowns, and surgical drapes (specific to the surgical field) • Real surgical devices or/adjuncts (cautery, CPB pump, surgical robot) • Real surgical elements (sutures, drains, gauze, valves, rings etc.)

Surgical field dimension	Anatomical fidelity	• Deficient anatomical details (no accurate and realistic anatomical relationship, shape, or structure) • Synthetic or plastic models (veins, arteries, or hearts) with no accurate anatomical or pathological details • No animate or alive models	• Use of animate model but involving a different anatomical area or field (practice coronary anastomosis on carotid artery) • Presence of anatomical details (including pathological anatomy) on a synthetic model (mitral valve prolapse on silicon model) • Hybrid models (synthetic vein on a swine heart)	• Use of animate models that mimic human anatomy in a proper context • Use of alive animate models • Cadaveric simulation
	Physiological fidelity	• Deficient physiological functions (beating, pressurization, bleeding, or relaxation of muscle) • Deficiency of an important pathological function (leaflet prolapse of a valve) • Static models (no vitality)	• Presence of an important physiological function (singular) that make a single task more complex (beating, bleeding, pressurization) • Presence of a pathological function that allows a single task to be performed (examination of leaflet prolapse of a valve)	• Presence of multiple physiological functions that provide realistic physiology and complexity for a whole procedure • Allow multiple tasks to be performed and interventions to be simulated

				• Ability to introduce pathological functions during simulation
	Procedural fidelity	• Procedural steps cannot be performed fully for a single task • Technical interruption of any performed task • No chronological order • No procedural completion	• Procedural steps can be performed fully with minimal technical interruption (inherent to the simulator design and not trainee ability) • Allow procedural steps to be done but not in chronological order (no accuracy) • A whole procedure cannot be carried out without missing a task (complete arterial and venous cannulation)	• Procedural steps can be performed without interruption and in chronological order • A whole procedure can be completed with almost all required essential tasks
Interactional dimension	Perceptual fidelity	• Physical properties are perceived to be unrealistic (feel, look, tissue feedback)	• Synthetic models with improved perceivable physical properties (improved tactile feedback)	• Physical properties are perceived to be as real (feel, look, tissue feedback)

		• The context doesn't include audiovisual cues or real communication • Physical properties are perceived in 2D dimension (using a robot to suture a virtual valve)	• Physical properties are unrealistic, but an added function provides a perceivable dimension (synthetic artery on beating station) • The context includes minimal audiovisual cues and real communication • Physical properties are perceived in 3D dimension (using a robot to suture 3D artery)	• Audiovisual cues and communications are realistic and accurate • Physical properties are perceived on an animate model in robotic surgery (using a robot to suture an animate heart)
	Psychological fidelity	• Unsupervised free practice or home-based • No added anatomical or physiological elements (complexity) • No immediate feedback or assessment • Unrecorded practice	• Supervision by an inexperienced member (trainee at the same level) • Minimal resemblance of the environment to a real setting (minimal elements of OR or ICU) • Training is video recorded but not for assessment or the trainee is not aware	• The trainee is supervised by an experienced member • Complex anatomical and physiological functions or alive animate model • Immediate feedback or instructions from the instructor

		• No team members were involved in the simulation • No context or interactive clinical scenario	• Training is designed to improve surgical exposure but not for skill acquisition (showcase rare repairs) • Feedback is expected but not immediate • Context doesn't involve real interaction with surgical team	• Training is timed and video recorded for assessment purposes and the trainee is aware • Real and accurate context or scenario (crisis scenario) • Simulated or real OR or ICU • Context involves an interaction with surgical team (non-technical skills)

Interactional dimension themes

The perceptual interactions, all the studies (n = 26) characterized to some extent the perceptual relationship of the trainee with the simulator. The majority of them have shown that employing surgical models with great anatomical details improves perceptual reaction (e.g., animate models or cadaveric tissues), as they provided a realistic appearance, and tissue feedback and reacted to surgical tasks accurately.[16,22,27,29,31,37,38] Alternatively, some studies had created highly interactive surgical scenarios with realistic audiovisual cues that were perceived as authentic by trainees as real.[17] On the other hand, virtual reality training on robots was not regarded to be realistic, however, the use of animate models with the robot markedly boosted realism perceptually.[39]

The psychological interaction, most of the studies (n = 25) were mapped for triggers that result in greater psychological or affective responses as a consequence of interaction with simulation experiences. For example, home practice and surgeon-supervised simulation sessions are very different experiences for any trainee. The combination of video recording and awareness of assessment has placed trainees in a more psychologically demanding situation.[20,24,33,37] Immediate and repetitive feedback from surgeons simulated a real trainee-instructor interaction throughout a procedure.[31,36,40] Multifunctional complex simulators involving team interaction certainly elicited far more realistic affective responses.

