Review
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Pediatric Cardiac Critical Care in the United States: Historical Perspectives and the Modern Era

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The fields of pediatric cardiology and congenital heart surgery have made significant advancements over the past 70 years, reversing an earlier era of nearly universal mortality for all forms of congenital heart disease. Pediatric cardiac patients, particularly those with congenital heart disease, represent some of the most heterogeneous and complex patients to manage with an array of pathophysiologies. A highly functioning and collaborative team is required to care for this population effectively. Here we review the history of the field of pediatric cardiac critical care, the current system in the United States, and some additional considerations in the modern era.

Keywords: pediatric cardiac intensive care, congenital heart disease

Introduction

The fields of pediatric cardiology and congenital heart surgery have made significant advancements over the past 70 years, reversing an earlier era of nearly universal mortality for all forms of congenital heart disease. Pediatric cardiac patients, particularly those with congenital heart disease, represent some of the most heterogeneous and complex patients to manage with an array of pathophysiologies. A highly functioning and collaborative team is required to care for this population effectively. Here we review the history of the field of pediatric cardiac critical care, the current system in the United States, and some additional considerations in the modern era.

History of Pediatric Cardiac Intensive Care

The development of pediatric cardiac intensive care is inextricably entwined with the advances in pediatric cardiology and cardiac surgery. Dr. Helen Taussig, lauded as the "mother of cardiology," pioneered the field in the 1940's using physical examination and fluoroscopy to describe patterns of congenital heart disease, including the common cyanotic lesion tetralogy of Fallot (TOF). With recognition that children with TOF and a patent ductus arteriosus (PDA) survived beyond infancy, she approached Dr. Robert E. Gross, a surgeon at Boston Children's Hospital renowned for ligating PDAs, who summarily dismissed Dr. Taussig's suggestion that an artificial PDA could be surgically created to prolong the lives of patients with cyanotic congenital heart disease.

Dr. Taussig persisted in her pursuit of treatment of "blue baby syndrome" and partnered with Dr. Alfred Blalock and his African-American research technician Vivien Thomas at Johns Hopkins University. Together they pioneered development of a systemic arterial to pulmonary arterial shunt, which originally was named the Blalock–Taussig shunt, but today is more appropriately known as the Blalock–Taussig–Thomas shunt in recognition of Vivien Thomas' instrumental role in its success. The first patient to undergo placement of a Blalock–Taussig–Thomas shunt was 15 month-old TOF patient Eileen Saxon in 1944, with remarkable improvement in her cyanosis and reversal of her failure to thrive.[1–3)]

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The next great advance in cardiac surgery was development of the cardiopulmonary bypass machine. This technology was originally intended to be used during pulmonary embolectomy. The original heart-lung machine was first successfully used for intracardiac cardiac repair in 1953 by Dr. John Gibbon to close an atrial septal defect.[4] The successful use of cardiopulmonary bypass during open heart surgery sparked a rapid expansion of its use for repair and palliation of a variety of congenital heart lesions, and the concomitant need for specialized post-surgical intensive care units.

The first pediatric intensive care unit (PICU) was established at the Children's Hospital in Gotebord, Sweden in 1955 where they successfully treated a moribund boy after surgery for a ruptured appendicitis with endotracheal intubation, manual ventilation, and blood transfusion. In this early model, the lead anesthesiologist, Dr. Goran Haglund, recognized the critical importance of nurses and nurse assistants to this successful outcome.[5] The subsequent decade saw development of similar units throughout Europe, Australia and the first PICU in the United States at the Children's Hospital of Philadelphia in 1967.[6] As these PICUs grew and expanded, specialized training programs evolved and the American Academy of Pediatrics created a section of critical care medicine in 1984, with the American Board of Pediatrics offering the first certifying exam in the field in 1987. The expansion PICUs and the technologic advances in monitoring and support devices have pushed the field of pediatric intensive care to its current state with the ability to rescue and support children, offering survival to patients who would have perished in previous eras.

