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Original Article

Anaesthetic complications associated with the treatment of patients with congenital cardiac disease: consensus definitions from the Multi-Societal Database Committee for Pediatric and Congenital Heart Disease

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Abstract Congenital heart defects are the most common cause of death in infants and young children in the developed world. As the mortality in this population has declined to less than 5%, more attention is being focused now on reducing post-procedural morbidities that may seriously impact the patient and their families. Because of multiple reasons, paediatric cardiac surgery and anaesthesia is a perfect model for studying human errors and their impact on patient safety. Congenital cardiac disease is a common lesion causing much morbidity, pain, and loss of life. Over 44,000 surgical procedures are performed yearly to repair congenital cardiac problems in the United States alone. The reduction or elimination of iatrogenic adverse outcomes, given the current mortality rates of 4.2%–4.5%, might lead to as many as 500 children achieving better outcomes or shorter hospitalizations.

Efforts to quantify the frequency of complications related to anaesthesia in patients undergoing congenital cardiac surgery have been difficult to date because of the low occurrence of this surgery compared to other surgeries on children and the relatively rare incidence of complications related to anaesthesia in this population. Anaesthesiologists play a crucial role in the reduction, recognition, and timely treatment of medical errors that impact this morbidity. Paediatric cardiac surgery encompasses many complex procedures that are highly dependent upon a sophisticated organizational structure, effective communication, coordinated efforts of multiple individuals working as a team, and high levels of cognitive and technical performance. Human factor error analysis in this patient population has shown how frequently both minor and major errors occur. The goal of this paper is to outline the frequency and sources of these errors and to suggest treatment strategies which may minimize their occurrence.

Keywords: Congenital heart disease; quality improvement; patient safety; outcomes; registry; operative morbidity; paediatric; surgery; congenital abnormalities; cardiac surgical procedures; heart; catheter; anaesthesia; Near Infrared Reflectance Spectroscopy; NIRS

Efforts to quantify the frequency of complications related to anaesthesia in patients undergoing congenital cardiac surgery have been difficult until recently because of the low occurrence of this surgery compared to other surgeries on children and the relatively rare incidence of complications related to anaesthesia in this population. Even the busiest of paediatric cardiac anaesthetic services at major North American paediatric institutions, such as Children's Hospital of Boston, the Children's Hospital of Philadelphia, Texas Children's Hospital, and the

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Hospital for Sick Children in Toronto, will each only have contact with 1000–2000 congenital cardiac patients per year. The majority of these cases are non-surgical cases such as diagnostic and therapeutic catheterizations and radiology procedures including computerized axial tomography and magnetic resonance imaging studies. The cardiac anaesthetic group at Children's Hospital Boston has recently published their frequency of cardiac arrests related to anaesthesia in patients with congenital cardiac disease undergoing cardiac surgery.[1] This report spans a 6 year period from January 2000 through December 2005 and includes 5213 anaesthetics in the congenital cardiac operating rooms at their institution. This retrospective, database-generated article is extremely important in identifying the frequency, causes, and outcomes of cardiac arrest in this sub-population of paediatric and adult-congenital patients, but does not attempt to quantify the incidence of other complications not resulting in arrest.

