Fundamental Competencies for Transcatheter Cardiac Surgery: Developing a paradigm for the acquisition of transcatheter skills by cardiac surgery residents

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Abstract

Introduction: Transcatheter procedures are increasingly being recognized as a priority for cardiac surgeons and cardiac surgery trainees. Though they have generated increasing interest in trainees and training programs alike, there are significant barriers to their integration. Importantly, the optimal method of teaching these procedures during cardiac surgery residency training has not been established. We sought to develop an evidence-based approach to systematically review the literature, identify competencies and confirm their relevance to cardiac surgery residents. This research is intended to inform future paradigms of transcatheter training in cardiac surgery.

Methods: A scoping review was first conducted to retrieve relevant literature on the performance of transcatheter cardiovascular procedures, identify competencies required by surgical residents learning to perform these procedures and develop a preliminary list of competencies for consideration during transcatheter training. MEDLINE, Scopus and ERIC were searched until April 1, 2020 using a systematic search strategy. No limitations were placed on publication date or type.

The results of the scoping review were then further explored during a Delphi study. Individuals with expertise in transcatheter structural heart and aortic procedures were recruited from across Canada to participate. A questionnaire was prepared using a 5-point Likert scale. During two rounds participants rated the competencies that they felt cardiac surgery residents should be required to achieve to perform transcatheter procedures. Data was analyzed and presented to participants between rounds. Competencies rated 4 or higher by at least 80% of respondents after the second round were considered fundamental to transcatheter cardiac surgical training.

Results: A total of 1456 sources of evidence were retrieved during the scoping review. After deduplication and screening there remained 33 that were included, published between 2006 and 2020. The distribution of publication types included 10 comparative studies (30.3% of total), 8 societal statements (24.2% of total), 5 surveys and 5 opinion articles (each 15.2% of total), 2 editorials and 2 descriptions of a simulator (each 6.1% of total) and one narrative review (3.0% of total). From these a total of 400 items were identified and organized into 97 competencies that were further investigated in the Delphi study.

A total of 46 individuals participated in the Delphi study, including 23 cardiac surgeons, 17 interventional cardiologists and 6 vascular surgeons. Participants with relevant experience performed a median of 75 (interquartile range 40 – 100) transcatheter aortic valve implantations in the prior year as primary or secondary operator and 15 (interquartile range 11 – 35) thoracic endovascular aortic repairs in the prior two years as primary operator. Median clinical and teaching experience consisted of 13 (interquartile range 7 – 19.5) years in practice and 8.5 (interquartile range 5- 15) residents taught per year, respectively. Of the included competencies, 53 were considered fundamental to transcatheter cardiac surgical training.

Conclusions: An evidence-based approach was successfully used to identify specific learning goals and objectives for transcatheter procedures during cardiac surgery residency training. The identified fundamental competencies can be used to develop educational strategies during transcatheter cardiac surgery training. Once processes are in place for curricular implementation and evaluation, this work will form the basis for a new transcatheter training paradigm.

Résumé

Introduction: Les procédures transcathéter sont reconnues comme une technique prioritiare pour les chirurgiens cardiaques et stagiaires en chirurgie cardiaque. Bien qu'ils aient généré de plus en plus l'intérêt pour les stagiaires et les programmes de formation, il existe des obstacles importants à l'intégration de cette nouvelle approche. La méthode optimale d'enseignement de ces procédures pendant les la formation en résidence en chirurgie n'a pas été établie. Nous avons cherché à développer un approche pour examiner systématiquement la littérature, identifier les compétences et confirmer leur pertinence pour les résidents en chirurgie cardiaque. Cette recherche est destinée à informer les futurs modalités de formation en chirurgie cardiaque portant sur les techniques transcathéter.

Méthodes: Une revue de la portée a d'abord été menée pour récupérer la littérature pertinente sur l'exécution des procédures cardiovasculaires transcathéter, identifier les compétences requises par les résidents en chirurgie apprenant à effectuer ces procédures et à dresser une liste préliminaire de compétences à prendre en compte lors de la formation transcathéter. MEDLINE, Scopus et ERIC a été fouillé jusqu'au 1er avril 2020 à l'aide d'une stratégie de recherche systématique. Aucune limitation ont été placés sur la date ou le type de publication. Les résultats de l'examen de cadrage ont ensuite été explorés plus en détail au cours d'une étude Delphi. Les personnes ayant une expertise dans les procédures cardiaques et aortiques structurelles transcathéter ont été recruté au Canada pour y participer. Un questionnaire a été préparé en utilisant un 5 échelle de Likert. Au cours de deux rondes, les participants ont évalué les compétences qu'ils

ressentaient les résidents en chirurgie cardiaque devraient être tenus de réaliser un transcathéter procédures. Les données ont été analysées et présentées aux participants entre les cycles. Compétences notées 4 ou plus par au moins 80% des répondants après le deuxième tour étaient considérés comme fondamentaux pour la formation en chirurgie cardiaque transcathéter.

<u>Résultats</u>: Au total, 1456 sources de preuves ont été extraites au cours de l'examen de la portée. Après déduplication et dépistage, il y 33 qui ont été inclus, publiés entre 2006 et 2020. La distribution des types de publications comprenait 10 études (30,3% du total), 8 déclarations sociétales (24,2% du total), 5 sondages et 5 opinions (chacun 15,2% du total), 2 éditoriaux et 2 descriptions d'un simulateur (chacun 6,1% total) et une revue narrative (3,0% du total). De ceux-ci, un total de 400 articles ont été identifiées et organisées en 97 compétences qui ont été approfondies dans l' étude de type Delphi. Au total, 46 personnes ont participé à l'étude Delphi, dont 23 cardiaques chirurgiens, 17 cardiologues interventionnels et 6 chirurgiens vasculaires. Les Participants avec expérience pertinente ont effectué une médiane de 75 (intervalle interquartile 40-100) implantations de valve aortique l'année précédente en tant qu'opérateur principal ou secondaire et 15 (intervalle interquartile 11 - 35) réparations aortiques endovasculaires thoraciques au cours des deux années précédentes. L'expérience clinique et pédagogique médiane était de 13 (interquartile intervalle 7 - 19,5) ans de pratique et forme en moyenne 8,5 (intervalle interquartile 5 à 15) résidents par année, respectivement. Parmi les compétences incluses, 53 ont été retenues comme essentiel pour une formation transcathéter.

Conclusions: Une approche factuelle a été utilisée avec succès pour identifier des buts et objectifs d'apprentissage pour les procédures transcathéter pendant la chirurgie cardiaque formation en résidence. Les compétences fondamentales identifiées peuvent être utilisées pour développer stratégies pédagogiques lors de la formation en chirurgie cardiaque transcathéter. Une fois les processus entrés lieu de mise en œuvre et d'évaluation du curriculum, ce travail constituera la base d'un nouveau paradigme d'entraînement transcathéter.

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Author contributions

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- Conceptual design of this thesis and all manuscripts contained herein
- Data collection and interpretation of all manuscripts contained herein
- Preparation of this thesis and all manuscripts contained herein

Ms Meagane Maurice-Ventouris and Dr Mohammed Alharbi:

- Support with conceptual design, data interpretation, editing and approval of all manuscripts contained herein

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- Statistical analysis, data interpretation, editing and approval of the Delphi study contained herein

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 all manuscripts contained herein
- Editing and approval of this thesis and all manuscripts contained herein

Chapter 1: Introduction

Cardiac surgery is a relatively young surgical specialty, the early repair of cardiac lesions being limited by the challenges of maintaining peripheral perfusion and tissue oxygenation while operating on the heart. The development of cardiopulmonary bypass during the 1950s, however, addressed these barriers and allowed the specialty to flourish.[1] The treatment of structural heart disease evolved to include direct surgical repair, such as the excision of stenotic aortic valves and replacement with prostheses in the case of surgical aortic valve replacement (SAVR).[1] Similarly, the treatment of coronary artery disease advanced greatly with the discovery of selective coronary angiography in 1962, eventually culminating in direct aortocoronary bypass.[1]

For many years open surgery was considered the standard of practice for treatment of severe cardiac diseases—however, while advances were being made in the operating room, so too were alternative procedures being developed in the cardiac catheterization laboratory. Selective coronary angiography—initially a diagnostic tool with which to plan surgical approaches—eventually progressed to include arterial catheterization and stent implantation in the form of percutaneous coronary intervention (PCI), a treatment that is now commonplace for ischemic heart disease.[2–4] An especially disruptive technology has been transcatheter aortic valve implantation (TAVI), which was introduced as an alternative to SAVR for the treatment of aortic stenosis in 2002.[5] The distinction between the operating room, where cardiac surgeons have performed open surgery for more than a half-century, and the cardiac catheterization laboratory, where interventional cardiologists developed transcatheter alternatives such as PCI and TAVI, has meant that the uptake of transcatheter procedures among cardiac surgeons has been lacking.[6–10]

As part of a commitment to maintaining a high-quality prospective data set of TAVI patients, the Society of Thoracic Surgeons (STS) and American College of Cardiology (ACC) have maintained a registry on all patients undergoing TAVI in the United States since the first TAVI device was approved by the Food and Drug Administration in 2011.[11] Since then a total of 276,316 patients have been included in the STS-ACC registry from sites in all 50 United States and in Puerto Rico.[11] Over the same time period the number of TAVIs performed yearly has increased dramatically, from 4,666 TAVRs performed at 198 centres in 2012 to 72,991 TAVIs performed at 669 centres in 2019.[11] In fact—with the exception of the first year of the registry during which TAVI volumes nearly doubled from 4,666 to 8,946 cases–there has yet to be a year that TAVI volumes have not increased by at least 8,000 and as much as 13,000 cases.[11]

Interestingly, and despite the surge of patients with aortic stenosis now being treated by transcatheter approaches, open surgical volumes have remained stable until relatively recently. This is likely the result of more patients with aortic stenosis being referred for any form of intervention, including those who were previously and incorrectly assumed to be non-surgical candidates. Nonetheless, the effect of growing TAVI volumes on the number of open surgical procedures performed is becoming evident. For example, in the year 2019 there were 20,971 isolated SAVRs performed in the United States compared to 30,432 in 2015 (the year that TAVI volume first surpassed isolated SAVR volume).[11] Similarly while TAVR volume surpassed all forms of SAVR in 2018, SAVR volume decreased from 64,705 in 2018 to 57,626 in 2019, which is the lowest that has ever been recorded in the registry.[11] With evidence from randomized clinical trials now suggesting that TAVI may be non-inferior to SAVR in certain low-risk patients,[12–14] it is likely that TAVI volumes will continue to increase while SAVR volumes continue to decline.

In addition to the treatment of structural heart disease, transcatheter approaches have become increasingly popular as a method for treating thoracic aortic disease. Rather than excise the segment of disease aorta and replace it with a woven graft (as in the open surgical approach), thoracic endovascular aortic repair (TEVAR) aims to exclude or otherwise stabilize diseased aortic segments by the implantation of expandable stents in the aortic lumen. This treatment is analogous to the stenting of coronary arteries during PCI. Although the growth of TEVAR has not been nearly as meteoric as that of TAVI, it is increasingly viewed as acceptable and even preferable to traditional open surgery,[15–18] perhaps due to the morbidity associated with open surgery. As catheter-based technologies evolve, offering less invasive treatment options to more patients with outcomes that are comparable to open surgery, cardiac surgeons will be required to adapt their practices in order to continue meeting the needs of their patients.

The evidence in favour of transcatheter treatments for structural heart and aortic disease relative to open surgery is compelling. Yet, as these procedures have generally been developed and performed outside of the cardiac operating room, cardiac surgeons have typically been in the position of needing to accommodate to such procedures once they are already commonplace. In Canada, for example, most transcatheter procedures are performed by interventional cardiologists or vascular surgeons and not cardiac surgeons.[6,9] The reality, therefore, is that few practicing cardiac surgeons possess the necessary skillset to perform such procedures and—by extension—to teach them to their residents. This has led to training experiences that are fragmented and generally inadequate.[6–9] Meanwhile, the rapid growth and reduced invasiveness of transcatheter procedures has caused concern among cardiac surgeons regarding reduced surgical volumes as more patients become eligible for transcatheter procedures. In fact, the issue is of such importance that it has been called a “burning platform” issue for the specialty.[10] Leaders within cardiac surgery have called for changes to training paradigms in order to meet the increasing demand for cardiac surgeons who are trained in transcatheter techniques.[10,19,20] In particular, owing to their extensive experience in the operating room repairing structural heart and thoracic aortic defects under direct vision, it is felt that cardiac surgeons who are trained in transcatheter techniques would be uniquely situated to offer their patients a spectrum of treatment options tailored to each individual’s pathology.[10] Competition with interventional cardiology, lack of opportunities for involvement, low procedural confidence and poor institutional support have repeatedly been cited as reasons why transcatheter competency has been limited in cardiac surgery residents to date.[6–9] Potential solutions have been proposed in the form of simulation-based training, increased exposure to transcatheter procedures through dedicated rotations during residency training and supporting trainees to pursue advanced transcatheter fellowships.[10,19,21] However, none of these have so far been demonstrably successful in producing adequately trained residents and uptake has been variable, perhaps further contributing to the issue of heterogeneity in training between programs. Considering the pace with which transcatheter cardiac surgery has progressed and the vast differences between traditional open cardiac surgery, a significant paradigm shift is required to approach training in such an innovative, new treatment modality. This thesis will aim to demonstrate the historical basis for current approaches to training, the limitations of contemporary models, the theoretical basis for establishing a new transcatheter training paradigm and progress to date in its development.

Chapter 2: Surgical residencies and the role of fundamental skills training

Surgical training has historically been modeled on the residency program established by Sir William Halsted at Johns Hopkins University in 1889.[22] Halsted's residency program, which was loosely modeled after German programs of the time, strongly emphasized the importance of hierarchy and maintained a rigid, pyramidal structure with many residents being admitted to the program at the junior levels but only a select few graduating to more senior positions.[23] This model incorporated elements from "apprenticeship" styles of training that were commonplace at the time, whereby aspiring surgeons would work closely with and imitate their mentors until becoming competent surgeons themselves.[24] The hallmark of the Halstedian model, however, was that of graded responsibility, whereby residents are given progressively greater independence and clinical responsibility as they advance through training. As advancement was not guaranteed, a consequence of the program as initially established by Halsted was intense competition and the need for exceptional devotion to developing one's surgical craft in order to be successful. Indeed, the origin of the term "resident" implies trainees who reside full-time at the hospital for the duration of their training.[25] While their instrumental role in shaping the field of surgical education cannot be denied, strict apprenticeship style models and even the rigid residency program as initially introduced by Halsted have since come under scrutiny.[22,24]

Contemporary surgical training has, by comparison, evolved to be less pyramidal in nature, but the requirement to spend a significant amount of time honing surgical skills has remained. At the same time, evidence has accumulated to suggest that burnout is rampant among surgical residents,[26] that the number of hours worked per week is associated with greater burnout and worse quality of life[26] and that burnout and reduced mental quality of life are in turn associated with major medical errors.[27] Concerns for patient safety and for resident wellness have therefore led to calls for greater regulation on the amount of time that residents spend in the hospital and specifically to the introduction of the 80-hour work week.[25] These changes have generally been viewed as positive developments for resident work-life balance although at the expense of clinical experience.

This has, however, resulted in a paradox for surgical educators. The standard to which graduating surgeons and their training institutions are held to has not changed, meaning that surgical training programs are tasked with continuing to produce surgeons of the utmost quality and technical ability despite residents spending less time in the operating room during their training. In many specialties this challenge has been compounded by the fact that (a) the profile of patients being referred for surgery has become increasingly complex[28,29] and, particularly, by (b) the development of new techniques, approaches and procedures that have displaced traditionally taught methods. As attending surgeons have been forced to adapt to the changing landscape within their respective fields, they have sought to develop ways of learning and subsequently passing these new skills on to their residents despite the same skills having never been required to complete their own residency training.