Models of Care for Pediatric Cardiac Patients

Paralleling the expanding fields of pediatric cardiology and pediatric cardiac surgery, the intensive care field saw further specialization of pediatric cardiac intensive care. In the current era, the pediatric intensivist is responsible for leading a multi-disciplinary team to provide cardiorespiratory support through disease or intervention, using a complex combination of medical therapies and technology. As cardiac surgical volumes and complexities have grown, there has been a growing need for expertise in the unique anatomic and physiologic challenges. Institutions have adopted a few different approaches to caring for pediatric cardiac patients. The first approach is to care for these patients in a defined pediatric cardiac ICU (CICU) which is designated specifically for the patient with a primary cardiac condition requiring ICU level care, separate from the care in the general medical and surgical PICU. The second approach is to provide care in a mixed ICU where care of the pediatric cardiac patients occurs in the same physical location as care of other critically ill children. In high volume cardiac surgical centers,[7), [1]] generally defined as greater than 350 surgical cases per year, most centers have designated a dedicated pediatric CICU. Programs with low cardiac surgical volumes (less than 150 surgical cases per year) represent about 44% of programs in the STS database (CHSD). In these low-volume programs, the pediatric cardiac intensive care typically occurs within the general PICU. A survey of the care models in the United States showed that out of one hundred and twenty ICUs, 59 (49%) were dedicated CICUs. In the mixed ICU structure, about one third had designated beds for cardiac patients.[8] Regardless of the care model, all institutions surveyed had advanced support capabilities with the availability of extracorporeal membrane oxygenation (ECMO). However, dedicated CICUs had more availability of durable cardiac support devices and cardiac subspecialists (electrophysiology, heart failure/transplant and cardiac anesthesia) compared to mixed ICUs.

Given the various models of care, the critical question is whether one model is superior to another with respect to outcomes. There has been conflicting data about the association of outcomes of patients undergoing pediatric heart surgery across different care models. A study of neonates with heart disease showed decreased mortality for those cared for preoperatively in a dedicated CICU.[9] A second neonatal study showed improved resource utilization, with shorter ICU and hospital lengths of stay and shorter duration of mechanical ventilation in a dedicated CICU.[10] However, another publication considering all patients undergoing congenital heart surgery, suggested there was no difference in mortality for patients cared for in a dedicated CICU, but there did appear to be a survival benefit for certain high-risk subgroups including those undergoing atrioventricular

[1] The Reference 7) was added by the Editorial office to clarify the circumstance of the so-called "high volume cardiac surgical centers" in the United States.

canal repair or arterial switch operation.[11] Morbidity may also be impacted by the ICU care model with one single-institution study (before and after establishment of a dedicated CICU) demonstrating lower rates of surgical site infection and re-exploration for bleeding in patients cared for in a dedicated CICU. This study did however note that following the establishment of a dedicated CICU there was also growth and improved coordination of the healthcare team.[12] The consolidation of expertise and cohesiveness of the team intuitively leads to better team performance regardless of the physical ICU space.

In addition to variability in the ICU care model, there exist many different training pathways for physicians responsible for the care of pediatric cardiac patient. Common backgrounds include pediatric intensive care, pediatric cardiology, pediatric anesthesiology and more recently, physicians dually-trained in pediatric cardiology and pediatric intensive care. For the general pediatric patient, studies have shown an improvement in outcomes, including survival, for patients cared for by a pediatric intensivist, but a study aimed at evaluating the superiority of a specific training background failed to find one.[13, 14] There has been much controversy with intense opinions about the ideal clinical preparation, and despite this debate, expert consensus training recommendations have been developed by a multi-disciplinary group.[15–19]

Multi-Disciplinary Team Structure

We believe that having a highly skilled and specialized team contributes significantly to quality care of this complex patient population with the ability to recognize decompensation sooner and prevent morbidity and mortality. This is a difficult belief to prove in an evidence based way, but one group studied the period before and after development of a dedicated cardiac ICU with reductions in chest re-explorations, wound infections, need for CPR and mortality.[12] The authors proposed that the stable, specialized team was the primary difference with focused education initiatives and dedicated staff. It is logical that the pattern recognition that occurs in high volume centers, consolidated in a dedicated team would increase the likelihood of consistency of care as well as early recognition and rescue of complications.