The American Society of Anesthesiology has sponsored multiple investigations using a "closed claims analysis" method to identify areas of concern for providers of anaesthesia, including claims for death, injury to the brain, injuries resulting from central venous lines, injury to nerves, and injury to the airway,[2–7] These reports have not generally examined the effects of age or type of surgery and do not have a denominator that is needed to determine the incidence of injury. Jimenez and colleagues used the data from "closed claims analysis" to investigate paediatric anaesthesia liability and segregated the data by type of surgery.[7]This report found that thoracic and cardiac surgeries accounted for slightly less than 10% of all claims that were settled. While that may appear low, it probably represents a disproportionately high number because of the relative paucity of thoracic and cardiac surgeries compared to all surgeries performed on paediatric patients. Malpractice data are a very insensitive tool for determining the incidence or causality of complications, as so many different factors apart from medical error determine whether or not a claim is initiated or settled. The denominator of paediatric patients undergoing surgical and diagnostic procedures with anaesthesia in the United States is not measurable with any accuracy due to the lack of a central reporting mechanism. Examining the caseload at children's hospitals is insufficient because many procedures are performed in mixed adult-paediatric general hospitals, ambulatory surgical centres, or offices of physicians. Furthermore, there are well known weaknesses to using the data from "closed claims analysis". These analyses rely upon the presence of a settled malpractice claim to be included, and the period examined may span decades during which significant changes in anaesthetic, medical, and surgical practice have occurred.

Many anaesthetic complications are multi-factorial in origin and it can be difficult to assign the relative contributions of different clinical services. For example, failure to successfully separate from cardiopulmonary bypass may be due to multiple inter-related issues:

- surgical issues such as technical difficulty or bleeding
- combined surgical and anaesthetic issues such as inotrope management
- anaesthetic issues such as ventilator management, and
- the underlying physiology of the patient such as intractable pulmonary hypertension.

These system factors are further exacerbated if there are communication difficulties between the various parties, including surgeons, anaesthesiologists, perfusionists, cardiologists and the preoperative, intraoperative, and postoperative medical and nursing teams.

James Reason has described the "Swiss Cheese Model" for evaluating complications experienced by patients due to human errors.[8] For a complication to occur, all the "holes" in the cheese have to line up, that is a sequential failure of the various mechanisms of defence in place to prevent, recognize and/or treat unwanted physiologic changes.

The landmark study by de Leval and colleagues in the United Kingdom investigated the impact of "human factors" and teams on surgical outcomes in congenital cardiac patients, focusing on the neonatal arterial switch operation as an exemplar of complex, high-risk surgery.[9] Patient and procedural data were collected on 243 operations performed by 21 cardiac surgeons in the United Kingdom in 16 centres over 18 months. Of these 243 patients, case-study data were collected on 173 arterial switch operations by two researchers of "human factors" who followed each case from time of induction of anaesthesia to handover in the intensive care unit. The events were divided into major and minor events depending on their impact on the safety of the patient. The identification and success of recovering from these events was observed. Multivariate logistic regression analyses determined that, after adjustment for patient factors, the total number of minor and major events per case were both strong predictors of the probability of death and near-miss, with a p-value less than 0.001. De Leval concluded that minor events go largely unnoticed by the team in the operating room, and are therefore left uncompensated. A subsequent analysis of the same data suggests that minor events impede the ability of the team in the operating room to compensate for future major events.[10]

In addition to the organizational factors, paediatric cardiac surgery procedures have a low tolerance of error. The reports of the Bristol Royal Infirmary Inquiry and the Manitoba Inquiry both recognized the importance of human factors and systems research in improving paediatric cardiac surgical outcomes.[11–13]