One approach that has been successful at improving resident education by deconstructing the complexity of new procedures has been the concept of fundamental skills training. Models incorporating fundamental skills training have had demonstrable benefits over apprenticeship-style training alone.[30] The most well-known example of this approach was developed at McGill and pioneered by the work of Dr. Gerald Fried.[31,32] As a response to changes within the field of general surgery that saw the rapid growth of laparoscopic approaches to diseases that had traditionally been treated by open surgery, Dr. Fried and colleagues sought to develop a method quantifying the proficiency of surgeons and trainees alike performing laparoscopy. Indeed, the disruptive nature of laparoscopic technology and pace with which it saw widespread clinical adoption is not unlike the current status of transcatheter cardiac surgery. In order for the evaluation and training criteria to be generalizable to all forms of laparoscopic procedures, the McGill Inanimate System for Training and Evaluation of Laparoscopic Skills (MISTELS) was developed as a non procedure-specific simulation curriculum encompassing the fundamental technical skills required to perform laparoscopy.[32] The MISTELS platform has since been incorporated into the Fundamentals of Laparoscopic Surgery (FLS) program, which is administered by the Society of Gastrointestinal and Endoscopic Surgeons as a required certification for many specialties that perform laparoscopic procedures.[33]

The FLS program has demonstrated the potential for simulation-based education as a viable solution to the aforementioned constraints of contemporary residency training. Simulation allows learners to train in an environment that is more conducive to learning and without the risk of endangering patients.[34–36] Where deficiencies or other needs are identified, simulation allows for greater repetition and exposure to relevant clinical scenarios than could otherwise be achieved clinically. Finally, simulation-based education is particularly suited to fundamental skills training as it naturally lends itself to assessment.

Following the success of the FLS program, modules for fundamental skills training have been developed and applied to a multitude of procedures including endoscopic surgery,[37,38] vascular surgery[39] and endovascular surgery.[40] There is at present no comparable program in existence for cardiac surgery and although efforts have been made to develop simulation-based training curricula,[34,41] the implementation of such curricula has remained at the discretion of each residency training program. Moreover and perhaps reflecting the current operative practice of most contemporary cardiac surgeons, transcatheter procedures have been largely absent. The problem therefore stems from a lack of standardized simulation-based cardiac surgery training in general and from inexperience with transcatheter procedures specifically. This stands in stark contrast to the growing importance of transcatheter procedures for becoming licensed as a cardiac surgeon at the level of the Royal College of Physicians and Surgeons of Canada[42] and to the aforementioned appeals for greater emphasis on transcatheter procedures during cardiac surgical training.[10,19,20] Although the Royal College of Physicians and Surgeons of Canada has successfully transitioned postgraduate residency training to curricula of competency by design,[43] this falls short of a fundamental skills training approach and will be explored further in the subsequent chapter. With respect to transcatheter cardiac surgery in particular, the shortcomings still inherent in the current training paradigm have been the primary motivation for the work contained in this thesis.

Chapter 3: Competency-based education

Established in 1929, the Royal College of Physicians and Surgeons of Canada (i.e., The Royal College) has been the regulatory body responsible for ensuring the education and certification of all specialized and non-specialized physicians and surgeons working in Canada. Included in their mandate is the post-graduate training of all medical and surgical residents across the country.

As stated previously, medical education is historically based on models of "time spent" such as the one established by Halsted for his surgical trainees.[22,23] This means that the traditional role of regulatory bodies such as the Royal College has been to establish the structure and durations of training for each speciality. As an example, until relatively recently the Royal College had determined that the requirements for certification in cardiac surgery should span a total of 6 years, divided into 78 4-week blocks and consisting of 26 "foundational" blocks, 20 blocks of adult cardiac surgery, 13 blocks of thoracic and vascular surgery, 6 blocks of congenital cardiac surgery and 13 blocks of academic or clinical enrichment.[44] Upon successful completion of this curriculum and a final summative examination, a trainee would be considered to have met the requirements for licensure in cardiac surgery. The degree to which a graduating trainee was capable of competently performing any cardiac surgeries was reflected only in the fact that they were promoted by their program, completed all of the aforementioned rotations and passed a combined written/oral examination. In other words, a trainee's competency was almost entirely implied by their time spent training.

Recognizing the shortcomings of this system, the Royal College endeavoured to establish a more objective system for resident advancement and certification, which they called Competence by Design (CBD). CBD and other competency-based education models aim to promote individuals on the basis of demonstrated proficiency in component tasks, which in the nomenclature of the Royal College are referred to as Entrustable Professional Activities (EPAs).[45] CBD was officially launched in July 2017 within anesthesiology and otolaryngology training programs, while the launch date for cardiac surgery training programs was in July 2019. Unfortunately, the vestiges of the time-spent mentality are still evident. Cardiac surgery training is still 6 years in duration and largely parallels the previously established structure. Importantly, although the EPAs have provided greater granularity regarding expectations for residents by the completion of training, most procedural-based EPAs are limited to observations of achievement by a supervisor. Attainment of proficiency therefore still relies heavily on experiential and apprenticeship-style learning.

CBD represents an improvement over previous approaches and a greater awareness of the needs of the contemporary surgical resident. However, while EPAs provide residents and their supervisors with ultimate learning goals or objectives, they fall short of providing the necessary guidance on how to eventually achieve them. We propose that the CBD training model for transcatheter cardiac surgery can be improved by defining procedures in terms of their component competencies, as in the fundamental skills training approach. These can, in turn, be achieved first through simulation-based training, then advancing to the clinical realm and eventually culminating in entire procedures. While such an approach is not yet commonplace, there is evidence to support its success within the field of vascular surgery.[46] We believe that such a paradigm shift is necessary to adapt to the changing landscape of surgical education and to meet the growing demand for innovative procedures such as transcatheter cardiac surgery.

Chapter 4: Objectives and hypothesis

The objectives of this thesis are as follows:

1. To establish the scope of available literature describing the performance of transcatheter cardiovascular procedures
2. To identify competencies that may be required by cardiac surgery residents learning to perform transcatheter procedures
3. To develop a preliminary list of competencies that may be considered for inclusion in a transcatheter cardiac surgery training curriculum
4. To select the competencies from Objective #3 that are most important for transcatheter cardiac surgery training using the Delphi method

We hypothesize that accomplishing the abovementioned objectives will lead to clearer, more empiric learning goals and objectives for transcatheter cardiac surgery than are currently available.

Chapter 5: The Kern model of curricular development

The Kern model of curriculum development for medical education (referred to as the Kern model for the remainder of this thesis) has been advanced as a framework for designing educational interventions in the medical field (see Figure 1). It was originally proposed by David Kern and colleagues in 1998 with the stated goal of providing medical faculty—many of whom are placed in teaching roles despite having minimal teaching experience—with a framework that is useful, uncomplicated, supported by educational theory and easily put into practice.[47] The authors of the Kern model define a curriculum as "a planned educational experience [encompassing] a breadth of educational experiences, from one or more sessions on a specific subject to a year-long course, from a clinical rotation or clerkship to an entire training program."[47] Whereas other models for medical curriculum development such as the SPICES model[48] and Harden's 10 Questions[49] have successfully been used in the past and likely still hold some relevance, the Kern model is relatively more contemporary and is presently viewed as the framework of choice.[50] Moreover, as it is intentionally generic by design, the Kern model is not limited by specialty and can be understood by medical and non-medical personnel alike. For these reasons, it is an ideal model on which to base the development of a transcatheter cardiac surgery curriculum.

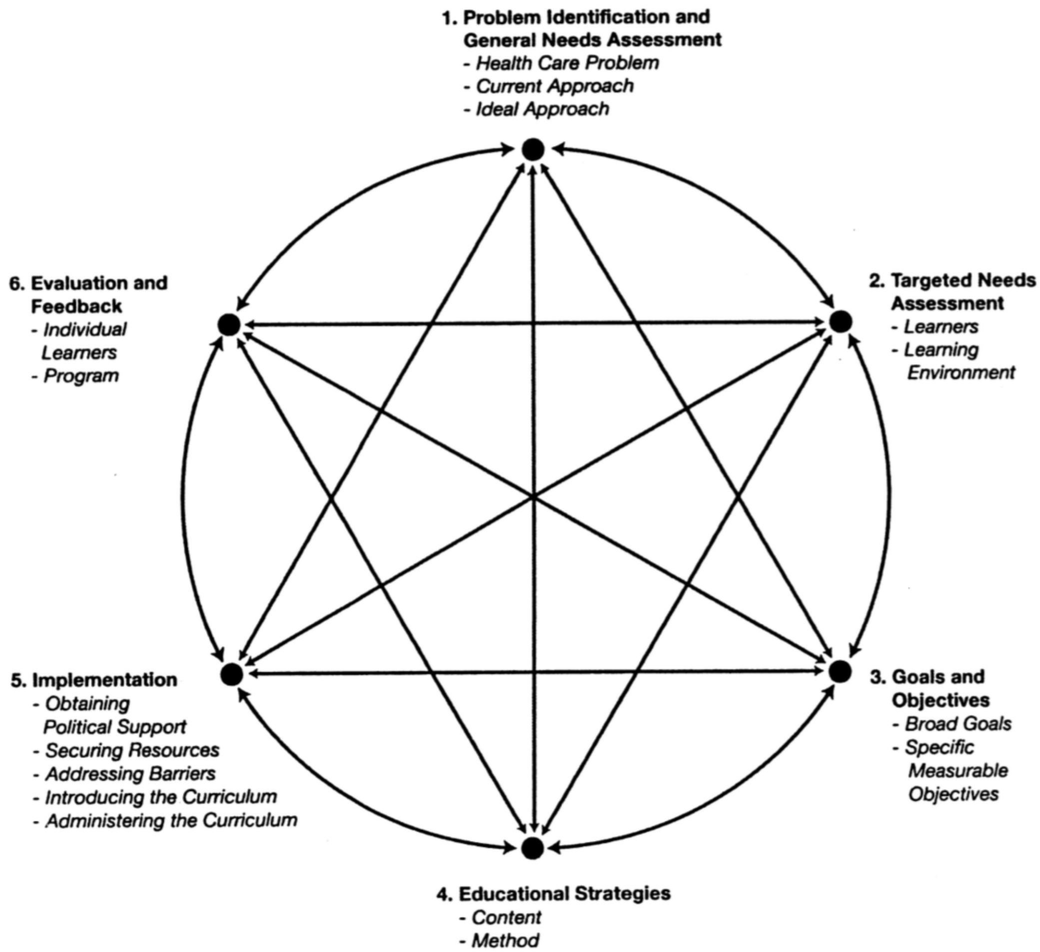

Figure 1: The Kern model represents a stepwise, but interconnected approach to curricular development in medical education[47]

The Kern model conceives of medical curricular development as being characterized by 6 stages:

1. Problem identification and general needs assessment: Requires the identification of one or more healthcare needs, which can relate to physician, patient or system-based factors. In particular, the general needs assessment enables educators to clearly delineate differences between the ideal educational approach (i.e. without limitations on time, resources or expertise) and the approach that is currently being taken.

2. Targeted needs assessment: Identifies the needs of a specific group of learners within a distinct learning environment. This step allows for the optimal integration of the planned curriculum into real-world settings.
3. Goals and objectives: This step aligns closely with the EPAs that are central to competency-based approaches to medical education, such that of the Royal College.[45] As the basis for future content selection and delivery, desired goals and objectives may range from broad to specific and encompass a range of learner, process or health care outcomes.
4. Educational strategies: The selection of content and delivery methods that will maximize the probability of achieving previously established goals and objectives.
5. Implementation: The practical administration of a planned curriculum, which may proceed through several phases such as pilot testing and gradual enrolment prior to more generalized dissemination to resolve unanticipated barriers during the implantation process.
6. Evaluation and feedback: Includes both individual assessment and program evaluation. Individual assessment can be summative or formative according to the stakes of the planned curriculum, while the inclusion of integrated program evaluation methods is vital towards improving the end product.

Although the steps above are presented in sequential fashion, the Kern model emphasizes curricular development as a dynamic process. This is indicated in Figure 1 by the bidirectional arrows connecting each of the above steps to one another, illustrating the fact that progress or barriers encountered in any one area may in turn influence others. As such, curricular development is emphasized as an iterative process that exists in a state of perpetual evolution. The present work therefore aims to develop a curriculum for transcatheter cardiac surgery according to the Kern model, which can in turn serve as the foundation for future work in this area. The relevance of the Kern model will be explored further in subsequent chapters and used to frame contributions to curricular development. In order to appreciate how this approach can be put into practice it is first necessary to understand how surgical training has progressed in the setting of procedural advances and philosophical changes, as well as the challenges faced by residents and institutions in the current training environment.

Chapter 6: Literature review

The identification of relevant competencies is a necessary antecedent to applying a fundamental skills training approach to transcatheter cardiac surgery. As the procedures performed by cardiac surgeons form a subset of related procedures by specialists in different fields (chiefly interventional cardiology and vascular surgery), *transcatheter cardiovascular procedures* will be used to denote this larger group of procedures on which transcatheter cardiac surgery is based. Given this overlap, transcatheter cardiovascular procedures served as a basis to inform the fundamental competencies for transcatheter cardiac surgery. This was accomplished by applying scoping review methodology[51] to comprehensively review the literature pertaining to the performance of transcatheter cardiovascular procedures. The following scoping review therefore completes the first stage of curricular development according to the Kern model (i.e. by performing a general needs assessment)[47] during which an ideal training approach was theorized by identifying the required competencies for transcatheter cardiovascular procedures. This crucial step was necessary to ensure the inclusion of any and all relevant competencies, while remaining free of biases and forming the foundation for all subsequent work.

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A scoping review to identify competencies for transcatheter cardiovascular procedures

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STRUCTURED ABSTRACT
Objectives: Transcatheter procedures are increasingly being recognized as a priority for cardiac surgeons and cardiac surgery trainees. The optimal method of teaching these procedures during residency training has not been established. We used an evidence-based approach to systematically review the literature and identify competencies to inform future paradigms of transcatheter training in cardiac surgery.

Methods: A scoping review was conducted to retrieve relevant literature on the performance of transcatheter cardiovascular procedures, identify competencies required by surgical residents learning to perform these procedures and develop a preliminary list of competencies for consideration during transcatheter training. MEDLINE, Scopus and ERIC were queried until April 1, 2020 using a systematic search strategy. No limitations were placed on publication date or type.

Results: A total of 1456 sources of evidence were retrieved. After deduplication and screening there remained 33 that were included in the scoping review, published between 2006 and 2020. The distribution of publication types included 10 comparative studies (30.3% of total), 8 societal statements (24.2% of total), 5 surveys and 5 opinion articles (each 15.2% of total), 2 editorials and 2 descriptions of a simulator (each 6.1% of total) and one narrative review (3.0% of total). From these a total of 400 items were identified and organized into 97 competencies.

Conclusions: Evidence on the competencies required to perform transcatheter cardiovascular procedures is available from a variety of sources. The identified competencies may be a useful resource for developing curricula and teaching transcatheter procedures to cardiac surgery residents.