DISCUSSION

This literature review and thematic analysis use the notion of multidimensional fidelity to establish seven major themes for cardiac surgical simulation fidelity. The detected themes were developed based on expansive dimensions from Kneebone et al. and Rystedt et al. work. Given our research question was aimed to identify fidelity themes and subthemes, this review successfully met its objectives. Since most of the included studies were published over the past decade, this thematic framework is formulated using recent data in a growing field of surgical simulation. As result, the dimensional fidelity themes established may guide future simulation and instructional design in cardiac surgical simulation-based training and may facilitate uniformity of fidelity meanings.

The analysis generated two themes by expanding the physical dimension which encompasses all major physical triggers outside the surgical field for the surgical trainee. Consequently, we compiled many codes under an environmental fidelity theme which included the location of the simulation exercise and its elements (i.e., home or simulation laboratory without physical elements of actual operating room or personnel to a real simulated operating room with dedicated staff). This theme was closely related to the psychological theme, where interaction with the simulation at a low environmental fidelity setting (e.g., home or residents lounge) resulted in reduced psychological responses and vice versa, see Table 2. Another is the equipment fidelity theme which maps physical tools and instruments (i.e., improvised items and surgical tools and elements to real ones). It is often associated with the perceptual theme, in which improvised items don't provide more perceptual realism. This also held true for anatomical fidelity, where realistic equipment resulted in the simulation being perceived as authentic (e.g., using cautery and retractors on cadaveric tissue). All these intertwined relationships between themes necessitated that, while designing a certain simulation exercise, one may consider how these themes would interact with one another and whether it is necessary.

Under the surgical field dimension, which was developed from Kneebone's innermost circle of focus, three themes that are specific to the surgical site were generated. The anatomical theme corresponded to the correctness and accuracy of anatomical details and relationships. It was evident that the level of realism increased when synthetic materials were replaced with hybrid and animate models. Rich anatomical features are sometimes necessary to replicate a surgical field but might be overlooked when the attention is on a strictly technical task requiring repetitive movements and deliberate practice (e.g., practicing complex suturing techniques and instrument manipulation). A second theme is physiological fidelity, which was mapped from models that replicated a normal or abnormal function, was critical when educators incorporated bleeding, and beating functions or used live animals to simulate a real surgical field. This translated into better authenticity and engagement, as well as produced complexity (e.g., practicing cardiopulmonary bypass on beating animate heart to observe the physiological responses). Lastly, the procedural fidelity theme was dependent on completion, interruption and chronological order for any given task or procedure. It provided an important simulation feature that might have a detrimental effect on learning outcomes if trained tasks were not performed completely or in order. As observed, procedural fidelity depends on the desired objectives (i.e., subthemes related to levels of realism were consistent when it is a simple singular task or a procedure with many tasks). Notably, non-procedural tasks such as situational awareness could not be accounted for since this theme is exclusive to performed surgical acts. Lastly, the three themes interacted with the interactional part when their realism enhanced (e.g., the addition of physiological functions such as bleeding would boost psychological fidelity).

The interactional dimension as proposed by Rystedt et al. generated two themes, a perceptual fidelity theme, in which simulation is perceived by the trainee to be realistic or unrealistic. It was evident that accurate features of synthetic non-animate models gave higher perceptual fidelity and were regarded to be better than models with inaccurate replication. Also essential were audiovisual cues, such as alarms, conversations and grey noise which enhanced realism. This theme is relevant to the surgical simulation since it enhances the authenticity of the surgical sense and physical interaction of the trainee with the model (e.g., inserting a cannula in a pressurized animal aorta has higher perceptual fidelity compared to a plastic tube). Lastly, the psychological fidelity theme featured stimuli that might heighten affective responses from trainees. Certainly, low anatomical, physiological, and environmental fidelity were associated with low complexity and psychological interaction and vice versa. Additional subthemes included supervision by a staff surgeon and instantaneous feedback are genuine stimuli facing trainees in real practice. Likewise, simulating a complicated urgent situation involving interaction with multiple teams would elicit a real psychological response. This theme provided elements that can be manipulated during simulation to raise or reduce psychological fidelity for trainees, hence aiding in the design of exercises suited to the trainee level and task required (e.g., less stressful exercises for novices to enable skill acquisition, followed by increasing the psychological load as they advance). Altogether, the seven surgical fidelity themes are not mutually exclusive since their presence depends on their level of realism for a given design rather than present and absent dichotomy.[41]