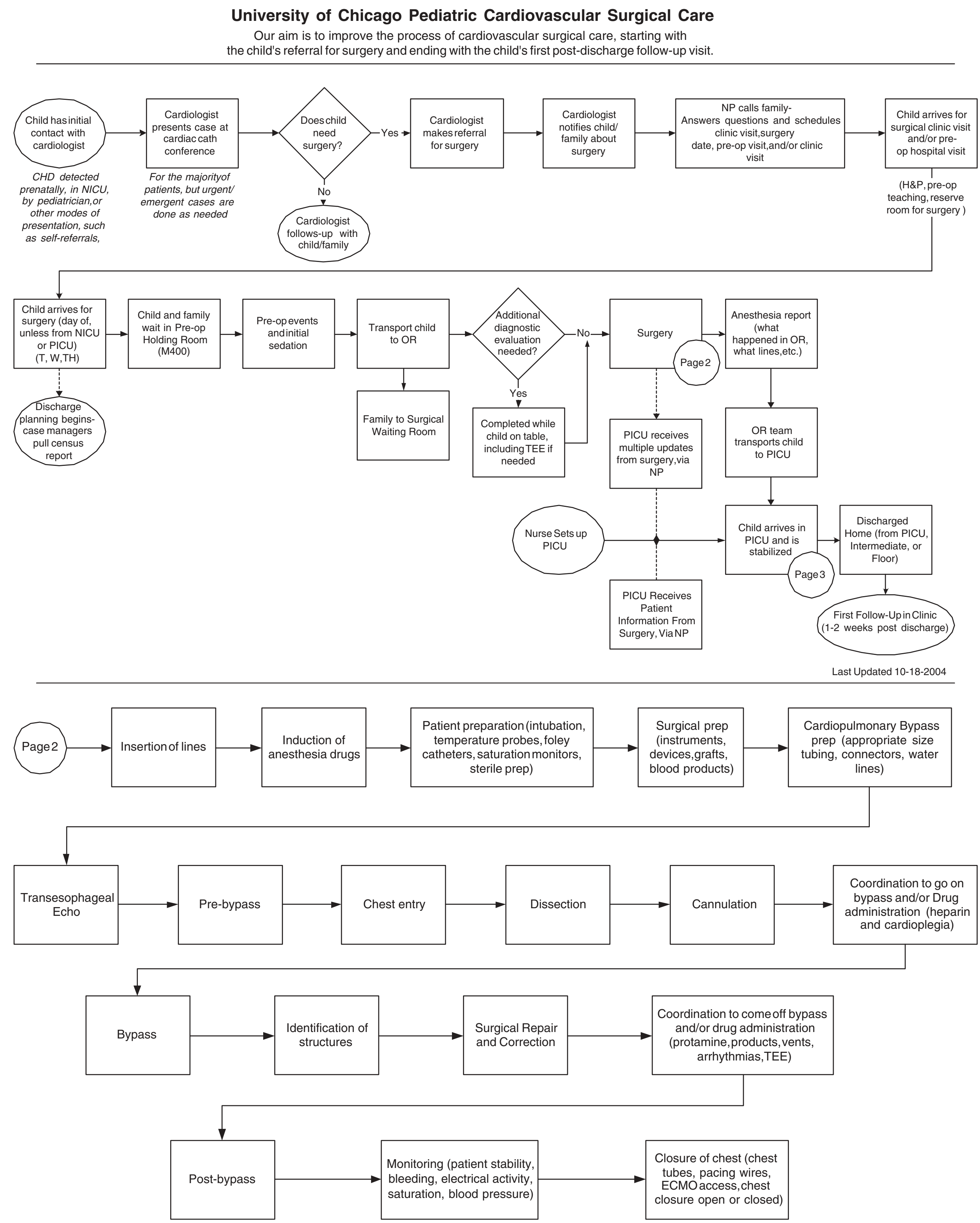

Figure 1.
Process map of paediatric cardiovascular surgical care.