Engaging a broad group of experts to collaborate in patient care is one of the hallmarks of care in the pediatric intensive care unit, and this is a model well suited for care of the pediatric cardiac intensive care patient. The team would ideally include a broad range of pediatric intensivists, pediatric cardiologists and cardiac surgeons, cardiac anesthesiologists, nursing, respiratory therapists, pharmacists, physical/occupational/speech therapists, and social workers. It is imperative that team work together collaboratively and feel psychological safety to voice expert opinions and raise any concerns. A highly functioning team may be the most important factor in reducing morbidity and mortality, particularly failure to rescue.

Failure to Rescue as a Modifiable Mortality Risk Factor

Several studies have shown that center volume and mortality are inversely associated in the pediatric cardiac surgery population. This inverse relationship is most well-studied in the Norwood operation which shows a modest survival benefit in high volume centers independent of patient risk factors. However, a closer examination of this survival benefit after Norwood operation suggests that it is not entirely explained by center volume alone.[20, 21] Given that post-operative complications across centers is relatively similar and likely reflective of patient comorbidities and risk factors, the field has sought to find a better measure of quality of care. From this analysis emerged the concept of Failure to Rescue (FTR) which is defined as mortality following a post-operative complication.[22] A review from the Society of Thoracic Surgeons Congenital Heart Surgery (STS-CHS) database showed an overall unadjusted mortality rate of 3.7%, a post-operative complication rate of 39%, and a FTR rate of 9%, with a very low rate of mortality in patients without any complication. There was a strong association between a center's mortality rate and FTR rate rather than between overall complication rate and mortality rate.[23] These data suggest that the recognition and management of complications is the potentially modifiable factor impacting mortality rates after pediatric heart surgery.[24] There has been more research in FTR in the adult populations, for example one study demonstrated a lower FTR rate in high volume centers in adults undergoing open abdominal aortic aneurysm repair, perhaps explaining the survival benefit observed in high volume centers.[25]

More research is needed in this vein to identify key

factors contributing to FTR and how best to combat it. One interview-based study identified themes that team members identify in successful rescue including teamwork, swift action taking and psychological safety.[26] These themes are intuitive that improved communication of observed and voiced concerns may lead to improved recognition of complications and the ability to reverse or support a patient adequately through that complication. It is difficult to measure and study effective teamwork, team and system dynamics and agility of a team to respond to changes in patient condition, but this is our belief of the intangible qualities that offer a significant quality benefit to patients.

Future Directions in Pediatric Cardiac Critical Care

Artificial intelligence as a supplement to augment the complex analysis and decision-making capabilities of the bedside provider is the next great frontier in our field. There is nothing imaginable that can replace a human, but artificial intelligence offers a wide array of potential for pattern recognition and a deviation from the expected clinical course, earlier detection of subtle signs of deterioration, and automation of some of the more routine aspects of medicine that may be expedited by machine learning and application of effective artificial intelligence.[27–29] Additionally, off-loading some of the routine cognitive burden from the provider may allow a shift of attention to more important issues. Some work already underway has shown that artificial intelligence can predict cardiac arrests in single ventricle patients.[30–32]

The field is continuing to advance in novel interventional techniques and application of those techniques to younger, smaller, and higher risk patient populations. This has continued the tradition within the field of offering survival to patients who would have otherwise died. Additionally, as survival of pediatric cardiology patients has improved, there has been a burgeoning population of adult congenital heart patients who are pushing the growth and advancement of that subspeciality, including their unique critical care needs.

Conflicts of Interest

The authors have no conflicts of interest to disclose.

Author Contribution

Dr. Vitale was the primary author and Drs. Aiyagari and Charpie advised and edited the manuscript.

Note

This is a review article based on the lecture given by Dr. Charpie (entitled: Pediatric Cardiac Intensive Care: Current State-of-the-Art and Special Considerations) at the 59th annual meeting of Japanese Society of Pediatric Cardiology and Cardiac Surgery on 7 July 2023.

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