Certainly, fidelity is not a well-established concept, and the published surgical education literature doesn't define it consistently.[10] In fact, cardiothoracic educators have urged for robust educational research since there is a paucity of high-quality research.[42] By mapping meanings of surgical fidelity beyond prior definitions and further extending previous simulation educators' work, this analysis can provide educators with universal definitions and standard operational frameworks.[5,13,14,43] This effort has the potential to bring consistency to the field with the indirect goal of improving simulation research through the use of uniform terminology and themes. Depending on their top-priority surgical fidelity themes and level of realism, educators may compare various simulations and their outcomes better. Additionally, the cost-benefit of healthcare simulation is understandably a limiting issue, with no clear evidence of a return on investment.[44] In fact, there is no strong evidence to back up the use of expensive, high-fidelity simulation for strong and tangible outcomes.[11] Alternatively, utilizing the framework of dimensional fidelity, augmentation of low-fidelity and affordable simulation may be a valid solution. As an illustration, adding pertinent perceptual fidelity elements (e.g., adding a synthetic tissue with actual feedback to a simple coronary anastomosis trainer or using a progressive anatomical fidelity to teach skill on a synthetic valve model before finetuning it on an animate heart) may enhance authenticity.

It is impossible to overlook the fundamental change in surgical education toward competency-based instruction and assessment.[2] In real practice, trainees must develop certain competencies that they would not have encountered throughout their training and may need simulation to fill in gaps. To do this, simulation instructional design and desirable outcomes, or in other words, competencies, must be in alignment. We propose that dimensional fidelity may flexibly help modify various simulation designs in order to target specific competencies more effectively. For example, a competency that requires pure technical skills can be exercised using a simulation design that prioritizes equipment and procedural fidelity while keeping cost efficiency. This implies that rather than seeking simulation that resembles the aviation industry in healthcare, surgical instructors should strive for fit-for-purpose design.[45] This is due to the fact that surgical simulation is unique to its discipline with many unpredictable clinical scenarios and different technical approaches. When compared to aviation, surgical simulation design must be adaptable to train various surgical skills and procedures within limited time and resources. However, this simplistic approach to fidelity shouldn't persuade educators to depend on it only to enhance simulation. In fact, fidelity is only one facet in the overall simulation mosaic. A recent systematic review, for instance, identified features that promote fidelity and authenticity in simulation-based education. They included featuring real-life content, feedback, performance expectations, logical scenarios, cueing and other elements.[46] Finally, the findings of this research, which support calls not to abandon fidelity as a simulation principle, further broaden understanding of dimensional fidelity from previous descriptions. They also support skill training via cost-efficient design by offering an operational fidelity framework in the era of competency-based cardiac surgical education.

LIMITATIONS

This literature review utilized deductive and inductive thematic analysis which provided a flexible and reliable methodology to extract meanings from a large body of data and highlight the similarities and subtleties of fidelity. This strategy fairly increased the overall mapping of the diverse literature and generated new findings but not without limitations. First, the exclusion of non-English language studies overlooked some cardiac surgical simulation studies. This decision was due to the linguistic limitation of the research team. Additionally, a quality appraisal was not performed since included articles had high heterogeneity of methodology and varying reporting of simulation design. Since our aim is limited to mapping the existing literature for fidelity themes, we decided not to exclude any study after the application of inclusion and exclusion criteria which helped capturing broader meanings. One author completed the thematic analysis since it needed the experience of surgical training and simulation and was overseen by the senior authors. Although one-author analysis is typical in qualitative research, the COVID-19 pandemic constraints also precluded the involvement of other authors. Finally, theme extraction was dependent on the quality of reporting of simulation design, conduct and results which varied across articles.