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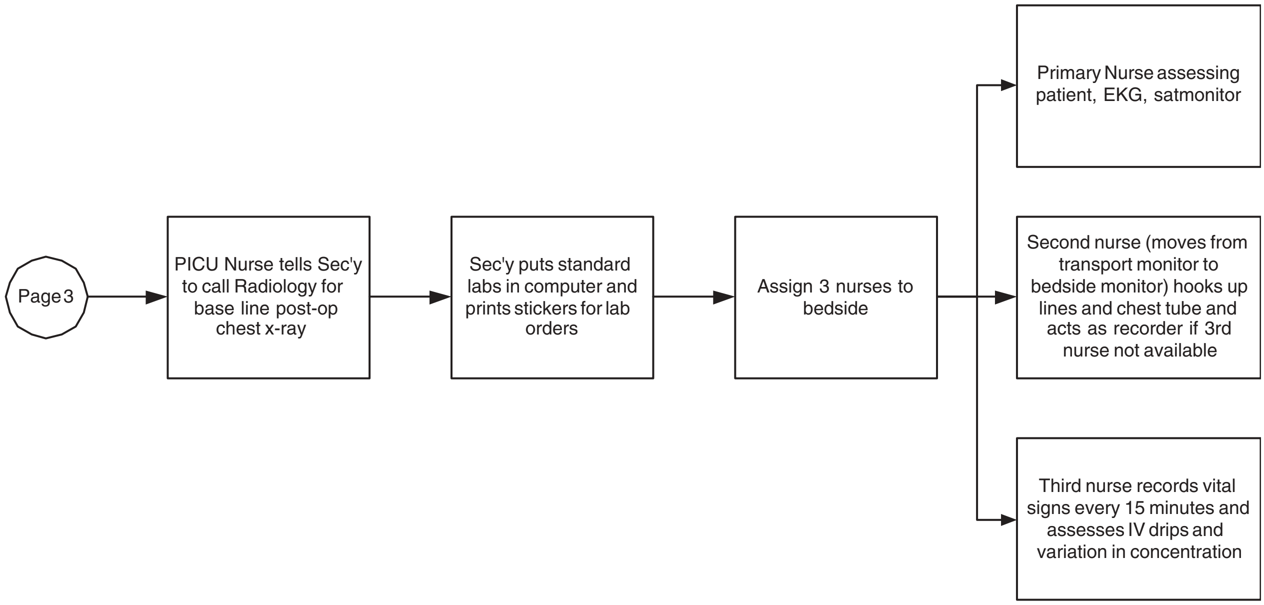

Figure 1.
Continued.

The report of the Manitoba Pediatric Cardiac Surgery Inquest found that "serious organizational and personnel problems experienced by the Health Sciences Center's Pediatric Cardiac Surgery Program during 1993 and throughout 1994 contributed to the deaths of these children." Galvan and colleagues recently published an initial observational study on complications in this complex population of patients and recorded on average 1.8 major compensated and 9 minor compensated complications per case.[14] While these complications were observed during the surgeries, they were all recognized and treated before injury resulted – all the "holes" in the Swiss Cheese did not line up because one or more of the various systems in place to prevent injury to the patient worked appropriately. Barach and colleagues, in 2006, reported on a comprehensive map of process, in which they outlined the multiple steps involved in the anaesthetic care provided to patients undergoing paediatric cardiac surgery and identified the potential sites for interventions related to safety[15–17] (Fig. 1). They observed 108 cardiac surgeries with open chest and found that failures of communication were the most common underlying cause of major events. Examples of the organizational and human factors challenges that Barach and colleagues, observed include:

- Unplanned transfusion of blood products correlated with a breakdown of communication between the anaesthesia team, the nurses, and the perfusionist
- Failure to identify a non-functioning infusion pump was directly related to poor communication between the attending physician anaesthesiologist and resident who was performing several tasks simultaneously
- Detection of increased chest tube bleeding was delayed and may have been related to suboptimal communication between residents and the attending physician.

"Near Misses" are important as they are 10–100 times more common than documented adverse events and yet share the same organizational and cognitive sources of error as major adverse events.[18] Determining the frequency and nature of "Near Miss" events is potentially far more important than just looking at failures of the system resulting in injury to the patient. However, analysis of "Near Miss" events is difficult as it requires a trained, independent observer to accompany the patient through the entire continuum of care.