INTRODUCTION

The recent growth of endovascular therapies has led to significant changes in the way in which care is delivered. Endovascular repair has emerged as an acceptable and sometimes preferable alternative to open surgery for disease of the thoracic aorta.[15–18] Many cardiovascular diseases that were previously the domain of open surgery are also now treatable using transcatheter alternatives. Supported by results from randomized controlled trials,[52–55] more transcatheter aortic valve replacements than open surgical aortic valve replacements now occur each year in the United States of America (USA).[56] Therapies are also available and being further developed for mitral and tricuspid valve disease, though their role in the clinical realm remains to be defined.[57,58]

As a result of these changes, the acquisition of transcatheter skills has become a priority for cardiac surgeons and cardiac surgery trainees.[42] Surveys of cardiac surgery trainees have repeatedly indicated that current training experiences are largely heterogeneous and insufficient to meet the needs of most trainees.[6–8] Despite calls for changes to the training of cardiac surgeons in order to meet this growing demand,[10] there is no universal curriculum for trainees to begin developing proficiency in transcatheter cardiovascular procedures during residency. Training program personnel are frequently not experienced enough in transcatheter procedures to develop such a curriculum. This scoping review will identify literature describing relevant competencies for their eventual inclusion in such a training curriculum.

Scoping review methodology is useful for describing the available body of knowledge related to a given topic. Scoping reviews differ from other knowledge synthesis approaches in that they do not aim to answer a focused question using a specific type of publication (e.g. meta-analyses of randomized controlled trials), but rather adopt a more general approach that includes identifying all available types of evidence and clarifying concepts or definitions such as by describing them in terms of key characteristics.[59] The process is intended to be iterative and allows for adjustments in methodology as important concepts are clarified. These differences are reflected in the distinct nomenclature used when describing a scoping review, such as "information sources" in lieu of "databases", "sources of evidence" in lieu of "studies", "data charting" in lieu of "data abstraction" and "critical appraisal" in lieu of "risk of bias."[51] Considering the evolving role of cardiac surgeons during transcatheter procedures,[10,60] unclear meaning of commonly used phrases such as "wire skills"[6,19] and disagreements over the degree to which such skills should be learned during residency or deferred to fellowship,[10,21,61] a scoping review is optimally suited to clarify important issues and competencies related to transcatheter training in cardiac surgery.

The objectives of this review are 1) to establish the scope of available literature describing the performance of transcatheter cardiovascular procedures, 2) to identify competencies that may be required by cardiac surgery residents learning to perform transcatheter procedures and 3) to develop a preliminary list of competencies that may be considered for inclusion in a transcatheter cardiac surgery training curriculum.

METHODS

Study design and search strategy

A scoping review was designed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR).[51] Information sources and coverage dates included MEDLINE (1946 to April 1, 2020), Scopus (1970 to April 1, 2020) and ERIC (1966 to Apr 1, 2020). Relevant Medical Subject Heading terms and keywords were compiled from target MEDLINE sources of evidence using the population (cardiac surgery trainees), concept (transcatheter competencies) and context (residency training) approach to designing a scoping review search strategy.[59] The final, comprehensive MEDLINE search (see Supplementary Table 1 in the Appendix) was then translated to Scopus and ERIC. No limitations were placed on publication type or year in order to retain the full extent of available evidence. Deduplication was performed using a simplified version of the Bramer method[62] in EndNote X9 (Clarivate Analytics, Pennsylvania).

Screening sources of evidence

Two authors screened the title and abstract of each source of evidence to identify those that would be suitable for full-text review. Any disagreements were resolved by consensus. Criteria for eligibility were 1) inclusion of cardiac surgery as a specialty, 2) description of a transcatheter procedure or procedures and 3) empiric description of one or more competencies. Consistent with scoping review methodology, empiric descriptions of competencies were initially considered in an exploratory manner. Based on their usage in the literature these were then defined as naming specific procedural steps, describing something using language such as “skill”, “ability”, “knowledge”, “competency” or “behaviour” or otherwise implying that something is crucial to successfully perform the procedure or deliver care. Non-English records were excluded along with those having pediatric patients due to the subspecialized care required by this population.

Data charting and synthesis

In-depth review was performed to verify eligibility of the screened sources of evidence using the aforementioned criteria. Sources lacking online full-text availability were excluded at this stage. Data charting was conducted independently, documenting citation information, publication type, country (defined by first author affiliation), procedure(s) discussed and descriptions of competencies. Attempts were made to preserve the original wording of each competency although simplifications were permitted in favour of conciseness, comprehensibility and generalizability. Assumptions were made to ensure a common structure among all competencies, while similar items were grouped together to prevent redundancies while frequency counts were preserved. For example, “appropriate diagnostics” (from the multisocietal statements on transcatheter aortic[63] and mitral[64] valve repair and replacement) and “knowledge of thoracic aortic pathology; its diagnosis” (from the clinical competence statement on thoracic endovascular aortic repair[65]) were all assumed to refer to the ability to diagnose pathological conditions and therefore grouped as “diagnose structural heart and thoracic aortic disease” with a frequency count of 3 (one for each relevant citation).

The authors participated in an iterative, inductive process to synthesize and further refine the list of identified competencies. Differences of opinion were addressed through group discussion until consensus was reached.

RESULTS

Results of search

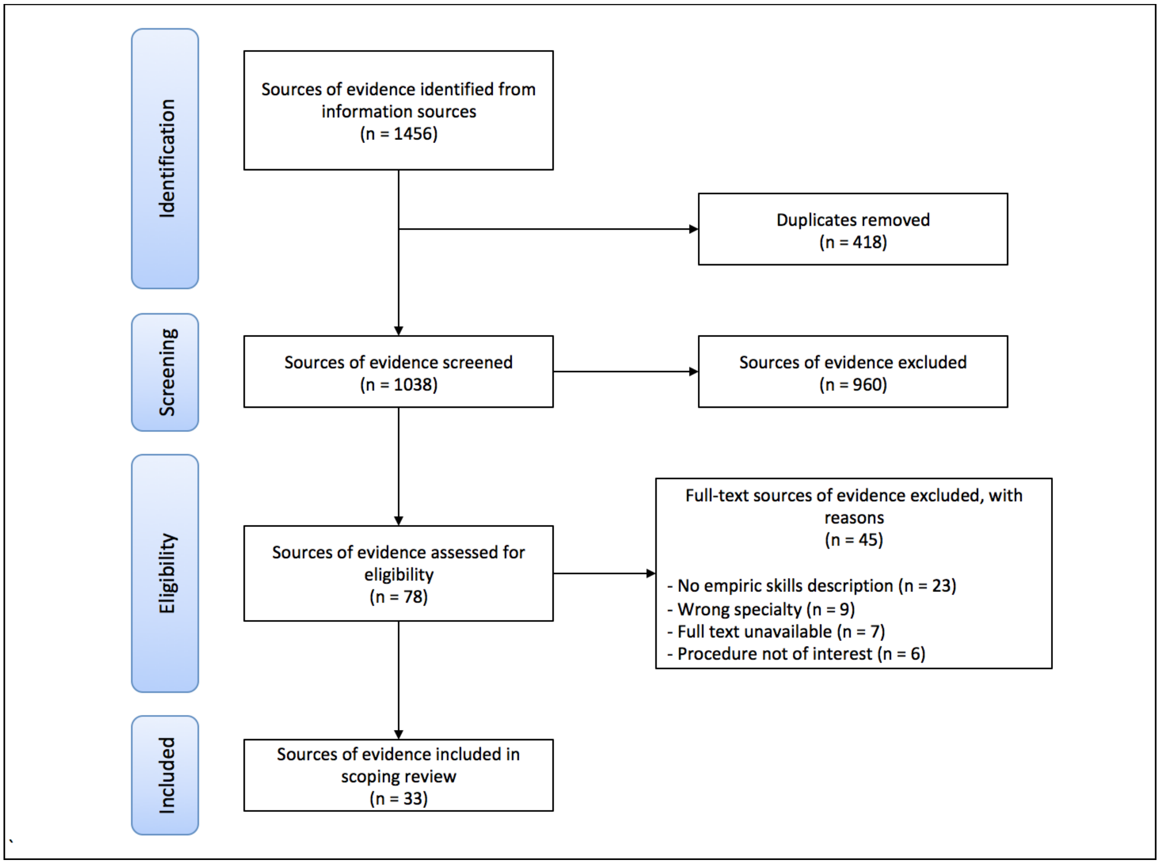

Figure 2: PRISMA-Scr diagram. A total of 1456 sources of evidence were retrieved using the search strategy. After deduplication, screening and full-text review there remained 33 sources of evidence included in this review.

A total of 1456 sources of evidence were retrieved, including 1038 unique records. After title and abstract screening only 78 records remained for full-text review. Of these, 33 records were found to meet criteria for inclusion in the scoping review (see Figure 2). The complete results of this scoping review are summarized in Figure 3.

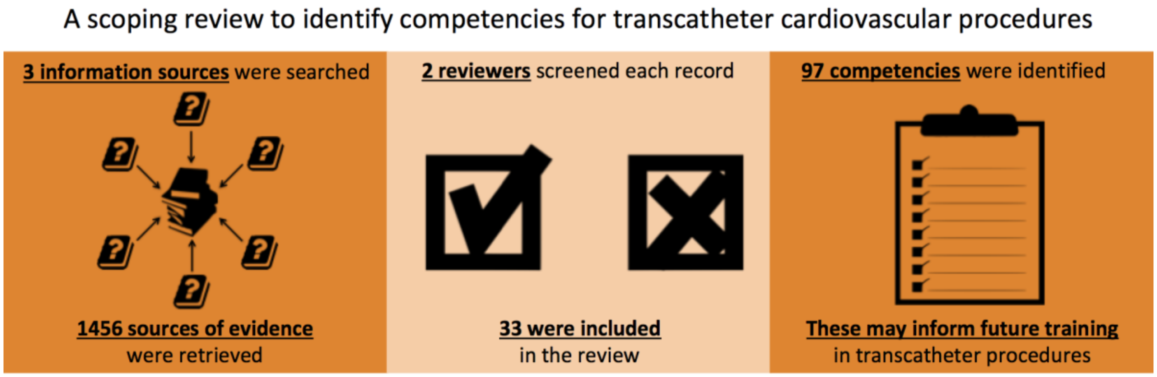

Figure 3: This scoping review has identified 97 competencies required to perform transcatheter cardiac surgery, with the goal of facilitating future training.

Scope of the literature

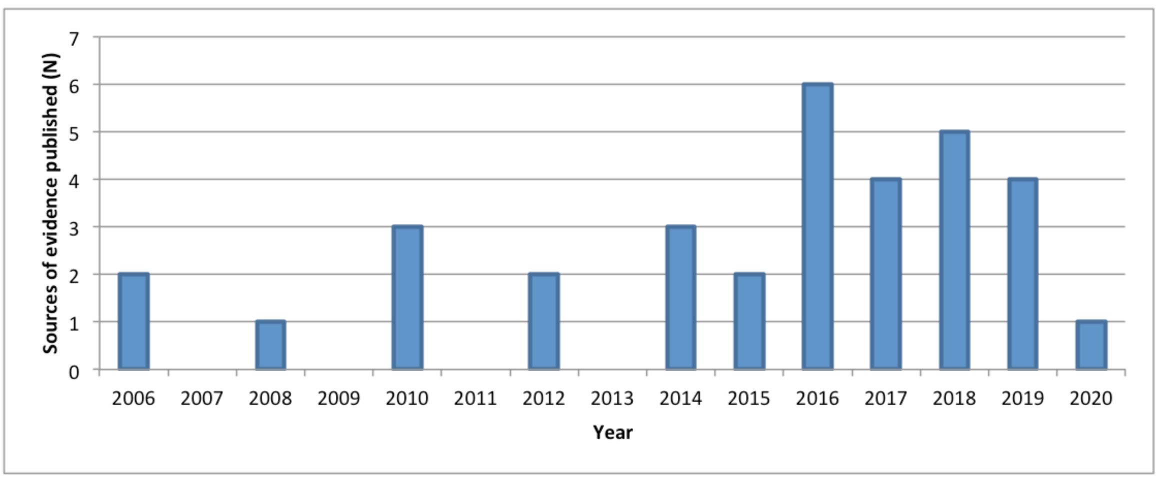

Figure 4: Sources of evidence published by year. There has been steady, though non-linear increase in the number of yearly publications that were included in this review, particularly since 2016.

The earliest identified sources of evidence were published in 2006 (see Table 1). Since then there has been steady, though non-linear increase in the number of publications, particularly from 2016-2020 during which 60.6% (n = 20) of identified records were published (see Figure 4). Publication types consisted mainly of comparative studies (30.3%; n = 10) and societal statements (24.2%; n = 8) with a smaller proportion of surveys and opinion articles (both 15.2%; n = 5). North America contributed 75.8% of publications (n = 25) of which 80% (n = 20) were from the USA and 20% (n = 5) from Canada (see Figure 5).

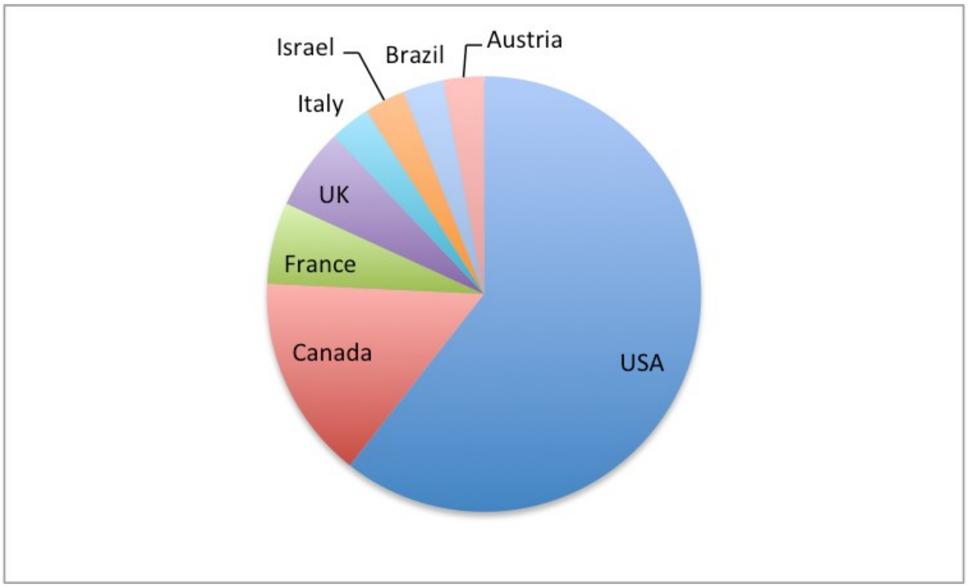

Figure 5: Sources of evidence published by country. The majority of included evidence was retrieved from North American sources, as defined by first author affiliation.

In terms of the representation of specialties, cardiac surgery alone comprised of 48.5% (n = 16) of publications, equivalent to the number of combined cardiac surgery and cardiology publications. Collaboration between the two specialties was especially reflected in societal statements, all but one of which included members of cardiac surgical societies (such as the Canadian Society of Cardiac Surgeons, Society of Thoracic Surgeons, American Association for Thoracic Surgery or European Association of Cardio-Thoracic Surgery) collaborating with members of interventional cardiology societies (such as the Canadian Association of Interventional Cardiology, Society for Cardiovascular Angiography and Interventions or European Association of Percutaneous Cardiovascular Interventions).

Transcatheter aortic valve implantation (TAVI) was by far the most described procedure. When considering only isolated procedures a total of 54.5% (n = 18) of sources of evidence described TAVI, followed by mitral valve interventions in 9.1% (n = 3) and thoracic endovascular aortic repair (TEVAR) in 3.0% (n = 1). By comparison, when all procedure types are considered, 90.9% (n = 30) of sources of evidence described TAVI, mitral valve interventions, or both.