CONCLUSION

A multidimensional framework was used to thematically map fidelity in cardiac surgery simulation. The analysis generated seven fidelity dimensional themes and various subthemes reflecting their levels of realism. The identified themes may inform cost-effective cardiac surgical simulation design within competency-based education.

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Chapter 4: Discussion

The thematic literature review has provided an operational framework to effectively utilize fidelity dimensions in designing surgical simulations. By mapping cardiac surgical simulation literature qualitatively, we were able to generate themes and subthemes for fidelity. As we will discuss later, the generated themes and subthemes will be employed for an instructional design that pairs various surgical competencies, surgical educational theory, and defined outcomes. This would form an adaptive model for surgical simulation in which exercises are tailored to the trainee's level, experience, skills, and gaps in competencies. It would be primarily proposed for all cardiac surgery trainees in competency-based training programs. Since our thematic analysis objectives were met, the following discussion will illustrate the structure of the competency-based model to design cost-effective simulations and facilitate the development of simulation curricula.

To better demonstrate the fidelity-based instructional design, we will showcase its integration into simulation planning and curricular development. The modified Kern model outlines seven steps for simulation-based curriculum development. They are problem identification, general and targeted needs assessment, goals and objectives, educational strategies, individual feedback, program evaluation and implementation.[43] Our proposed model involves setting goals and utilizing educational strategies. For example, the educator would identify surgical competencies, outline deconstructed tasks (or milestones), and accurately define outcomes. After that, they align the educational content with the fidelity themes that best fulfill a specified learning goal with a simulation exercise (see Figure 5). In addition, the educator chooses the levels of realism based on a priority list of these fidelity themes. The decision to choose the degree of realism would depend on multiple factors like trainee level, the nature of the competency or task and simulation resources and personnel. This fidelity framework novelty relies on its thematic nature which provides flexibility and versatility to adapt to various needs. In fact, we cited an article in which a similar approach was used to design a simulation program. Cristancho et al. created a progressive simulation to train on off-pump coronary artery bypass (OPCAB) based on the training level and objectives.[44] Therefore, based on the evolution of the competencies, they successfully enhanced the level of realism gradually. Starting with skill training simulation (e.g., a station for handling a Castroviejo forceps and suturing a synthetic drain), then they added more realism to the procedural simulation to perform a specific task (e.g., performed a proximal and distal coronary anastomosis on a still plastic heart), followed by even higher realism simulation when trainees were expected to perform a whole procedure (e.g., performed procedural steps of coronary anastomosis on a complex beating heart simulator). In their program, simulation fidelity was operationalized brilliantly to adapt to competency and outcome without adding unnecessary realism. To clarify, the first station prioritized higher realism to equipment and lower perceptual fidelity (synthetic drain), which was goal-appropriate, cost-effective, and easily reproducible. In the second simulation, they introduced higher realism in anatomical fidelity (plastic heart) and increased procedural fidelity to perform a single task (coronary anastomosis), which was fit for competency. Finally, the last simulation introduced higher physiological (beating), environmental (simulated operating room), procedural (full complex procedure) and psychological fidelity (observed by staff surgeon and recorded the session) to train a high-risk procedure. However, there was no clear definition or discussion of fidelity in their article, which stresses the need to have a uniform and clear fidelity lexicon.

In competency-based surgical training, milestones indicate surgical skill development, including the ability to perform a task or performing a whole procedure (an operation).

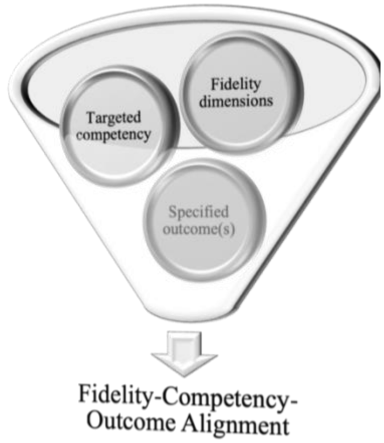

Figure 5: Competency-Fidelity-Outcome alignment concept.