The Congenital Cardiac Anesthesia Society has joined with The Society of Thoracic Surgeons to include fields of data specific to anaesthesia in an anaesthetic module of future iterations of their existing Congenital Heart Surgery Database (Table 1). One purpose of this effort is to harness the power of multiple sites to determine the frequency of recognized adverse events on a more contemporaneous basis. The Multi-Societal Database Committee for Pediatric and Congenital Heart Disease has developed consensus definitions for the complications associated with the treatment of patients with congenital and paediatric cardiac disease: The subcommittee of The Multi-Societal Database Committee for Pediatric and Congenital Heart Disease responsible for anaesthetic

Table 1. Categories of anaesthetic complications.

Airway/Ventilation	
	Difficulty with ventilation prior to intubation, including laryngospasm
	Difficulty with intubation or reintubation (defined as > 3 attempts by at least 2 individuals)
	Aspiration during induction or intubation of gastric contents
	Failed intubation
	Trauma to anatomical structures (dental, pharyngeal or glottic injury, barotrauma, oesophageal injury)
	Difficulty with ventilation once intubated (inadvertent mainstem intubation, bronchospasm, airway obstruction (such as with placement of TEE))
	Inadvertent extubation
	Difficulty with ventilation post-extubation, including laryngospasm
	Need for re-intubation after planned extubation in operating room (i.e. failed extubation)
Medication	
	Wrong medication
	Wrong dosing of correct medication (under, over or too quickly)
	Wrong site of injection (arterial or epidural instead of venous)
	Anaphylactic, Anaphylactoid or other drug reaction
	Malignant hyperthermia
	Timing of medication (example: failure to administer antibiotics or anti-rejection Rx)
Vascular	
	Difficult vascular access (defined as > 5 attempts for peripheral intravenous access, >2 extremities for percutaneous arterial line placement)
	Complications from vascular access
	Pneumothorax, Haemothorax, Arrhythmia, Haematoma, Infiltration, Nerve injury
	Inadvertent removal of vascular lines during transport or intra-op
	Inadvertent arterial puncture
Regional anaesthesia	
	Inadvertent subarachnoid injection
	Intravenous injection of local anaesthetic
	Infection
	Haematoma
	Nerve injury
Cardiovascular events	
	Inadequate fluid therapy
	Air embolus (not secondary to intracardiac air post-operatively)
	Arrhythmia not secondary to surgical manipulations or line placement
Miscellaneous	
	Intraoperative recall
	Trauma with TEE insertion or manipulation
	Positioning complication with nerve injury (temporary or permanent)
	Infection due to poor sterile technique, i.e. catheter site infection
	Communication issues with other team members that result in delays or change in surgical plan
	Transport issues (i.e. patient falling out of bed)
	Integument damage (examples: pressure-related alopecia or skin slough, warming blanket burn)
	Equipment failure

complications reviewed the available data and contributed to the consensus definitions. The terms in the final list of anaesthetic complications developed by The MultiSocietal Database Committee for Pediatric and Congenital Heart Disease, along with their official definitions, are listed in Part 4 of this Supplement.

Another factor in accurately determining the incidence of complications in congenital cardiac procedures is that patients frequently receive care at multiple institutions over their lifetime. The Multi-Societal Database Committee for Pediatric and Congenital Heart Disease is currently developing and implementing into their databases secure unique identifiers of all patients, compliant with the Health Insurance Portability and Accountability Act of the federal government of the United States of America. The successful implementation of this initiative will create a scenario where the same patient can be tracked across multiple sites participating in The Congenital Heart Surgery Database of The Society of Thoracic Surgeons, and also across the multiple databases of the members of The Multi-Societal Database Committee for Pediatric and Congenital Heart Disease.