Table 1: Characteristics of included sources of evidence

#	Authors	Year	Publication type	Country	Specialty	Procedure	Competencies identified (N)
1	Alli et al.[66]	2016	Comparative study	USA	Cardiac surgery, cardiology	TAVI	1
2	Arai et al.[67]	2016	Comparative study	France	Cardiac surgery	TAVI	2
3	Asgar et al.[68]	2019	Societal statement	Canada	Cardiac surgery, cardiology	TAVI	9
4	Barbash et al.[69]	2015	Comparative study	Israel	Cardiac surgery, cardiology	TAVI	8
5	Bavaria et al.[70]	2019	Societal statement	USA	Cardiac surgery, cardiology	TAVI	27
6	De Vecchi et al.[71]	2018	Comparative study	UK	Cardiac surgery, cardiology	Mitral	3
7	Gollmann-Tepekoylu et al.[72]	2018	Description of simulator	Austria	Cardiac surgery	Mitral	9
8	Gomes et al.[73]	2018	Description of simulator	Brazil	Cardiac surgery	TAVI TEVAR	3
9	Groves et al.[74]	2014	Comparative study	USA	Cardiac surgery, cardiology	TAVI	1
10	Hage et al.[61]	2020	Opinion	Canada	Cardiac surgery	TAVI	17
11	Herrmann et al.[75]	2010	Survey	USA	Cardiac surgery, cardiology	TAVI Mitral Other	12
12	Hodgson et al.[65]	2006	Societal statement	USA	Cardiac surgery, vascular surgery, radiology	TEVAR	24
13	Holmes et al.[76]	2012	Societal statement	USA	Cardiac surgery, cardiology	TAVI	28
14	Ikonomidis et al.[77]	2016	Survey	USA	Cardiac surgery	TEVAR Other	6
15	Indolfi et al.[78]	2017	Comparative study	Italy	Cardiac surgery, cardiology	TAVI	3
16	Jilaihawi et al.[79]	2010	Comparative study	UK	Cardiac surgery	TAVI	4
17	Juanda et al.[9]	2016	Survey	Canada	Cardiac surgery	TAVI Mitral Other	10

18	Lazar[21]	2016	Editorial	USA	Cardiac surgery	TAVI TEVAR	4
19	Minha et al.[80]	2016	Comparative study	USA	Cardiac surgery, cardiology	TAVI	5
20	Neely et al.[81]	2014	Narrative review	USA	Cardiac surgery	TAVI	20
21	Nguyen and George[20]	2015	Opinion	USA	Cardiac surgery	TAVI	9
22	Nguyen et al.[10]	2019	Opinion	USA	Cardiac surgery	TAVI Mitral Other	32
23	Pelletier et al.[19]	2017	Opinion	USA	Cardiac surgery	TAVI TEVAR Mitral Other	17
24	Ruiz et al.[82]	2010	Societal statement	USA	Cardiac surgery, cardiology	TAVI Mitral Other	52
25	Tam et al.[6]	2018	Survey	Canada	Cardiac surgery	TAVI	8
26	Tommaso et al.[63]	2012	Societal statement	USA	Cardiac surgery, cardiology	TAVI TEVAR Mitral	33
27	Tommaso et al.[64]	2014	Societal statement	USA	Cardiac surgery, cardiology	Mitral	10
28	Vahanian et al.[83]	2008	Societal statement	France	Cardiac surgery, cardiology	TAVI	28
29	Vahidkhah and Azadani[84]	2017	Comparative study	USA	Cardiac surgery, cardiology	TAVI	1
30	Vardas et al.[7]	2017	Survey	USA	Cardiac surgery	TAVI TEVAR Mitral Other	6
31	Wassef et al.[85]	2018	Comparative study	Canada	Cardiac surgery, cardiology	TAVI	5
32	Wheatley[86]	2019	Editorial	USA	Cardiac surgery	TAVI	1
33	Wheatley and Diethrich[87]	2006	Opinion	USA	Cardiac surgery	TEVAR Other	4

Competencies

A total of 400 items, comprising 97 unique competencies, were identified from the literature (see Table 2). The median frequency count per competency was 3 (interquartile range 1-6). The most commonly identified competencies included obtaining vascular access and closure (63.6% and 42.4% of included sources of evidence, respectively), procedural decision-making (51.5% of included sources of evidence) and interpreting echocardiography (39.4% of included sources of evidence). There were 29 competencies that were only identified from single sources of evidence; all other competencies were identified in at least 2 sources.

Table 2: Identified competencies with frequency counts and relative proportion of included sources of evidence

Competency	Frequency (N)	Proportion (%)	Sources of evidence (as numbered in Table 1)
General knowledge and skill	***8***	***24.2***	
Diagnose structural heart and thoracic aortic disease	3	9.1	5, 12, 26
Understand the etiology, pathophysiology and natural history of structural heart and aortic disease	5	15.2	5, 12, 22, 24, 26
Understand the hemodynamic consequences of treated and untreated structural heart disease	6	18.2	5, 7, 15, 22, 24, 26
Recommend optimal medical therapy	3	9.1	5, 24, 26
Understand the relevant anatomy	3	9.1	22, 24, 27
Take a history	1	3.0	24
Perform a physical exam	1	3.0	24
Communication and collaboration	***11***	***33.3***	
Collaborate with multidisciplinary team members	11	33.3	3, 5, 10, 13, 20, 22-24, 26-28
Interact with patients and their families	3	9.1	13, 24, 26
Participate in registries and outcome studies	2	6.1	24, 26
Perioperative care	***13***	***39.4***	
Evaluate a patient and optimize them prior to the procedure	9	27.3	5, 10, 21-24, 26-28
Manage coexisting conditions	1	3.0	13
Develop a preprocedural plan for the case	3	9.1	8, 12, 22
Provide postprocedural care	8	24.2	3, 5, 21, 22, 24, 26-28
Provide follow up	7	21.2	5, 12, 13, 23, 24, 26, 27
Patient selection	***14***	***42.4***	
Know, interpret and apply the outcomes of clinical trials to decide the optimal interventional strategy	6	18.2	5, 12, 13, 22, 24, 26
Perform a pre-operative risk assessment	7	21.2	3, 4, 13, 20, 26-28
Select candidates for transcatheter procedures using clinical practice guidelines, indications and contraindications	10	30.3	10, 12, 20-24, 26-28
Imaging	***18***	***54.5***	

Echocardiography	*14*	*42.4*	
Acquire echocardiography	2	6.1	11, 22
Interpret echocardiography	13	39.4	3, 5, 7, 10, 13, 16, 20, 22, 24, 26-28, 31
Fluoroscopy	*10*	*30.3*	
Acquire fluorscopic images	6	18.2	5, 10, 12, 22, 23, 28
Interpret fluoroscopic images	6	18.2	4, 8, 12, 22, 24, 28
Interpret coronary angiography	2	6.1	3, 28
Computed tomography	*12*	*36.4*	
Interpret computed tomographic scans	12	36.4	3-5, 8, 10, 12, 13, 20, 22, 24, 26, 28
Magnetic resonance imaging	*4*	*12.1*	
Interpret magnetic resonance imaging	4	12.1	13, 22, 24, 28
Cardiac catheterization laboratory and hybrid operating room environment	***10***	***30.3***	
Understand radiation safety	3	9.1	5, 10, 26
Interpret hemodynamics in the cardiac catheterization laboratory	4	12.1	5, 24, 26, 28
Know how to use relevant equipment in the cardiac catheterization laboratory or hybrid operating room, including the C-arm and contrast injection systems	8	24.2	10, 12, 22, 23, 25, 26, 28, 30
Understand how to use contrast agents	2	6.1	5, 26
Work in a sterile environment	1	3.0	28
Vascular access	***23***	***69.7***	
Insert a central venous line or Swan-Ganz catheter	2	6.1	10, 18
Insert an arterial line	2	6.1	10, 18
Obtain vascular access using surgical or percutaneous approach	21	63.6	1-3, 5, 7, 10, 12, 13, 17, 18, 20-26, 28, 30, 31, 33
Achieve vascular closure by direct repair or by using a vascular closure device	14	42.4	3-5, 7, 12, 13, 19, 20, 22-26, 28
Access the heart and great vessels via transthoracic approaches	4	12.1	13, 20, 21, 28
Select an approach	5	15.2	2, 13, 20, 23, 30
Dilate access vessel under fluoroscopic vision	1	3.0	13
Perform surgical procedures on the LV apex	4	12.1	13, 20, 26, 28
Place pursestring sutures	2	6.1	13, 28
Wire management and manipulation	***15***	***45.5***	
Select wires, catheters and sheaths	6	18.2	4, 10, 12, 21, 22, 24
Insert wires, catheters and sheaths	6	18.2	13, 20-23, 28
Navigate vascular anatomic structures by manipulating wires and catheters	7	21.2	5, 7, 12, 23-26
Manage brachial-femoral wires	1	3.0	33

Perform wire exchange	1	3.0	13
Prostheses	21		
Perform size measurements for transcatheter prostheses	9	27.3	3, 4, 12, 13, 15, 16, 20, 22, 30
Select a transcatheter prosthesis	6	18.2	4, 6, 10, 12, 15, 23
Deliver a transcatheter prosthesis	8	24.2	7, 10, 12, 13, 19, 20, 22, 31
Position a transcatheter prosthesis	10	30.3	6, 7, 9, 13, 16, 20, 22, 23, 28, 29
Deploy a transcatheter prosthesis	12	36.4	7, 12, 13, 19-25, 28, 31
Pacing	***6***	***18.2***	
Insert a temporary pacing device (wire or epicardial lead)	3	9.1	13, 20, 25
Perform rapid ventricular pacing	5	15.2	13, 19, 20, 24, 28
Cardiac surgery	***9***	***27.3***	
Develop surgical experience with valve of interest	3	9.1	24, 27, 28
Insert and manage peripheral mechanical circulatory support	5	15.2	5, 10, 13, 26, 28
Insert cannulae for initiating cardiopulmonary bypass	1	3.0	18
Perform a frozen elephant trunk	1	3.0	33
Transcatheter interventions	***25***	***75.8***	
Make decisions during the procedure including anticipating, recognizing and treating procedural complications	17	51.5	4-6, 12, 13, 16, 20-24, 26-28, 31, 33
Perform intravascular ultrasonography	1	3.0	12
Utilize cerebral embolic protection	1	3.0	22
Perform intravascular snaring and retrieval	2	6.1	5, 12
Perform coil embolization	1	3.0	12
Perform side-branch angioplasty and stenting	1	3.0	12
Valvular cardiac interventions	*12*	*36.4*	
Perform transcatheter pulmonary valve implantation (TPVI)	1	3.0	24
Cross the stenotic aortic valve in antegrade or retrograde fashion	7	21.2	13, 20, 22-25, 28
Perform paravalvular leak closure	3	9.1	5, 11, 24
Perform balloon aortic, mitral, tricuspid or pulmonary valvuloplasty	11	33.3	5, 11, 13, 17, 19, 20, 22, 24, 25, 26, 28
Non-valvular cardiac interventions	*10*	*30.3*	
Perform transhepatic access	1	3.0	24
Perform balloon pericardiotomy	1	3.0	24
Perform ventricular pseudoaneurysm closure	1	3.0	24
Perform endovascular endoleak closure	1	3.0	24
Perform aortic pseudoaneurysm closure	1	3.0	24

Perform angioplasty and stenting for coarctation of the aorta	1	3.0	24
Perform angioplasty and stenting of surgical conduits, baffles and homografts	1	3.0	24
Perform angioplasty and stenting of interatrial septum and Fontan fenestrations	1	3.0	24
Perform coronary angiography	6	18.2	5, 10, 17, 22, 26, 30
Perform PCI	4	12.1	5, 10, 17, 22
Perform transseptal puncture	6	18.2	7, 11, 22, 24, 26, 32
Perform transseptal left heart catheterization	1	3.0	24
Perform ASD closure	3	9.1	11, 24, 30
Perform pulmonary vein stenting	2	6.1	11, 24
Perform VSD closure	2	6.1	11, 24
Access the coronary sinus	2	6.1	24, 26
Perform septal ablation	2	6.1	11, 24
Perform PFO closure	2	6.1	11, 24
Perform PDA closure	2	6.1	11, 24
Perform LAA exclusion	2	6.1	11, 24
Perform PA stenting	2	6.1	24, 26
Perform coronary fistula embolization	2	6.1	11, 24
Vascular interventions	*6*	*18.2*	
Perform brachiocephalic transposition or extra-anatomic revascularizations	1	3.0	12
Perform carotid artery stenting	1	3.0	14
Perform endovascular treatment of aortoiliac disease	1	3.0	14
Perform endovascular treatment of great vessel occlusive disease	1	3.0	14
Perform endovascular treatment of mesenteric vascular disease	1	3.0	14
Perform percutaneous embolectomy/thrombectomy	1	3.0	17
Perform interventions for PVD	4	12.1	5, 14, 17, 26
Perform peripheral angiography	2	6.1	17, 26
Perform EVAR	4	12.1	5, 14, 17, 26
Perform balloon angioplasty	2	6.1	17, 23

DISCUSSION

This scoping review provides an overview of the literature describing the performance of transcatheter cardiovascular procedures. The study objectives were successfully met, namely establishing the scope of available literature, identifying competencies required to perform the procedures and developing a list of competencies for consideration in a training curriculum. By establishing the scope of the literature and clarifying the competencies that may be required by cardiac surgery residents learning to perform transcatheter procedures, we have established a suitable foundation to inform future evidence-based research. The growing number of publications—particularly in the past five years—and number of comparative studies emphasizes the fact that this is a rapidly developing field. This is likely driven by the favourable clinical outcomes of randomized trials comparing transcatheter to traditional cardiac surgery. Considering the number of large, multicentre and multinational randomized trials that have compared TAVI to surgical aortic valve replacement,[12,14,52–54,88] it is unsurprising that TAVI was the most frequently described procedure among the identified sources of evidence. The distribution of specialties among identified sources of evidence highlights the desire and initiative of cardiac surgeons to be involved in transcatheter procedures as well as the multidisciplinary nature of cardiac surgical practice, which in the clinical realm is embodied by the heart team concept. Cardiac surgeons should strive for continued involvement in all elements of transcatheter procedures in order to maintain their role in the treatment of structural heart and aortic disease.

The rapid growth of transcatheter techniques and desire to remain involved in the care of patients with structural heart or aortic disease has prompted surgeons to advocate for changes to training paradigms that would increase the focus on transcatheter training.[10,61,87] Considering the vastly different nature of transcatheter and traditional cardiac surgery, however, few tangible changes have been made. This, coupled with conflicting opinions on the amount of transcatheter training that should occur during residency versus fellowship, has led to ambiguous expectations regarding the level of transcatheter competency that a resident should possess by the end of their training. Moreover, the evidence is clear that simply increasing the number of transcatheter rotations is unlikely to meet the needs of most residents.[6,7,9] Instead clear, actionable and evidence-based educational interventions are required. For example, rather than being told to focus on "wire skills," the results of this review could be used to provide residents with more clearly delineated goals such as obtaining vascular access, performing a wire exchange, crossing a stenotic aortic valve and so forth according to their needs and stage of training. The advantage of this approach is that it is informed by the literature rather than operator experience or clinical gestalt. While we identified several sources of evidence describing competencies required for transcatheter cardiovascular procedures, until now no group has attempted to synthesize this evidence in a comprehensive manner with cardiac surgery residents in mind. Indeed, we only identified one relevant review article, which was a narrative review by Neely and colleagues in 2014.[81] As part of their review they discussed new approaches to cardiac surgery, including percutaneous valve interventions. However they used a more general approach by describing the procedures and results from early trials without the overt intent of identifying learning goals. We hope that the competencies we have identified will prove useful for surgeon-educators who are designing interventions to teach transcatheter procedures to cardiac surgery trainees.