Predefined entrustable professional activities (EPAs) are a way of reporting the fulfillment of milestones and documenting competencies have been attained. When integrating EPAs in simulation-based training, the surgical educator can start with the milestones to delineate the surgical tasks necessary for a specific competency. For example, to perform axillary artery cannulation (competency), the trainee would be required to identify steps and carry them adequately (milestones). Listed tasks include identification of surgical indication, describing correct anatomy, dissecting tissues and control the artery and performing arteriotomy and sew graft (tasks). This competency can be trained by utilizing dimensional fidelity framework and varying degrees of realism. Surely, not all procedural tasks can be performed on a simulation that has low level of realism (e.g., utilizing a manikin for anatomical teaching and a synthetic graft for anastomosis). However, almost all procedural tasks can be performed on simulations with higher realism (e.g., an animal or a cadaver). To add more authenticity, a simulation can be performed in a simulated operating room with nursing personnel to provide more interaction for non-technical tasks (e.g., communication with the team). To recap, trainee experience, resources and learning outcomes all influence the choice of fidelity dimensions and their level. To represent this visually, a graphic model of dimensional fidelity can demonstrate the themes and their levels for a certain competency, see Figure 6. Using radar charts for given milestones, educators can be guided as to which fidelity theme is of priority and given a rough estimate of the total fidelity required.

Figure 6: Radar chart for dimensional fidelity models for surgical competency. [The right chart demonstrates fidelity required for only skill training (e.g., vascular suturing and knot tying). The middle chart introduces added anatomical and perceptual fidelity to perform a full task (e.g., performing a valve replacement on an animate heart in a simulation laboratory). The left chart demonstrates more fidelity themes to perform a full task in a complex setting (e.g., perform internal mammary harvest on a cadaver in a simulated operating room with required equipment and personnel).]

Educational theories employment within simulation instructional design may facilitate learning as we discussed earlier in Chapter 1. This makes it easier for educators to offer trainees simulations according to their experience (novice, advanced beginner etc.), skills, and desired outcomes (theoretical knowledge, skill acquisition, non-technical skill training). To illustrate, when designing a simulation for trainees who have mastered a basic skill (taking valve sutures) or knowledge (anatomical relationships of the aortic valve) educators may decide to keep an active zone of proximal development as described by Vygotsky et al.[30] This zone would keep the trainee at the edge of their skill and knowledge and give them optimal chance to learn and progress (e.g., introduce more procedural fidelity and add anatomical fidelity by using an animate heart to advance their basic skill and knowledge). According to the same theory, learning should be guided by educators and sometimes delivered within a social learning experience (e.g., engaging their co-trainees socially by role-playing). The educator may utilize dimensional fidelity to plan environmental or psychological elements to enhance the social zone, for example performing valve replacement in an operating room including personnel with a surgeon as a surgical assistant. The framework also can introduce some elements such as the disease context, the presentation of imaging, and the subtleties of the operative setting to induce social interactions. A related concept, the scaffolding approach would involve simulations for senior trainees who are moving to a stage of unsupervised learning.[31] To illustrate it, a trainee who masters advanced surgical skills can be placed in a complex simulation without cues or guidance from supervisors. This would create an experience without scaffolds in which the trainee would utilize higher cognitive functions to guide themselves with minimal supervisor input. Certainly, fidelity dimensions provide a wide range of thematic options that enable designing such exercises. For example, managing a pathological animate mitral valve after mastering valve examination and repair techniques on a synthetic model without supervision. These examples are based on the association of educational theory and dimensional fidelity in simulation design which expands the notion of surgical fidelity further for better learning.

Human skill acquisition research has evolved greatly in recent years and its models have been utilized in cardiovascular surgical education and training specifically as described by Yokohama et al.[45] They utilized a variety of cardiovascular simulators combined with skill acquisition theories to build a simulation-based training program. The program brought adjustments to surgical simulation design to improve skill training via deliberate practice. This meant that simulations like valve replacements are modified so that learners may repetitively practice suture placement and valve placement to acquire dexterity. Here, the fidelity framework is utilized to minimize realism and create reproducible valve models for focused practice. In fact, evidence for deliberate practice in professionals' training, which outlines strategies to utilize simulation to hone technical skills, supports this.[38] This would entail designing simulation training for focused, goal-specific, and repetitive skill training. For instance, placing mitral valve sutures using minimally invasive techniques on a bench-top mannikin model with a synthetic valve is reproducible and cost-effective (low environmental, anatomical, and physiological fidelity). On the other hand, the Fitts-Posner model for motor skills contends that novice learners are at a stage where they understand tasks, demonstrate destructed and primitive skills and rely on supervision and guidance.[34] It is also true, when applying cognitive load theory, that novices' learning is hampered and sometimes diminished due to higher cognitive load.[36] Indeed, a simulation with complex functions or excessive perceptual triggers would distract them from learning key skills. For example, training a novice to manage a needle holder and needle angles for valve sutures can be achieved using a benchtop improvised suturing box rather an animate beating heart in a simulated operating room (low environmental, equipment, anatomical, physiological, and psychological fidelity). In both previous examples, dimensional fidelity can offer an approach to create objective-oriented simulation by removing unnecessary distracting realism for a novice or modifying a simulation for an expert to engage in deliberate practice.