Complications related to anaesthesia

Cardiac arrest

Published reports have identified children as being at a higher risk of perioperative complications and death since the 1950s.[19] The Pediatric Perioperative Cardiac Arrest Registry[20–23] identified all children, 18 years of age or younger, at participating institutions, who suffered cardiac arrest. Cardiac arrest was defined by the perioperative administration of chest compressions or death during anaesthesia or within 24 hours after surgery.[20,23] The registry prospectively enrolled 63 North American institutions and collected data anonymously from 1993 through 1997 on the 150 reported cases involving cardiopulmonary resuscitation in children under age 18 that were determined to be related to anaesthesia, out of 289 cases of arrest. A follow-up report, published recently, examined the cases between 1998–2004. Difficulties with separation from bypass were specifically excluded from the analysis. The mean incidence of cardiac-arrest was 1.4±0.45 per 10,000 anaesthetics in the earlier report but the more recent manuscript specifically avoids citing an incidence because of the limited demographic data available. Multivariable analysis of the data from the Pediatric Perioperative Cardiac Arrest Registry identified the following criteria as placing a patient at higher anaesthetic risk of arrest from 1993–1997:

- age at time of surgery less than 1 year
- severity of underlying illness, as defined by classification of pre-operative physical status of The American Society of Anesthesiologists to be level three to five, and
- emergency surgery.

Only classification of pre-operative physical status of The American Society of Anesthesiologists to be level three to five, or emergency surgery, however, were predictive of mortality. The data from the Pediatric Perioperative Cardiac Arrest Registry is extremely important, but it does not allow the analysis of complications in cases that do not result in cardiopulmonary resuscitation but might seriously affect patient care and outcomes.

Of the 39 patients who died secondary to care related to anaesthesia in the original study from the Pediatric Perioperative Cardiac Arrest Registry, 15 had congenital cardiac disease. The breakout of patients with congenital cardiac disease who died during procedures was not reported in the more recent data, but it was noted that in those cases in which the cause of arrest could not be identified, the patients had a high incidence of congenital cardiac defects.

Many of the arrests and deaths reported in the data from the Pediatric Perioperative Cardiac Arrest Registry were associated with the use of halothane for general anaesthesia, particularly with assisted ventilation. Halothane is a profound dose-dependent myocardial depressant, and its use has largely been supplanted by sevoflurane in the paediatric population. Sevoflurane is generally well-tolerated for mask induction and is associated with significantly less bradycardia and myocardial depression in infants than halothane,[24,25] though it too can be a myocardial depressant at high-enough levels. Additionally, the vaporizer used on anaesthetic machines for sevoflurane was designed intentionally to make it difficult to deliver a cardiotoxic concentration quickly, unlike the older vaporizers for halothane. The vaporizer for sevoflurane is an excellent example of using ergonomic and functional design to help clinicians from committing an overdose of medication. The more recent report from the Pediatric Perioperative Cardiac Arrest Registry specifically cites the change in agents as a potential reason why fewer patients suffered cardiac arrests who were less than 1 year of age and fewer patients suffered cardiac arrests who were classified to be level 1 or 2 of the pre-operative physical status of The American Society of Anesthesiologists.

In the earlier report of the Pediatric Perioperative Cardiac Arrest Registry, medication errors, likely involving halothane, were the single highest cause of cardiac arrest; while in the more recent data, cardiovascular complications had the highest involvement in events leading to cardiac arrest. Hypovolemia associated with blood loss was the most common identifiable cause, and the majority of these arrests occurred during either spinal fusion surgery or craniotomy/craniectomy procedures – both of which are associated with potential major loss of blood. For the purposes of providers of paediatric and congenital cardiac anaesthesia, two significant causes of cardiac arrest should be noted in particular: hyperkalemia associated with transfusion of stored blood and complications associated with central venous lines. Another problem noted within the data from the Pediatric Perioperative Cardiac Arrest Registry, insufficient peripheral intravenous access, is typically not as much an issue for patients undergoing cardiac surgery.

A number of cardiac arrests in children in both groups in the Pediatric Perioperative Cardiac Arrest Registry were related to respiratory obstruction, many of which were secondary to laryngospasm. As early extubation in the operating room becomes more common in congenital cardiac anaesthesia, it is possible that arrests or complications due to respiratory obstruction and laryngospasm, hypoventilation and/or hypoxia at the end of the case may increase. The more recent data from the Pediatric Perioperative Cardiac Arrest Registry specifically notes that of the 11 cases of laryngospasm leading to cardiac arrest, 7 patients arrested in the post-surgical period after extubation during emergence or transport.