The results of this review, however, should not be interpreted as a reference for the competencies that cardiac surgeons absolutely must be require to perform transcatheter procedures. Indeed, it may not be practical to introduce such an extensive list of objectives when designing specific interventions for a transcatheter curriculum. Rather, the intent has been to summarize the entirety of available evidence to identify all of the competencies that a cardiac surgeon in-training *may potentially* attain assuming no constraints of time, resources or expertise. This approach is guided by the Kern model of curricular development, which first requires the identification of a problem and a general needs assessment, after which more targeted needs assessments may inform the selection of educational goals and interventions specific to a group of learners in a particular setting or environment.[47] As the problem of transcatheter skills acquisition by cardiac surgery trainees is well established,[6–8,10] the identified competencies represent rather the conclusion of this first step in curricular design, namely a general needs assessment. While it is possible—and even likely—that some of the identified competencies may not ultimately be required by cardiac surgery residents, educators may still find it beneficial to consider the gaps between what is currently taught to residents at their institution and what *may potentially* be taught in an ideal setting. The results of this review can therefore inform future stages of curricular development including targeted needs assessments and developing, implementing then refining educational interventions according to the identified needs.

Strengths of this review include the number of information sources searched, systematic approach to collect sources of evidence, methodology facilitating the inclusion of broad publication types and iterative approach to compile the final list of competencies that addresses an important gap in the literature. This review has several limitations. While frequency count was included as a preliminary indication of relative importance (since more frequently referenced competencies would presumably hold greater weight), it may favour easily described competencies at the expense of those that are more subtle. Furthermore, the relative importance of a given competency may evolve depending on a resident's stage of training and career goals. We attempted to account for this by including individuals from diverse backgrounds as a quality control method while compiling the list of competencies, however a more rigorous approach—such as by confirming the relevance of these competencies with subject matter experts—is required to refine this list further and will be the focus of an upcoming Delphi consensus study. Limiting the eligibility criteria to English language only may have resulted in an inadvertent geographic bias producing a disproportionate number of North American publications. While this limits the generalizability of our review, it is unlikely that broader inclusion criteria would have produced vastly different results—particularly regarding the competencies that were identified—as the procedures themselves remain unchanged regardless of geographic location.

CONCLUSION

Literature on performing transcatheter cardiovascular procedures is available from a multitude of sources and origins. Information obtained from these sources of evidence may be useful for teaching residents to perform transcatheter procedures. The identified competencies will form the basis of future work prioritizing those that are considered fundamental for learning to perform transcatheter cardiovascular procedures.

Chapter 7: Identifying the Fundamental Competencies for Transcatheter Cardiac Surgery

The above scoping review represents a significant step in the development of a new transcatheter training paradigm. By intentionally maintaining broad inclusion criteria and seeking evidence from multiple specialties, the result is a set of competencies that consciously exceeds the anticipated expectations for a cardiac surgeon. This is emphasized by the distinction of transcatheter cardiac surgery from transcatheter cardiovascular procedures. Stated otherwise, a trainee who theoretically attains all of the identified competencies would necessarily be capable of performing at the level of a cardiac surgeon, vascular surgeon or interventional cardiologist. While this is clearly excessive and impractical for the purposes and scope of a cardiac surgery residency training program, it forms the conceptual justification with which the most relevant competencies for cardiac surgery residents can be identified through the refinement of these results.

What is lacking from the review is a sense of broader perspective. In other words, to what degree are physicians, patients and the system at large supportive of improved transcatheter training in cardiac surgery residents? This is a complex and multifaceted question as the answer likely depends on how each stakeholder would be affected by such a paradigm shift. Within the specialty of cardiac surgery at least, the desire is evident.[6–10,19,20,89,90] Given this uncertainty, it is reasonable to anticipate some divergences of opinion during the implementation stage of curricular development. Nonetheless, such uncertainty and the possibility of conflict should not preclude continuation of the curricular development process.

Therefore, while the results of the scoping review have clarified important elements related to transcatheter cardiovascular procedures, further work is required to ensure that these results are practical for trainees, training programs and the curricular development process itself. It is necessary that they be refined to identify learning goals and objectives that are directly applicable to cardiac surgery residents in the process of completing their primary residency training. A suitable approach would therefore be to use the Delphi method, which has the additional benefits of objectivity and collaboration with subject matter experts.

Pan-Canadian Initiative on Fundamental Competencies for Transcatheter Cardiac Surgery: A Modified Delphi Consensus Study

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STRUCTURED ABSTRACT

Objective: Transcatheter cardiac procedures have generated increasing interest in trainees and training programs alike. Using the modified Delphi method, we sought to clarify the transcatheter competencies that cardiac surgery residents should be expected to attain by the completion of training.

Methods: Individuals with expertise in transcatheter structural heart and aortic procedures were recruited across Canada. A questionnaire was prepared using a 5-point Likert scale. During two rounds participants rated the competencies that they felt cardiac surgery residents should be required to achieve to perform transcatheter procedures. Data was analyzed and presented to participants between rounds. Competencies rated 4 or higher by at least 80% of respondents after the second round were considered fundamental to transcatheter cardiac surgical training.

Results: A total of 46 individuals participated in the study including 23 cardiac surgeons, 17 interventional cardiologists and 6 vascular surgeons. Participants with relevant experience performed a median of 75 (interquartile range 40 – 100) transcatheter aortic valve implantations in the prior year as primary or secondary operator and 15 (interquartile range 11 – 35) thoracic endovascular aortic repairs in the prior two years as primary operator. Median clinical and teaching experience consisted of 13 (interquartile range 7 – 19.5) years in practice and 8.5 (interquartile range 5- 15) residents taught per year, respectively. Of the included competencies, 53 were considered fundamental to transcatheter cardiac surgical training.

Conclusions: The identified fundamental competencies can be used to develop educational strategies during transcatheter cardiac surgery training. Future efforts should focus on collecting evidence for their validity.

INTRODUCTION

Transcatheter approaches are increasingly being used to treat patients with structural heart and thoracic aortic disease.[56,91] While outcomes after open surgery remain excellent, favorable initial results—combined with reduced invasiveness, improved procedural familiarity and evolution of technology—have led to an expansion in the indications for transcatheter procedures.[15,16,68,92] In order to continue offering their patients the highest standard of care, cardiac surgeons must become proficient in both transcatheter and traditional open cardiac surgery.[19,20]

A recent scoping review has identified competencies for transcatheter cardiovascular procedures.[93] A total of 97 competencies were identified from 33 sources of evidence, facilitating the development of evidence-based interventions to teach such procedures. However, considering the generalized nature of the identified competencies and the need to develop targeted educational interventions as part of the curriculum development process,[47] further work is required to identify more specific goals and objectives for learners. In particular, the degree to which these competencies reflect the level of performance expected of a cardiac surgery resident is not known. It is therefore imperative to identify competencies that should be considered foundational and therefore included in cardiac surgery residency training.

The goal of this study was to help define the Fundamental Competencies for Transcatheter Cardiac Surgery (FCTCS) using the Delphi method. The Delphi method was established as a means of obtaining consensus from expert opinion while mitigating the shortcomings of traditional group response techniques.[94] It has been used in surgical education to establish consensus from experts on diverse topics including training guidelines,[95] assessment tools,[95–97] curricular development,[98] research[99] and training priorities.[40] In this study, the Delphi technique was used to establish consensus among Canadian experts and determine the transcatheter competencies that are important for cardiac surgery residents.

METHODS

Recruitment

Although largely dependent on the centre, cardiac surgeons typically share responsibility for transcatheter procedures with interventional cardiologists and vascular surgeons. Therefore, to reflect the diversity of specialties performing transcatheter structural heart and aortic interventions, cardiac surgeons, interventional cardiologists and vascular surgeons were invited to participate. Potential participants with experience in transcatheter aortic valve implantation (TAVI), thoracic endovascular aortic repair (TEVAR), or both were contacted, as these are the transcatheter procedures that the Royal College of Physicians and Surgeons of Canada requires for cardiac surgical training.[43] Individuals were identified based on information provided by industry partners, by asking training program directors to identify individuals at their centre or in their province performing the procedures of interest and through word of mouth (asking individuals with known experience to recommend similarly experienced colleagues). All individuals were contacted by email. Efforts were made to obtain wide representation from across Canada, soliciting individuals in each province and within each centre with no restrictions placed on geographic location or teaching hospital status. An electronic invitation was sent to 172 individuals at 32 centres on October 12, 2020 with a single reminder sent 5 days later on October 13, 2020. Recruitment was initially planned to remain open for two weeks, but was closed prematurely on October 20, 2020 once target enrolment had been achieved. As it is recommended to include at least 5-10 participants per discipline in multidisciplinary Delphi studies,[100] recruitment was continued until these minimums were met for each specialty. Institutional research ethics board approval was obtained prior to commencement of the study with informed consent considered implicit in the decision to complete the questionnaires.

Delphi questionnaire

A questionnaire was designed based on all 97 competencies identified from the scoping review to permit experts to comprehensively review the identified competencies.[93] The questionnaire was distributed using the online platform SurveyMonkey (San Mateo, California). After providing demographic information, participants were asked to indicate on a 5-point Likert scale the competencies that they felt all cardiac surgery residents should be required to achieve in order to perform transcatheter cardiac procedures. The following anchors were used: 5) Absolutely needed = Absolutely necessary to have this competency to perform the procedure, cannot complete any case without this competency; 4) Needed = Advantageous to have this competency to perform procedure, some cases cannot be done without this competency; 3) Could be needed = In a few situations, this competency may be needed to perform the procedure; 2) Probably not needed = Most if not all procedures can be performed without this competency; 1) Not needed = All procedures can be performed without this competency. Additionally, participants were given the option of listing any additional competencies that they felt cardiac surgery residents should be required to achieve in order to perform transcatheter procedures, which were not included in the questionnaire.

Following this initial round of responses, the data was analyzed and provided to the group in the form of an aggregate statistical analysis of each questionnaire item. Participants were then asked to repeat the questionnaire with the opportunity to anonymously revise any of their answers from the first round, as well as to rate the additional competencies suggested by their co-participants. Only individuals who completed the first round of the study were eligible for participation in the second round. The study concluded upon completion of the second round (see Figure 6).

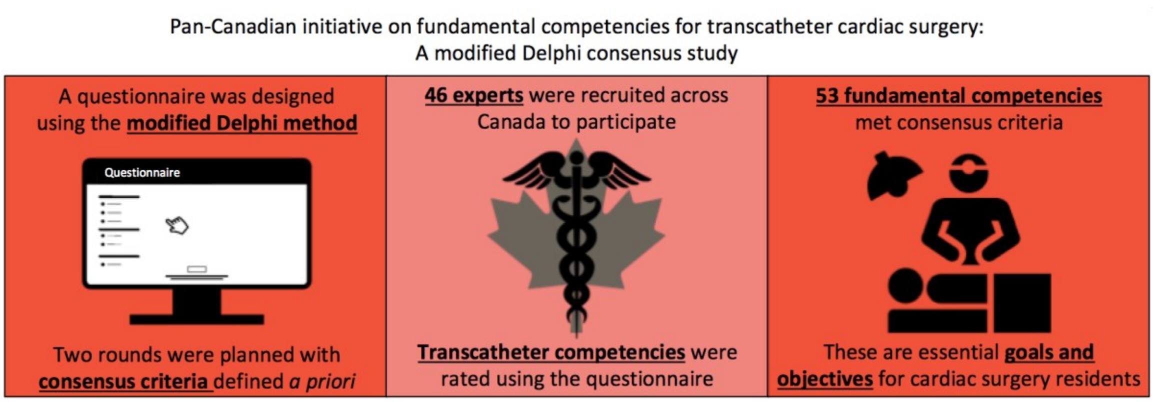

Figure 6: This modified Delphi study has identified 53 competencies that are supported by expert consensus and which cardiac surgery residents should be required to achieved by the completion of their primary residency training

Statistical analysis

Consensus was defined based on the level of agreement among participants at the conclusion of the study. Specifically, a threshold was defined *a priori* whereby competencies would be considered part of FCTCS if 80% or more of participants felt that cardiac surgery residents needed or absolutely needed (i.e. rating of 4 or 5 on the

5-point Likert scale) to achieve a given competency during residency training. An average rating was calculated for each competency by converting ordinal data from responses using the Likert scale anchors to interval data with 1 representing the lowest (i.e. “not needed”) and 5 the highest (i.e. “absolutely needed”) items on the scale. Missing data accounted for less than 1% of responses and was treated by omission.

Clinical, procedural and teaching experience were in turn defined by years in practice, case volume and residents taught per year. When considering procedural and teaching experience only non-zero responses were retained as the absence of procedural volume or of residents taught was felt to be less reflective of intrinsic inexperience and more reflective of specialty (i.e. specialties who perform only one type of procedure) and teaching hospital status, respectively. In this fashion, only individuals with relevant experience were included in analyses of procedural and teaching experience.

Cronbach’s alpha was used to assess the internal consistency of responses during each round. A sensitivity analysis was performed to verify the internal consistency of results among respondents who completed both survey rounds.

A number of supplementary post-hoc analyses were performed to explore whether respondent specialty or level of experience was related to their responses. First, a series of Kruskal-Wallis H tests were used to compare differences in responses between specialties. Dwass-Steel-Critchlow-Fligner pairwise comparisons were then performed on the statistically significant results that met consensus inclusion criteria. This was done to verify whether results were skewed by responses from a single specialty. As there are no clearly defined criteria denoting levels of experience, respondents with more than the median value of clinical, procedural or teaching experience were considered to be more experienced and consensus levels were reanalyzed in these high experience groups. For the purposes of this analysis, procedural experience included both TAVI and TEVAR volume.

All statistical analyses were performed using R via Jamovi (version 1.6).

RESULTS

Study population

A total of 46 individuals participated in the study (see Table 3). This included 23 cardiac surgeons, 17 interventional cardiologists and 6 vascular surgeons. The majority (91.3%) of respondents practiced at teaching hospitals. Pan-Canadian representation was achieved. The group's median combined experience included 13 years in practice (interquartile range 7 – 19.5 years). Among TAVI operators the median number of TAVIs performed in the prior year as primary or secondary operator was 75 (n = 37; interquartile range 40 – 100 TAVIs). Similarly, among TEVAR operators the median number of TEVARs performed in the prior two years as primary operator was 15 (n = 19; interquartile range 11 – 35 TEVARs). Individuals with experience teaching residents taught a median of 8.5 residents per year (interquartile range 5 – 15), inclusive of all types and specialties. There were 32 individuals who completed both survey rounds.

Table 3: Demographic description of first round participants

Characteristic	**Respondents (n = 46)**
Gender	
Male	43 (93.5%)
Female	3 (6.5%)
Other	0 (0.0%)

Primary specialty	
Cardiac surgery	23 (50.0%)
Interventional cardiology	17 (37.0%)
Vascular surgery	6 (13.0%)
Location of primary practice	
Teaching hospital	42 (91.3%)
Non-teaching hospital	4 (8.7%)
Region of primary practice	
Western Canada	16 (34.8%)
Ontario	12 (26.1%)
Quebec	12 (26.1%)
Atlantic Canada	6 (13.0%)
Clinical and teaching experience†	
Number of years in practice	13 (7 - 19.5)
Number of TAVI performed in past year as primary or secondary operator	75 (40 - 100)
Number of TEVAR performed in past two years as primary operator	15 (11 - 35)
Number of residents taught per year (all types and specialties)	8.5 (5 - 15)

*Continuous variables expressed as median (interquartile range); Categorical variables expressed as N (%)

†Calculated from individuals with relevant experience only

Competencies

Of the 97 included competencies from the previous scoping review,[93] 53 achieved criteria for inclusion in FCTCS (see Table 4). Among these the level of consensus ranged from 81.25% to 100% with 6 additional competencies meeting criteria for inclusion between the first and second Delphi rounds. A number of items were highly rated including "understand the relevant anatomy", "perform a pre-procedural risk assessment", "work in a sterile environment", and "make decisions during the procedure including anticipating, recognizing and treating procedural complications" all of which attained unanimous ratings of 5.0. This indicates that all participants felt these items were absolutely needed of cardiac surgery residents at the completion of their training. Low ranked items included “insert a central venous line or Swan-Ganz catheter”, “insert an arterial line” and “manage brachial-femoral wires” all of which reached the minimum included level of consensus (i.e. 81.25%). Cronbach’s alpha was 0.965 and 0.957 during the first and second Delphi rounds, respectively, indicative of strong internal consistency. Among individuals who responded to both survey rounds, Cronbach’s alpha was 0.963, consistent with the main study results. A decreasing standard deviation during the second round—which has been proposed as a marker for convergence of opinions and therefore stability between Delphi rounds[101,102]—was observed in the rating of 88 competencies. In addition to the 97 competencies that comprised the first Delphi round, four competencies were suggested by first round respondents and included in the second Delphi round, of which all but one achieved criteria for inclusion.