Finally, by utilizing fidelity themes and subthemes, the competency-based simulation model associates competency-based cardiac surgical milestones with simulation design. With a greater emphasis on operational dimensional fidelity rather than on an abstract description of its meanings; this would allow additional modification as simulation technologies continue to advance and as educators push the boundaries of competency-based surgical education.

Chapter 5: Conclusion and Future Directions

The work presented in this thesis is an attempt to define and characterize fidelity with a focus on clarifying its functions and themes and measuring its levels in cardiac surgical simulations. The effort was aimed to operationalize fidelity by utilizing a dimensional typology originating from the clinical field and the simulation literature. Furthermore, we described using the framework jointly with educational theory and contemporary skill acquisition models aiming for effective application in competency-based curricula. However, the educational impact of this model is yet to be investigated and established in a simulation program since it was not part of the aims of this master's project. As with other suggested model, it's essential that this model is tested and validated in future research before further application. In reality, as the COVID-19 pandemic has negatively impacted cardiac and cardiothoracic training across the globe, surgical simulation became increasingly crucial.[46,47] This obviously meant putting a greater emphasis on simulation training as a means of mitigating these effects, which calls for more extensive and higher-quality simulation research.

This proposed model was developed for cardiac surgical training since the primary researcher and one of the supervisors are members of the discipline. Although publications of cardiac surgical simulation were used to construct this framework, it is feasible to implement this model in other surgical disciplines. This is made possible because the dimensional concepts used in this work are generalizable to all surgical disciplines. Additionally, the utilized competence by design model is the main educational approach for surgical residency programs in Canada. This is also true for educational and skill acquisition models which are not specific to one domain and can be generalizable. Lastly, the fidelity model was expanded from dimensions from the operating room that is universal across various surgical fields. In the same way, thematic analysis can map any surgical publications for meanings which can be further developed, validated, and advanced. Similar work would certainly bring more understanding of surgical fidelity and may guide future research in non-surgical domains.

There are high hopes and expectations for the future of surgical education thanks to the advent of modern surgical simulation. Just as surgeons-educators are constantly developing innovative solutions to train the next generation of surgeons, so too advances in surgical simulation are ensuring the provision of safe and high-quality surgical training. This thesis makes a small-scale, but hopefully meaningful contribution to surgical simulation research aiming to drive its evolution forward.