The Department of Anesthesia at Mayo Clinic began an electronic "Anesthesia Quality Assurance System" on November 1, 2007 as part of their department's performance improvement efforts. The series from the Mayo Clinic summarized 92,881 paediatric patients, from 1988 through 2005, of which 4242 anaesthetics, or 5% of all paediatric anaesthetics, were conducted for surgical repair of congenital cardiac malformations.[26] Perioperative cardiac arrest was defined as open or closed cardiac compressions while in the continuous care of anaesthetic teams. Cardiac arrest occurred in 54 patients with underlying congenital cardiac conditions and constituted 88% of all arrests. The incidence of arrest in paediatric patients undergoing cardiac surgery versus non-cardiac surgery was 100-fold higher, and was found to be 127 per 10,000 cases versus 2.9 per 10,000 for non-cardiac paediatric surgical procedures including cardiac catheterizations. Failure to wean from bypass was included as a cardiac arrest, unlike in the Pediatric Perioperative Cardiac Arrest Registry, and made up 37 of the 54 arrests recorded in cardiac cases. It is difficult to compare the data from the Mayo Clinic to the Pediatric Perioperative Cardiac Arrest Registry because of fundamental differences in definitions of anaesthetic causation and the nature of the collection of data.

The Cardiac Anesthesia Service at the Children's Hospital of Boston has kept a registry of all patients with congenital cardiac disease anaesthetized in the cardiac operating rooms and catheterization labs since January, 2000. They recently reported on their incidence of cardiac arrests in their operating rooms through December, 2005.[1] During this period 5213 anaesthetics were delivered for 4069 open procedures and 1144 closed procedures, and there were 41 cardiac arrests in 40 patients. 33 patients were excluded from the study because they either were unable to be weaned from cardiopulmonary bypass in the operating room, and died in the operating room or were placed onto extracorporeal membrane oxygenation immediately post-bypass. The early mortality for all patients, defined as mortality prior to hospital discharge, was 1.8%, and the overall incidence of cardiac arrest was 0.83 per 100 closed cases and 0.7 per 100 open cases. Their highest risk cases were

- repair of the common arterial trunk (truncus arteriosus), with 17.4 arrests per 100 cases
- modified Blalock-Taussig shunt for pulmonary atresia with intact ventricular septum, with 3.6 arrests per 100 cases
- neonates with aortic coarctation with ventricular septal defect or interrupted aortic arch with ventricular septal defect with 3.5 arrests per 100 cases, and
- Stage 1 palliation for hypoplastic left heart syndrome, with 2.2 arrests per 100 cases.

Of 41 cardiac arrests, 11, or 26.8%, were associated with anaesthesia for an incidence of 21.1 per 10,000 anaesthetics. The group from Boston divided their anaesthetic complications into two pools: likely-related to anaesthesia and possibly-related to anaesthesia. Of the 11 cases of cardiac arrest with an anaesthetic component, 6 were felt by the reviewers to be likely-related and the other 5 possibly-related. The remaining 30 cardiac arrests were determined to be procedure-related.

Arrests related to anaesthesia consisted of 2 issues related to the airway, 1 related to monitoring, 1 related to medication, and 7 cases of suspected myocardial ischaemia. All occurred after induction of anaesthesia but prior to completion of sternotomy. Of these 11 arrests, all were quickly and successfully resuscitated and survived to discharge. Full details of each of the 11 cases are outlined in their manuscript. Specific complications include one case each of ventricular fibrillation associated with central venous line wire placement, laryngospasm and aspiration during an inhalation induction, failed intubation with hypoxemia, asystole after neostigmine, and multiple episodes of myocardial ischaemia associated with hypotension. Altered coronary perfusion and/or anatomy was a common element in many of the cases of myocardial ischaemia, with 7 of the 11 anaesthesia-related cases having some element of coronary malperfusion. This problem may have also played a role in many of the procedure-related episodes of cardiac arrest by subjecting the myocardium to a chronic level of subendocardial ischaemia that predisposed the heart to ventricular fibrillation with relatively minimal additional stress.