Table 4: Fundamental Competencies for Transcatheter Cardiac Surgery according to modified Delphi consensus. Consensus was defined by the percentage of respondents rating each item as 4 or higher on the 5-point scale, with 80% considered the minimum for inclusion.

Competency	Round 1 rating M (SD)	Round 2 rating M (SD)	Round 1 consensus	Round 2 consensus
Identified by scoping review				
Diagnose structural heart and thoracic aortic disease	4.78 (0.70)	4.81 (0.74)	95.7%	96.9%
Understand the etiology, pathophysiology and natural history of structural heart and aortic disease	4.85 (0.63)	4.81 (0.74)	97.8%	96.9%
Understand the hemodynamic consequences of treated and untreated structural heart disease	4.83 (0.64)	4.84 (0.72)	97.8%	96.9%
Recommend optimal medical therapy	4.35 (0.90)	4.38 (0.83)	87.0%	93.8%
Understand the relevant anatomy	5.00 (0.00)	5.00 (0.00)	100.0%	100.0%
Take a history	4.76 (0.74)	4.78 (0.75)	93.5%	96.9%
Perform a physical exam	4.65 (0.77)	4.59 (0.80)	93.5%	96.9%
Collaborate with multidisciplinary team members	4.87 (0.40)	4.91 (0.39)	97.8%	96.9%
Interact with patients and their families	4.74 (0.68)	4.81 (0.59)	97.8%	96.9%
Evaluate a patient and optimize them prior to the procedure	4.70 (0.76)	4.88 (0.55)	93.5%	96.9%
Develop a preprocedural plan for the case	4.87 (0.62)	4.97 (0.18)	97.8%	100.0%
Provide postprocedural care	4.74 (0.71)	4.84 (0.57)	95.7%	96.9%
Provide follow up	4.48 (0.91)	4.47 (0.80)	87.0%	96.9%

Know, interpret and apply the outcomes of clinical trials to decide the optimal interventional strategy	4.72 (0.72)	4.81 (0.74)	95.7%	96.9%
Perform a pre-procedural risk assessment	4.76 (0.74)	5.00 (0.00)	93.5%	100.0%
Select candidates for transcatheter procedures using clinical practice guidelines, indications and contraindications	4.78 (0.66)	4.94 (0.25)	97.8%	100.0%
Acquire fluoroscopic images	4.35 (1.02)	4.56 (0.67)	87.0%	90.6%
Interpret fluoroscopic images	4.70 (0.76)	4.88 (0.34)	93.5%	100.0%
Interpret coronary angiography	4.63 (0.80)	4.81 (0.40)	91.3%	100.0%
Interpret computed tomographic scans	4.67 (0.79)	4.75 (0.67)	91.3%	93.8%
Understand radiation safety	4.48 (0.86)	4.66 (0.55)	87.0%	96.9%
Interpret hemodynamics in the cardiac catheterization laboratory	4.39 (0.91)	4.34 (0.75)	87.0%	90.6%
Know how to use relevant equipment in the cardiac catheterization laboratory or hybrid operating room, including the C-arm and contrast injection systems	4.46 (0.94)	4.66 (0.55)	84.8%	96.9%
Understand how to use contrast agents	4.33 (0.97)	4.59 (0.50)	84.8%	100.0%
Work in a sterile environment	5.00 (0.00)	5.00 (0.00)	100.0%	100.0%
Insert a central venous line or Swan-Ganz catheter	3.91 (1.19)	4.19 (0.90)	65.2%	81.3%*
Insert an arterial line	4.28 (1.00)	4.47 (0.88)	80.4%	81.3%
Obtain vascular access using surgical or percutaneous approach	4.83 (0.68)	4.94 (0.25)	95.7%	100.0%
Achieve vascular closure by direct repair or by using a vascular closure device	4.70 (0.73)	4.84 (0.37)	95.7%	100.0%
Access the heart and great vessels via transthoracic approaches	4.52 (0.78)	4.63 (0.61)	87.0%	93.8%
Select a procedural approach	4.82 (0.58)	4.97 (0.18)	95.6%	100.0%
Dilate access vessel under fluoroscopic vision	4.35 (0.99)	4.47 (0.72)	82.6%	87.5%
Place pursestring sutures	4.43 (1.11)	4.72 (0.81)	84.8%	93.8%
Select wires, catheters and sheaths	4.54 (0.84)	4.75 (0.51)	89.1%	96.9%
Insert wires, catheters and sheaths	4.70 (0.76)	4.81 (0.47)	93.5%	96.9%
Navigate vascular anatomic structures by manipulating wires and catheters	4.61 (0.80)	4.84 (0.37)	91.3%	100.0%
Manage brachial-femoral wires	4.00 (1.10)	4.09 (0.78)	69.6%	81.3%*
Perform wire exchange	4.71 (0.76)	4.78 (0.49)	93.3%	96.9%
Perform size measurements for transcatheter prostheses	4.39 (1.08)	4.69 (0.47)	87.0%	100.0%
Select a transcatheter prosthesis	4.58 (0.92)	4.81 (0.40)	93.3%	100.0%
Deliver a transcatheter prosthesis	4.57 (1.00)	4.91 (0.30)	89.1%	100.0%
Position a transcatheter prosthesis	4.59 (0.98)	4.88 (0.34)	91.3%	100.0%
Deploy a transcatheter prosthesis	4.59 (0.98)	4.88 (0.34)	91.3%	100.0%
Insert a temporary pacing device (wire or epicardial lead)	4.50 (0.86)	4.69 (0.54)	87.0%	96.9%
Perform rapid ventricular pacing	4.54 (0.96)	4.81 (0.47)	89.1%	96.9%
Develop open surgical experience with valve of interest	4.41 (1.09)	4.81 (0.40)	87.0%	100.0%
Insert and manage peripheral mechanical circulatory support	4.02 (1.06)	4.34 (0.70)	76.1%	87.5%*

Insert cannulae for initiating cardiopulmonary bypass	4.52 (0.86)	4.84 (0.45)	87.0%	96.9%
Make decisions during the procedure including anticipating, recognizing and treating procedural complications	4.96 (0.21)	5.00 (0.00)	100.0%	100.0%
Cross the stenotic aortic valve in antegrade or retrograde fashion	4.30 (1.13)	4.66 (0.55)	84.8%	96.9%
Suggested by first round participants				
Appropriate stiff wire manipulation	n.a.	4.84 (0.37)	n.a.	100.0%*
Wire control	n.a.	4.94 (0.25)	n.a.	100.0%*
Exposure to many cases	n.a.	4.78 (0.49)	n.a.	96.9%*

DISCUSSION

This is the first pan-Canadian initiative to identify competencies that cardiac surgery residents must achieve to perform transcatheter procedures. While this initial skillset may be further developed through structural heart or aortic surgery fellowships and beyond, the results obtained by Delphi consensus should be relevant to all cardiac surgery residents. This high level of agreement supports the identified competencies as fundamental for transcatheter cardiac surgery. Trainees, training programs and licensing bodies may benefit by incorporating these results to improve the quality and homogeneity of current training experiences. While not necessarily indicative of relevance to clinical practice or patient outcomes, the average rating of each competency may serve as a surrogate marker for its relative importance during cardiac surgery training. A first step to improve the transcatheter training of cardiac surgery residents may therefore be to target the most highly rated competencies during educational interventions.

The concept of training surgical residents by identifying fundamental competencies or skills is not novel and has been applied to many procedures including laparoscopic surgery,[31] endoscopic surgery,[37,38] vascular surgery[39] and endovascular surgery.[40]

Identifying the fundamental components of a procedure is a crucial step towards developing a targeted educational curriculum. For several of the aforementioned procedures such curricula have even been incorporated into licensing and certification requirements. To the best of our knowledge, this is the first time that this approach has been applied to a cardiac surgical procedure. The next logical steps for curriculum development are to design and implement educational interventions targeted at one or more of these specific learning goals and objectives, with processes in place to permit feedback leading to further refinement and therefore completing the cycle of curriculum development.[47] Future studies should focus on establishing the relative merits of this strategy over traditional transcatheter training paradigms.

It is important to realize that adequate power was not sought *a priori* to thoroughly investigate intra-group differences. Nonetheless, the supplementary analyses that were performed have suggested that—in a minority of cases—the specialty and experience level of respondents might have potentially affected the results (see Supplementary Appendix). These differences are likely not substantial enough to call into question the main study results, which they largely paralleled with the few aforementioned exceptions. Nonetheless, it remains to be determined whether specialty and experience level may substantially affect the perceived importance of transcatheter competencies for cardiac surgery residents.

Using FCTCS to develop educational strategies

As an example of how FCTCS could be used to develop educational strategies, one may consider how best develop a "wire skills" module. The importance of acquiring these competencies has repeatedly been stressed in a high level sense,[6,19] but granularity regarding their precise nature is lacking. Components of FCTCS pertaining to "wire skills" could include wire selection, insertion, navigation, manipulation (including stiff wire manipulation) and control, all of which achieved >95% expert consensus. A relevant module could therefore easily be organized for these competencies using a virtual reality simulator, of which several are commercially available for endovascular procedures.[36] Such an approach would present the opportunity to concurrently develop assessment tools and to validate performance metrics. Depending on the desired learning outcome, elements of varying difficulty could also be incorporated. Similarly, extant simulation platforms could be leveraged to develop FCTCS modules for vascular access and closure, fluoroscopic image acquisition and interpretation, or selection and use of transcatheter prostheses, among others. Indeed, technical as well as non-technical FCTCS content could be delivered using a multitude of platforms and technologies.

Strengths and limitations

The strength of a Delphi study is not predicated on sample size in the way that a randomized clinical trial would be, however, the number of recruited individuals could certainly be seen as a strength of this study—reflecting a strong, nationwide level of engagement. Indeed, while diminishing returns may be met pursuing greater recruitment, certain recommended minimums do exist for multidisciplinary Delphi studies (5-10 participants per discipline), which were achieved here.[100]

This study may have been limited by the inclusion criteria that were used. A number of differences in the ratings of competencies between specialties were identified post-hoc, suggesting that the recruitment of individuals from multiple specialties may have potentially influenced results in a minority of cases (see Tables S1 and S2 in the Supplementary Appendix). We felt, however, that it was important to include individuals from multiple relevant specialties to reflect the way that these procedures are performed in clinical settings. Similarly, the supplementary analysis of experience level suggested that—depending on the definition used—consensus differed among individuals with greater experience (see Table S3 in the Supplementary Appendix). Given the uncertainty regarding the elements that constitute expertise in surgery,[103] we did not aim to be prescriptive in our inclusion criteria and instead aimed to recruit individuals with a spectrum of clinical, procedural and teaching expertise.

An additional limitation relates to the criteria that were used for consensus, which have not been standardized across Delphi studies. Although an 80% threshold of 4 or greater on a 5-point Likert scale has been used previously,[95,98] it may nonetheless be seen as somewhat arbitrary. Thresholds of 70%[100] and 90%[40,96] have also been used and would have resulted in the inclusion of more or less competencies in FCTCS, respectively. As the goal of this study was to achieve high consensus for the most relevant competencies while remaining reasonably inclusive, a threshold of 80% was felt to be optimal. Additionally, this decision is supported by precedent; among Delphi studies that have defined consensus based on percentage agreement (the most commonly used form of consensus definition), a threshold of 80% has been used in the majority of studies.[104]

Finally, the classical form of a Delphi includes an initial round during which participants themselves generate the items to be considered during subsequent survey rounds,[94,95,98,99] however this step was omitted in favour of the competencies identified by a recent scoping review.[93] Nonetheless, the fact that these competencies were generated through an evidence-based approach likely strengthens the robustness of this method and is perhaps an improvement over the method of including items based on the opinions of study investigators, which has been used in other modified Delphi studies.[40,97,100]

CONCLUSION

The Fundamental Competencies for Transcatheter Cardiac Surgery have evolved from an evidence-based process including a structured review of the literature and verification by experts of diverse backgrounds from across the country. With the identification of these specific educational goals and objectives, future efforts can now focus on developing the necessary interventions for cardiac surgery residents to achieve these competencies within the context of their primary residency training.

Chapter 8: Discussion

The published scoping review[93] and completed Delphi study have contributed to transcatheter cardiac surgical training in several ways. By extensively reviewing the competencies required to perform transcatheter cardiovascular procedures, an exhaustive description of these competencies has been obtained. By engaging with experts across the country, a more rigorous analysis of these competencies has been obtained than could have been otherwise accomplished. The present work sought to remain applicable to all cardiac surgery residents for the duration of their training, however, it could easily be adapted for other target groups such as novices, experienced operators or even to specific training environments (e.g. a transcatheter rotation midway through training). Finally, by framing these results within the context of the Kern model, they can easily be translated into future stages of curricular development. All the previously specified objectives were therefore met and overall, the work contained herein will hopefully provide greater direction for cardiac surgery residents and educators than has existed to date.

To more clearly illustrate how exactly the above scoping review and Delphi study have contributed to transcatheter curricular development, consider the fact that with this work, evidence-based learning goals and objectives (in the form of competencies) have now been identified to guide the acquisition of transcatheter skills by cardiac surgery residents. As previously discussed, this level of granularity has not been achieved even at the level of the CBD curriculum by the Royal College. What remains is to organize the identified competences according to discrete education modules, ultimately forming the vehicles for curricular content delivery. As Kern and colleagues so aptly describe, the content of a curriculum can be said to flow from its goals and objectives.[47] The work that has been done therefore makes it clear to learners what will be expected of them, allows educators to focus on the elements that are most important to teach and directs the prioritization of institutional resources.

The deconstruction of complex transcatheter procedures into their component competencies was inspired by the fundamental skills training approach. It is aligned with, but provides greater granularity than, the current EPAs as outlined in the Royal College of Physicians and Surgeons of Canada's CBD curriculum. There is a precedent for using the Delphi method to identify fundamental skills in this manner[40] however less rigid forms of expert consensus have also been used.[31,37–39] Regardless of how they were derived, the common benefit to retaining generalized, non procedure-specific competencies (i.e. fundamental skills) is the way that this complements traditional training. For example, rather than completing educational modules to learn each of a related set of procedures (as in transcatheter cardiac surgery), fundamental skills training allows trainees to focus on attaining proficiency in the competencies that will enable them to acquire, perform and master new procedures *in vivo*. This is an important conceptual departure from the historical Halstedian model, which relied mainly on sheer volume of exposure to ensure that residents were suitably trained. There can ultimately be no substitute for being in the operating room and operating on real patients. Yet, a fundamental skills training approach that incorporates models of competency- and simulation-based education may ease the transition for novices and, most importantly, provide trainees with the means to thrive in the operative environment.