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Appendix

1 Supplementary to the thesis

Examples of cardiac surgery EPAs as published by RCPSC

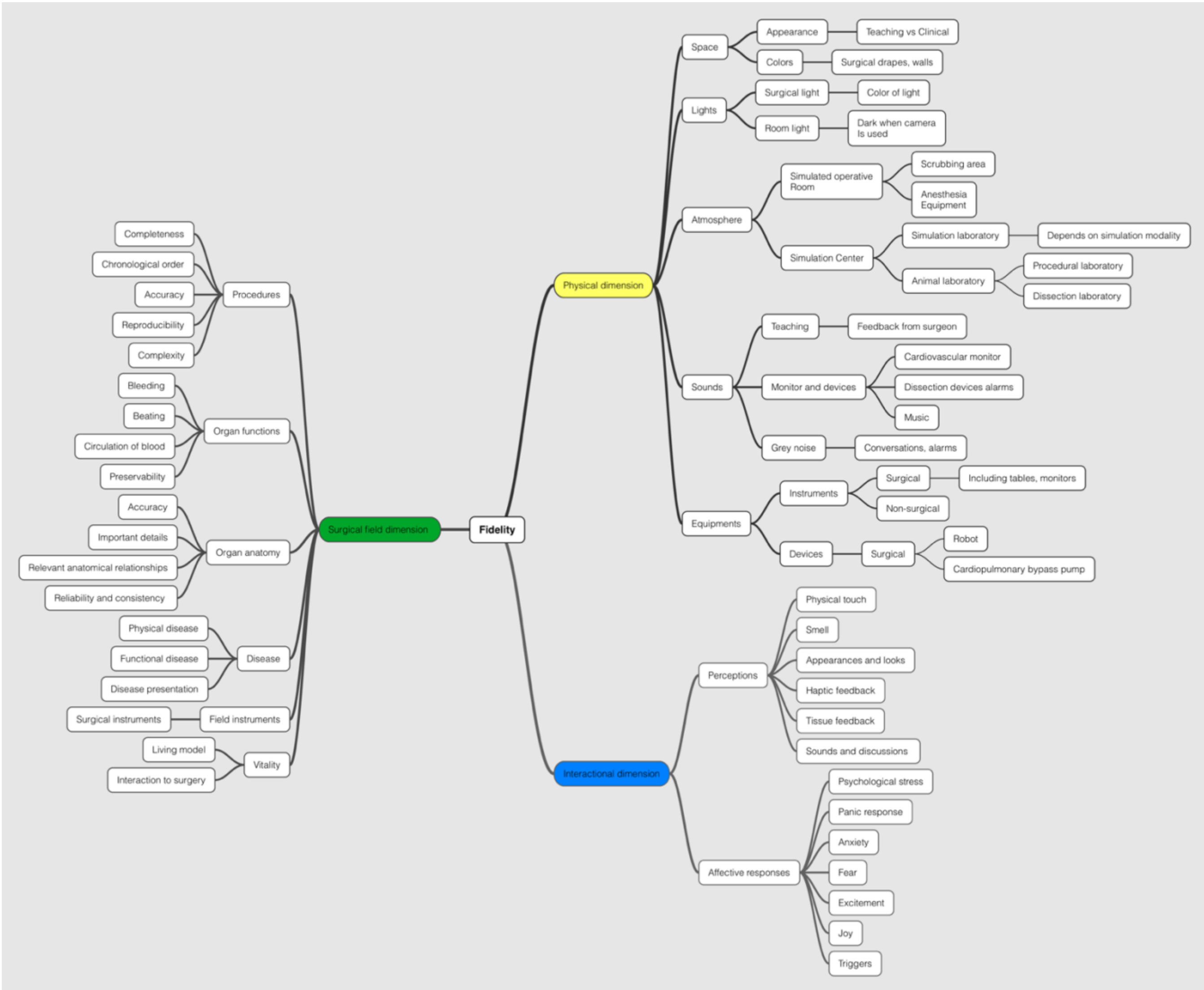
https://www.royalcollege.ca/rcsite/documents/cbd/epa-guide-cardiac-surgery-v2-e.pdf

2 Supplementary to the literature review

Table: MEDLINE and EMBASE search strategy

- **Ovid MEDLINE** - 1 (simulation* or simulator*).ti,ab. AND (learn* or train* or skill* or educat* or transfer or performance).ti,ab. AND ((Cardiac or Cardio* or heart) adj2 (surg*)).ti,ab. - 2 exp Simulation Training/ AND exp Cardiac Surgical Procedures/ - 3 exp Education, Medical, Graduate/ AND exp Cardiac Surgical Procedures/ AND (simulation* or simulator*).ti,ab. AND (learn* or skill* or train* or educat* or transfer or performance).ti,ab.
- **EMBASE** - 1 (simulation* or simulator*).ti,ab. AND (learn* or train* or skill* or educat* or transfer or performance).ti,ab. AND ((Cardiac or Cardio* or heart) adj2 (surg*)).ti,ab. - 2 exp simulation training/ AND exp heart surgery/ - 3 exp Education, Medical, Graduate/ AND exp Heart Surgery/ AND (simulation* or simulator*).ti,ab. AND (learn* or skill* or train* or educat* or transfer or performance).ti,ab.

Thematic maps: 1- Initial thematic map showing three dimensions with 13 themes and various subthemes after initial search and coding before reviewing and naming final themes/subthemes.



2- Final thematic map showing three dimensions with 8 coded final themes and refined subthemes after reviewing and naming them.