The aviation sector has often been compared with surgery as both are fields with high stakes, low margins for error and potentially disastrous adverse outcomes.[105,106] In fact, out of a desire for improved patient safety, many changes in the delivery of surgical care—such as the use of safety checklists—have been adopted that are directly inspired by aviation.[105,106] Still, the incidence of so-called "never events" (catastrophic events that are largely preventable) is approximately 1 per 20,000 surgeries compared to 1 per 2.6 million flight departures.[105] It is therefore interesting to note, despite their similarities, how different training and maintenance of competence is for a surgeon as for a pilot. The deconstruction of technical and non-technical components required to successfully complete complex procedures—not unlike what has been proposed in this thesis—is commonplace in the aviation industry where pilots rigorously rehearse these components to near perfection using simulation.[106] Moreover, licensed pilots regularly participate in maintenance of competency activities to worldwide, universally agreed-upon standards. A counterpart exists within medicine in the form of continuing medical education, but as is the case with postgraduate training an inappropriate emphasis is placed on time spent and not on proficiency maintained; continuing medical education requirements for physicians almost entirely depend on providing documentation for the number of hours spent participating in qualifying activities. Therefore, while the methods proposed in this thesis are a departure from current surgical training, they are not entirely without precedent.

It would be misguided to expect that simply advancing the status of transcatheter cardiac surgical curricular development will rectify the difficulties encountered by cardiac surgery residents on a daily basis and the real-world barriers to implementation of such a curriculum.[6–9] Yet, it would be equally erroneous to expect these issues to resolve without concerted efforts by surgeons to ensure that their trainees are in the best possible condition prior to arriving in the cardiac catheterization laboratory or hybrid operating room. For this reason, curricular development in transcatheter cardiac surgery is worth pursuing even if it is not immediately clear how the curriculum will be administered. Indeed, difficulties can be anticipated during the implementation stage of any new curricula as this is the stage that requires obtaining necessary political support and resources to transition the curriculum from theory to practice.[47] In this regard, these issues are not unique to transcatheter cardiac surgery.

Finally, as surgical education has expanded to include contemporary educational theory, so too has our understanding of the elements that contribute to competence in surgery. The stereotypical surgeon of Halsted's time possessed an unparalleled mastery of the technical elements of their craft, however, was arrogant and lacking in bedside manner. In the modern day it is increasingly recognized that technical and non-technical elements alike are equally important. Perhaps due to their more abstract nature, such non-technical elements have been variously described. Attempts to differentiate these elements have included the knowledge-skills-attitudes framework,[40] defining learning objectives as "cognitive (knowledge), affective (attitudinal) or psychomotor (skill and behavioral)"[47] or simply distinguishing declarative knowledge from procedural knowledge.[31,37,38] Unfortunately there is no single accepted framework and in any case such definitions are likely to continue changing with greater understanding of the way that these various elements interact. For this reason, no attempts were made to include such distinctions within this thesis, although it is acknowledged that more proper definitions could be developed. Ultimately the definition itself may be secondary to the chosen methods of content delivery and implementation; educational value will be maximized as long as any chosen educational strategies are appropriately aligned with the desired learning goals and objectives.

Chapter 9: Conclusion and future directions

This thesis represents the culmination of work intended to address the deficiencies in transcatheter cardiac surgical training that exist within current paradigms. Whereas previously there existed minimal evidence to guide would-be educators in cardiac surgery wishing to improve the transcatheter training of their residents, the present work provides an empirical, theoretically sound foundation—based on the Kern model—with which to develop future educational modules. By reducing the procedures of interest to their most relevant competencies—as in a fundamental skills training approach—residents can feasibly be trained to an acceptable level of competence within the constraints of contemporary surgical training. What remains is to determine the educational strategies that are best suited for each of the identified training goals and objectives, to secure the necessary resources and support for their implementation and to holistically evaluate any end-products so that cardiac surgery residents can continue benefiting from iterative improvements to these new transcatheter training paradigms. Though this was regrettably not attainable within the scope of a Masters project, particularly during the COVID-19 pandemic, with the completion of this thesis sufficient preparatory work has been done to facilitate such future endeavours.

Apart from the educational implications, there are implications from the perspective of future research that relate to this work. As novel educational strategies are developed, there will be innumerable opportunities to engage in the process of collecting evidence for their validity. This may include designing assessment tools, evaluating performance metrics or comparing methods of content delivery, to name a few. Importantly, as curricular elements are refined through future iterations, the need will remain to ensure that sufficient evidence supporting their validity persists to justify their continued use. Finally, as an extension and once supported by sufficient evidence, there may be a role for considering the appropriateness of high-stakes assessments. The summative component of a cardiac surgical residency currently occurs at the end of training, however it may be desirable to introduce summative elements relating to transcatheter procedures earlier than this to ensure consistent standards of training across the country and to accommodate the anticipated growth of transcatheter procedures. Depending on the success of the proposed training paradigm, a question that will need to be addressed is whether such an approach should be expanded to include more routinely performed procedures and to other specialties.

The development of disruptive transcatheter technology has revolutionized treatment options for patients with structural heart and aortic disease. It is uncertain what further developments the future may bring, but it is clear that the status of open surgery as the gold standard treatment is being challenged. This thesis represents the first steps in what will hopefully evolve to be a new, improved paradigm for the acquisition of transcatheter skills in cardiac surgery residents.

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Appendix

SUPPLEMENT TO:
A scoping review on the performance of transcatheter cardiac surgery

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Supplementary Table 1: Ovid MEDLINE search strategy

1. cardiac surgical procedures/
2. cardio* surge*.tw,kf.
3. cardiac surg*.tw,kf.
4. 1 or 2 or 3
5. radiology, interventional/
6. interventional radiolog*.tw,kf.
7. 5 or 6
8. vascular surgical procedures/
9. vascular surg*.tw,kf.
10. 8 or 9
11. cardiology/
12. cardiolog*.tw,kf.
13. interventional cardiolog*.tw,kf.
14. 11 or 12 or 13
15. structural heart.tw,kf.
16. 4 or 7 or 10 or 14 or 15
17. endovascular procedures/
18. endovascular.tw,kf.
19. endo vascular.tw,kf.
20. intravascular.tw,kf.
21. intra vascular.tw,kf.
22. transcatheter.tw,kf.
23. trans catheter.tw,kf.
24. wire.tw,kf.
25. wires.tw,kf.
26. catheter*.tw,kf.
27. 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26
28. 16 and 27
29. clinical competence/
30. "Task Performance and Analysis"/
31. competen*.tw,kf.
32. performance.tw,kf.

33. proficien*.tw,kf.
34. fundament*.tw,kf.
35. skill.tw,kf.
36. skills.tw,kf.
37. curricul*.tw,kf.
38. teach*.tw,kf.
39. train.tw,kf.
40. training.tw,kf.
41. simulat*.tw,kf.
42. 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37 or 38 or 39 or 40 or 41
43. 28 and 42
44. exp education, medical, graduate/
45. trainee*.tw,kf.
46. intern.tw,kf.
47. interns*.tw,kf.
48. residen*.tw,kf.
49. 44 or 45 or 46 or 47 or 48
50. 43 and 49
51. exp cardiac catheterization/
52. angioplasty, balloon, coronary/
53. atherectomy, coronary/
54. exp percutaneous coronary intervention/
55. catheterization, peripheral/
56. angioplasty/
57. angioplasty, balloon/
58. cardiac catheterization.tw,kf.
59. heart catheterization.tw,kf.
60. angioplast*.tw,kf.
61. percutaneous coronary intervention.tw,kf.
62. 51 or 52 or 53 or 54 or 55 or 56 or 57 or 58 or 59 or 60 or 61
63. 42 and 49 and 62
64. aortic stenosis/
65. heart valve prosthesis implantation/
66. 27 and 64 and 65
67. transcatheter aortic valve replacement/
68. tavi.tw,kf.
69. tavr.tw,kf.
70. transcatheter aortic valve implantation.tw,kf.
71. transcatheter aortic valve replacement.tw,kf.
72. 67 or 68 or 69 or 70 or 71
73. 66 or 72

74. tevar.tw,kf.
75. evar.tw,kf.
76. endovascular aortic replacement.tw,kf.
77. endovascular aortic repair.tw,kf.
78. endovascular aneurysm repair.tw,kf.
79. 74 or 75 or 76 or 77 or 78
80. Stents/
81. blood vessel prosthesis implantation/
82. stent.tw,kf.
83. 80 or 81 or 82
84. aortic aneurysm, thoracic/
85. aorta, thoracic/
86. 84 or 85
87. 83 and 86
88. 79 or 87
89. 73 or 88
90. 42 and 49 and 89
91. advisory committees/st
92. clinical competence/st
93. certification/
94. clinical competence statement*.tw,kf.
95. 91 or 92 or 93 or 94
96. 89 and 95
97. 50 or 63 or 90 or 96

SUPPLEMENT TO:

Pan-Canadian Initiative on Fundamental Competencies for Transcatheter Cardiac Surgery: A Modified Delphi Consensus Study

Hellmuth R. Muller Moran MD, Meagane Maurice-Ventouris BSc, Mohammed Alharbi MD, Byunghoon "Tony" Ahn BSc MEd, Jason M. Harley MA PhD, Kevin J. Lachapelle MDCM FACS FRCPSC

Supplementary Table 2: Results of Kruskal-Wallis H test comparing results between specialties. Items that met consensus criteria are indicated in bold.

Competency	Cardiac surgery (n = 16)	Interventional cardiology (n = 11)	Vascular surgery (n = 5)	P
Diagnose structural heart and thoracic aortic disease	**4.75(1)**	**4.91(0.302)**	**4.8(0.447)**	**0.702**
Understand the etiology, pathophysiology and natural history of structural heart and aortic disease	**4.75(1)**	**4.91(0.302)**	**4.8(0.447)**	**0.702**
Understand the hemodynamic consequences of treated and untreated structural heart disease	**4.75(1)**	**5(0)**	**4.8(0.447)**	**0.344**
Recommend optimal medical therapy	**4.31(1.01)**	**4.55(0.688)**	**4.2(0.447)**	**0.428**
Understand the relevant anatomy	**5(0)**	**5(0)**	**5(0)**	**1.000**
Take a history	**4.75(1)**	**4.82(0.405)**	**4.8(0.447)**	**0.633**
Perform a physical exam	**4.56(1.03)**	**4.55(0.522)**	**4.8(0.447)**	**0.523**
Collaborate with multidisciplinary team members	**4.88(0.5)**	**5(0)**	**4.8(0.447)**	**0.344**
Interact with patients and their families	**4.69(0.793)**	**4.91(0.302)**	**5(0)**	**0.494**
Participate in registries and outcome studies	3.38(1.02)	3.64(0.505)	3.75(0.5)	0.590
Evaluate a patient and optimize them prior to the procedure	4.81(0.75)	5(0)	4.8(0.447)	0.344
Manage coexisting conditions	4.13(0.619)	3.82(0.603)	3.6(0.548)	0.188
Develop a preprocedural plan for the case	**4.94(0.25)**	**5(0)**	**5(0)**	**0.607**
Provide postprocedural care	**4.75(0.775)**	**4.91(0.302)**	**5(0)**	**0.703**
Provide follow up	**4.31(1.01)**	**4.55(0.522)**	**4.8(0.447)**	**0.476**
Know, interpret and apply the outcomes of clinical trials to decide the optimal interventional strategy	**4.69(1.01)**	**5(0)**	**4.8(0.447)**	**0.393**
Perform a pre-procedural risk assessment	**5(0)**	**5(0)**	**5(0)**	**1.000**
Select candidates for transcatheter procedures using clinical practice guidelines, indications and	**4.94(0.25)**	**5(0)**	**4.8(0.447)**	**0.321**

contraindications				
Acquire echocardiography	3(0.966)	2.82(0.751)	3(0.707)	0.783
Interpret echocardiography	4(0.894)	3.73(0.786)	3.6(0.548)	0.175
Acquire fluoroscopic images	**4.5(0.632)**	**4.64(0.809)**	**4.6(0.548)**	**0.609**
Interpret fluoroscopic images	**4.81(0.403)**	**4.91(0.302)**	**5(0)**	**0.507**
Interpret coronary angiography	**4.94(0.25)**	**4.73(0.467)**	**4.6(0.548)**	**0.171**
Interpret computed tomographic scans	**4.81(0.75)**	**4.64(0.674)**	**4.8(0.447)**	**0.390**
Interpret magnetic resonance imaging	3.25(0.683)	2.73(0.647)	3.8(0.447)	0.016
Understand radiation safety	**4.5(0.516)**	**4.82(0.603)**	**4.8(0.447)**	**0.116**
Interpret hemodynamics in the cardiac catheterization laboratory	**4.31(0.793)**	**4.45(0.82)**	**4.2(0.447)**	**0.558**
Know how to use relevant equipment in the cardiac catheterization laboratory or hybrid operating room, including the C-arm and contrast injection systems	**4.56(0.512)**	**4.82(0.603)**	**4.6(0.548)**	**0.236**
Understand how to use contrast agents	**4.63(0.5)**	**4.55(0.522)**	**4.6(0.548)**	**0.920**
Work in a sterile environment	**5(0)**	**5(0)**	**5(0)**	**1.000**
Insert a central venous line or Swan-Ganz catheter	**4.25(0.683)**	**4.27(1.01)**	**3.8(1.3)**	**0.698**
Insert an arterial line	**4.63(0.719)**	**4.55(0.82)**	**3.8(1.3)**	**0.253**
Obtain vascular access using surgical or percutaneous approach	**4.94(0.25)**	**5(0)**	**4.8(0.447)**	**0.321**
Achieve vascular closure by direct repair or by using a vascular closure device	**4.75(0.447)**	**4.91(0.302)**	**5(0)**	**0.321**
Access the heart and great vessels via transthoracic approaches	**4.56(0.629)**	**4.73(0.647)**	**4.6(0.548)**	**0.620**
Select a procedural approach	**4.94(0.25)**	**5(0)**	**5(0)**	**0.607**
Dilate access vessel under fluoroscopic vision	**4.44(0.727)**	**4.73(0.647)**	**4(0.707)**	**0.103**
Perform surgical procedures on the left ventricular apex	4(0.73)	4.36(1.03)	4.2(0.837)	0.328
Place pursestring sutures	**4.69(1.01)**	**4.82(0.603)**	**4.6(0.548)**	**0.347**
Select wires, catheters and sheaths	**4.81(0.403)**	**4.64(0.674)**	**4.8(0.447)**	**0.816**
Insert wires, catheters and sheaths	**4.81(0.403)**	**4.82(0.603)**	**4.8(0.447)**	**0.835**
Navigate vascular anatomic structures by manipulating wires and catheters	**4.88(0.342)**	**4.82(0.405)**	**4.8(0.447)**	**0.888**
Manage brachial-femoral wires	**4.06(0.854)**	**4.18(0.751)**	**4(0.707)**	**0.881**
Perform wire exchange	**4.75(0.447)**	**4.82(0.603)**	**4.8(0.447)**	**0.679**
Perform size measurements for transcatheter prostheses	**4.69(0.479)**	**4.82(0.405)**	**4.4(0.548)**	**0.258**
Select a transcatheter prosthesis	**4.75(0.447)**	**5(0)**	**4.6(0.548)**	**0.117**
Deliver a transcatheter prosthesis	**4.88(0.342)**	**5(0)**	**4.8(0.447)**	**0.382**
Position a transcatheter prosthesis	**4.94(0.25)**	**4.91(0.302)**	**4.6(0.548)**	**0.134**
Deploy a transcatheter prosthesis	**4.94(0.25)**	**4.91(0.302)**	**4.6(0.548)**	**0.134**
Insert a temporary pacing device (wire	**4.81(0.403)**	**4.73(0.647)**	**4.2(0.447)**	**0.032**

or epicardial lead)				
Perform rapid ventricular pacing	**4.94(0.25)**	**5(0)**	**4(0.707)**	**< .001**
Develop open surgical experience with valve of interest	**4.88(0.342)**	**4.7(0.483)**	**4.8(0.447)**	**0.557**
Insert and manage peripheral mechanical circulatory support	**4.5(0.73)**	**4.18(0.751)**	**4.2(0.447)**	**0.345**
Insert cannulae for initiating cardiopulmonary bypass	**4.94(0.25)**	**4.73(0.647)**	**4.8(0.447)**	**0.556**
Perform a frozen elephant trunk (great vessel debranching and deployment of an endoluminal graft into the aortic arch)	3(0.966)	2.82(0.603)	3.6(0.548)	0.166
Make decisions during the procedure including anticipating, recognizing and treating procedural complications	**5(0)**	**5(0)**	**5(0)**	**1.000**
Perform intravascular ultrasonography	2.94(0.772)	2.18(0.603)	3.2(0.447)	0.007
Utilize cerebral embolic protection	2.94(0.772)	3.09(0.701)	3(0.707)	0.992
Perform intravascular snaring and retrieval	3(0.516)	3.36(0.809)	2.8(0.447)	0.275
Perform coil embolization	2.13(0.885)	2.18(0.751)	2.4(0.548)	0.684
Perform side-branch angioplasty and stenting	2.06(0.854)	1.91(1.14)	2.4(0.548)	0.254
Perform transcatheter pulmonary valve implantation	2.13(0.885)	2(0.775)	3(0)	0.044
Cross the stenotic aortic valve in antegrade or retrograde fashion	**4.63(0.619)**	**4.91(0.302)**	**4.2(0.447)**	**0.027**
Perform percutaneous paravalvular leak closure	2(0.816)	2.09(0.944)	2.8(0.837)	0.234
Perform balloon aortic, mitral, tricuspid or pulmonary valvuloplasty	3.13(1.15)	3(1.1)	2.8(0.837)	0.827
Perform transhepatic access	1.38(0.619)	1.09(0.302)	1.8(0.447)	0.027
Perform balloon pericardiotomy	1.63(0.719)	1.45(0.522)	2.4(0.894)	0.099
Perform percutaneous ventricular pseudoaneurysm closure	1.56(0.629)	1.6(0.699)	2.2(0.837)	0.244
Perform endovascular endoleak closure	2.06(0.929)	2(0.894)	1.6(0.894)	0.594
Perform percutaneous aortic pseudoaneurysm closure	2.06(0.929)	1.91(0.944)	2.2(0.837)	0.813
Perform angioplasty and stenting for coarctation of the aorta	2.06(0.854)	1.73(0.786)	2.8(0.447)	0.059
Perform angioplasty and stenting of surgical conduits, baffles and homografts	1.75(0.775)	1.73(0.647)	2.6(0.548)	0.069
Perform angioplasty and stenting of interatrial septum and Fontan fenestrations	1.56(0.629)	1.18(0.405)	2.4(0.548)	0.004
Perform coronary angiography	2.94(1.12)	2.27(1.19)	2.2(0.447)	0.168

Perform percutaneous coronary interventions	2.06(1.24)	1.55(1.21)	1.8(0.837)	0.253
Perform transseptal puncture	2.88(1.02)	2.55(1.21)	2.4(0.548)	0.425
Perform transseptal left heart catheterization	2.13(1.02)	2.18(1.33)	2.2(0.447)	0.966
Perform percutaneous atrial septal defect closure	1.94(0.998)	1.82(0.874)	2.4(0.548)	0.407
Perform pulmonary vein stenting	1.44(0.892)	1.27(0.647)	1.8(0.447)	0.101
Perform percutaneous ventricular septal defect closure	1.44(0.814)	1.27(0.905)	2(0.707)	0.037
Access the coronary sinus using percutaneous approach	1.94(0.998)	1.27(0.647)	2(1.22)	0.127
Perform septal ablation	1.25(0.577)	1(0)	1.8(0.837)	0.020
Perform percutaneous patent foramen ovale closure	1.5(0.894)	1.18(0.603)	1.8(0.837)	0.155
Perform percutaneous patent ductus arteriosus closure	1.31(0.793)	1.18(0.603)	1.6(0.548)	0.122
Perform percutaneous left atrial appendage exclusion	1.63(0.957)	1.27(0.647)	1.8(0.447)	0.166
Perform pulmonary artery stenting	1.31(0.602)	1.09(0.302)	1.6(0.548)	0.117
Perform coronary fistula embolization	1.19(0.544)	1(0)	1.4(0.548)	0.102
Perform brachiocephalic transposition or extra-anatomic revascularizations	1.75(1)	1.09(0.302)	2.2(0.837)	0.031
Perform carotid artery stenting	1.25(0.577)	1.09(0.302)	1.2(0.447)	0.752
Perform endovascular treatment of aortoiliac disease	2(1.26)	1.91(1.04)	1.4(0.548)	0.668
Perform endovascular treatment of great vessel occlusive disease	2(0.894)	1.64(0.809)	1.6(0.894)	0.453
Perform endovascular treatment of mesenteric vascular disease	1.44(0.629)	1.27(0.467)	1(0)	0.267
Perform percutaneous embolectomy/thrombectomy	1.94(0.998)	1.55(0.688)	1.6(0.894)	0.579
Perform endovascular interventions for peripheral vascular disease	1.75(0.931)	2.09(0.944)	1.2(0.447)	0.175
Perform peripheral angiography	2.75(1)	3.64(1.03)	2(0.707)	0.009
Perform endovascular aneurysm repair	2.63(1.54)	1.55(0.82)	1(0)	0.025
Perform balloon angioplasty	2.31(1.3)	2.55(1.13)	2.4(0.894)	0.846
Appropriate stiff wire manipulation	4.88(0.342)	4.91(0.302)	4.6(0.548)	0.267
Wire control	**5(0)**	**4.91(0.302)**	**4.8(0.447)**	**0.254**
Exposure to many cases	**4.88(0.342)**	**4.82(0.405)**	**4.4(0.894)**	**0.327**
Percutaneous fenestration for dissection	**2.69(0.793)**	**2.45(1.21)**	**3(0.707)**	**0.346**

*Continuous variables listed as mean (standard deviation)

Supplementary Table 3: Dwass-Steel-Critchlow-Fligner pairwise comparisons of items that met consensus criteria with statistically significant differences in responses between specialties.

Competency	Pairwise comparison	W	P
Insert a temporary pacing device (wire or epicardial lead)	Cardiac surgery and interventional cardiology	-0.103	0.997
	Cardiac surgery and vascular surgery	-3.5	0.036
	Interventional cardiology and vascular surgery	-2.817	0.114
Perform rapid ventricular pacing	Cardiac surgery and interventional cardiology	1.17	0.685
	Cardiac surgery and vascular surgery	-4.72	0.002
	Interventional cardiology and vascular surgery	-4.65	0.003
Cross the stenotic aortic valve in antegrade or retrograde fashion	Cardiac surgery and interventional cardiology	1.93	0.361
	Cardiac surgery and vascular surgery	-2.34	0.222
	Interventional cardiology and vascular surgery	-3.88	0.017

Supplementary Table 4: Re-analysis of main study results among individuals with high clinical, procedural or teaching experience. Responses reaching the prespecified threshold consensus of 80% are indicated in bold.

Competency	High clinical experience (n = 14)	High procedural experience (n = 12)	High teaching experience (n = 15)	Entire cohort (n = 32)
Diagnose structural heart and thoracic aortic disease	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Understand the etiology, pathophysiology and natural history of structural heart and aortic disease	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Understand the hemodynamic consequences of treated and untreated structural heart disease	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Recommend optimal medical therapy	**85.7%**	**91.7%**	**93.3%**	**93.8%**
Understand the relevant anatomy	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Take a history	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Perform a physical exam	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Collaborate with multidisciplinary team members	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Interact with patients and their families	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Participate in registries and outcome studies	50.0%	50.0%	78.6%	54.8%
Evaluate a patient and optimize them prior to the procedure	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Manage coexisting conditions	**85.7%**	**83.3%**	73.3%	78.1%
Develop a preprocedural plan for the case	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Provide postprocedural care	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Provide follow up	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Know, interpret and apply the outcomes of clinical trials to decide the optimal interventional strategy	**92.9%**	**91.7%**	**100.0%**	**96.9%**
Perform a pre-procedural risk assessment	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Select candidates for transcatheter procedures using clinical practice guidelines, indications and contraindications	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Acquire echocardiography	42.9%	41.7%	13.3%	28.1%

Interpret echocardiography	71.4%	**83.3%**	73.3%	75.0%
Acquire fluorscopic images	**92.9%**	**83.3%**	**93.3%**	**90.6%**
Interpret fluoroscopic images	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Interpret coronary angiography	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Interpret computed tomographic scans	**92.9%**	**83.3%**	**100.0%**	**93.8%**
Interpret magnetic resonance imaging	35.7%	33.3%	46.7%	34.4%
Understand radiation safety	**100.0%**	**91.7%**	**100.0%**	**96.9%**
Interpret hemodynamics in the cardiac catheterization laboratory	**92.9%**	**83.3%**	**93.3%**	**90.6%**
Know how to use relevant equipment in the cardiac catheterization laboratory or hybrid operating room, including the C-arm and contrast injection systems	**92.9%**	**100.0%**	**100.0%**	**96.9%**
Understand how to use contrast agents	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Work in a sterile environment	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Insert a central venous line or Swan-Ganz catheter	**100.0%**	**83.3%**	**80.0%**	**81.3%**
Insert an arterial line	**100.0%**	**83.3%**	**80.0%**	**81.3%**
Obtain vascular access using surgical or percutaneous approach	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Achieve vascular closure by direct repair or by using a vascular closure device	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Access the heart and great vessels via transthoracic approaches	**92.9%**	**83.3%**	**100.0%**	**93.8%**
Select a procedural approach	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Dilate access vessel under fluoroscopic vision	**85.7%**	**91.7%**	**86.7%**	**87.5%**
Perform surgical procedures on the left ventricular apex	78.6%	**75.0%**	**80.0%**	**78.1%**
Place pursestring sutures	**85.7%**	**83.3%**	**93.3%**	**93.8%**
Select wires, catheters and sheaths	**92.9%**	**100.0%**	**100.0%**	**96.9%**
Insert wires, catheters and sheaths	**92.9%**	**100.0%**	**100.0%**	**96.9%**
Navigate vascular anatomic structures by manipulating wires and catheters	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Manage brachial-femoral wires	**85.7%**	**91.7%**	**80.0%**	**81.3%**
Perform wire exchange	**92.9%**	**100.0%**	**100.0%**	**96.9%**
Perform size measurements for transcatheter prostheses	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Select a transcatheter prosthesis	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Deliver a transcatheter prosthesis	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Position a transcatheter prosthesis	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Deploy a transcatheter prosthesis	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Insert a temporary pacing device (wire or epicardial lead)	**100.0%**	**100.0%**	**93.3%**	**96.9%**
Perform rapid ventricular pacing	**100.0%**	**100.0%**	**93.3%**	**96.9%**
Develop open surgical experience with valve of interest	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Insert and manage peripheral mechanical circulatory support	**92.9%**	**83.3%**	**100.0%**	**87.5%**
Insert cannulae for initiating cardiopulmonary bypass	**100.0%**	**100.0%**	**100.0%**	**96.9%**
Perform a frozen elephant trunk (great vessel debranching and deployment of an endoluminal graft into the aortic arch)	50.0%	25.0%	26.7%	31.3%
Make decisions during the procedure including anticipating, recognizing and treating procedural complications	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Perform intravascular ultrasonography	21.4%	16.7%	13.3%	12.5%
Utilize cerebral embolic protection	28.6%	16.7%	20.0%	15.6%
Perform intravascular snaring and retrieval	14.3%	25.0%	20.0%	12.5%
Perform coil embolization	14.3%	8.3%	6.7%	6.3%
Perform side-branch angioplasty and stenting	14.3%	8.3%	6.7%	6.3%
Perform transcatheter pulmonary valve implantation	7.1%	0.0%	0.0%	3.1%
Cross the stenotic aortic valve in antegrade or retrograde fashion	**100.0%**	**91.7%**	**100.0%**	**96.9%**
Perform percutaneous paravalvular leak closure	7.1%	8.3%	13.3%	6.3%
Perform balloon aortic, mitral, tricuspid or pulmonary valvuloplasty	50.0%	25.0%	40.0%	34.4%
Perform transhepatic access	0.0%	0.0%	0.0%	0.0%
Perform balloon pericardiotomy	0.0%	0.0%	0.0%	0.0%
Perform percutaneous ventricular pseudoaneurysm closure	0.0%	0.0%	0.0%	0.0%
Perform endovascular endoleak closure	7.1%	0.0%	0.0%	3.1%
Perform percutaneous aortic pseudoaneurysm closure	7.1%	0.0%	0.0%	3.1%
Perform angioplasty and stenting	0.0%	0.0%	0.0%	0.0%

for coarctation of the aorta				
Perform angioplasty and stenting of surgical conduits, baffles and homografts	0.0%	0.0%	0.0%	0.0%
Perform angioplasty and stenting of interatrial septum and Fontan fenestrations	0.0%	0.0%	0.0%	0.0%
Perform coronary angiography	21.4%	25.0%	13.3%	15.6%
Perform percutaneous coronary interventions	21.4%	25.0%	13.3%	12.5%
Perform transseptal puncture	14.3%	16.7%	6.7%	12.5%
Perform transseptal left heart catheterization	14.3%	8.3%	6.7%	6.3%
Perform percutaneous atrial septal defect closure	7.1%	0.0%	0.0%	3.1%
Perform pulmonary vein stenting	7.1%	0.0%	0.0%	3.1%
Perform percutaneous ventricular septal defect closure	14.3%	8.3%	6.7%	6.3%
Access the coronary sinus using percutaneous approach	7.1%	0.0%	6.7%	6.3%
Perform septal ablation	0.0%	0.0%	0.0%	0.0%
Perform percutaneous patent foramen ovale closure	7.1%	0.0%	0.0%	3.1%
Perform percutaneous patent ductus arteriosus closure	7.1%	0.0%	0.0%	3.1%
Perform percutaneous left atrial appendage exclusion	7.1%	0.0%	0.0%	3.1%
Perform pulmonary artery stenting	0.0%	0.0%	0.0%	0.0%
Perform coronary fistula embolization	0.0%	0.0%	0.0%	0.0%
Perform brachiocephalic transposition or extra-anatomic revascularizations	0.0%	0.0%	0.0%	0.0%
Perform carotid artery stenting	0.0%	0.0%	0.0%	0.0%
Perform endovascular treatment of aortoiliac disease	14.3%	8.3%	6.7%	9.4%
Perform endovascular treatment of great vessel occlusive disease	7.1%	0.0%	0.0%	3.1%
Perform endovascular treatment of mesenteric vascular disease	0.0%	0.0%	0.0%	0.0%
Perform percutaneous embolectomy/thrombectomy	7.1%	0.0%	0.0%	3.1%
Perform endovascular interventions for peripheral vascular disease	0.0%	0.0%	0.0%	3.1%
Perform peripheral angiography	35.7%	41.7%	40.0%	37.5%
Perform endovascular aneurysm	14.3%	16.7%	6.7%	12.5%

repair				
Perform balloon angioplasty	21.4%	16.7%	6.7%	12.5%
Appropriate stiff wire manipulation	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Wire control	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Exposure to many cases	**92.9%**	**100.0%**	**93.3%**	**96.9%**
Percutaneous fenestration for dissection	21.4%	16.7%	20.0%	12.5%