Co-morbidity and congenital cardiac patients

It is clinically challenging at times to separate the symptoms of progressive congestive heart failure, requiring more urgent surgical intervention, from an infection of the upper respiratory tract, which might increase the risk of perioperative complications. Malviya and colleagues examined prospectively the effect of concurrent upper respiratory infections on children ages 1 month to 16 years undergoing congenital cardiac surgery at C.S. Mott Children's Hospital at the University of Michigan from 1996–1999.[27] Previous research has demonstrated that anaesthesia, particularly involving an endotracheal tube, increases the risk of post-operative pulmonary complications if the patient has a current or recent infection of the upper respiratory tract and that this risk persists for six to eight weeks after resolution of symptoms.[28–30]

In the group undergoing congenital cardiac surgery studied by Malviya and colleagues, the presence of two or more symptoms of infection of the upper respiratory tract, such as rhinorrhea, sore or scratchy throat, sneezing, nasal congestion, malaise, cough, or fever greater than 38 degrees Centigrade, when combined with confirmation by the primary caregiver, placed the patient in the category of active infection of the upper respiratory tract. Children with evidence of infections of the lower respiratory were excluded from the study. The presence of an active infection of the upper respiratory tract was associated with an increased incidence of respiratory complications and extended time in the intensive care unit compared to their cohort without the presence of an active infection of the upper respiratory tract, and it was a predictor of post-operative infection and multiple complications. These complications were easily managed without long-term adverse outcomes and with no effect on the duration of intubation or overall length of stay. Pulmonary complications seen in the group with active infection of the upper respiratory tract at a higher frequency included laryngospasm, breath-holding, bronchospasm, and desaturation of oxygen compared to baseline. It should be noted that the group with active infection of the upper respiratory tract was significantly younger and weighed less than the control group in this study.

Minimizing complications related to anaesthesia

Over the past decade new monitoring technologies have become available that may reduce the incidence of both anaesthetic and surgical complications. Examples include the more extensive use of ultrasound-guided central venous cannulation and the application of Near Infrared Reflectance Spectroscopy and other neurological monitors in children.

The first reports of ultrasound-guided central venous cannulation date back to the early 1990s. The technology allows for direct visualization of the target vessel, thus reducing the likelihood of inadvertent arterial puncture or cannulation and subsequent complications, and increasing the probability of successful venous cannulation with fewer attempts.[31–34] As the probes and equipment for ultrasound have improved, the quality of the images and ease of use have increased proportionally.[31–34]

With the release of the "Somanetics Invos™ 5100C monitor", it is now possible to have up to four channels of Near Infrared Reflectance Spectroscopy monitoring, allowing for both bilateral cerebral and two-site somatic monitoring. The FDA has recently approved a competing monitor of Near Infrared Reflectance Spectroscopy for use, namely the "CasMed Fore-Sight™ MC2000". This recently approved monitor measures absolute cerebral oximetry as opposed to the regional oxygenation saturation index, often referred to as "rSO_2", generated by the algorithm utilized by Somanetics. Data for paediatrics with the device from CasMed is still unavailable. A recent publication compared the "NIRO-100" Near Infrared Reflectance Spectroscopy monitor, which is not readily available in the United States and which determines the cerebral oximetric "Tissue Oxygenation Index", to the "Somanetics Invos 4100™", the two channel predecessor to the 5100C.[35] The authors determined that the Tissue Oxygenation Index was less affected in adult patients by haemoglobin concentration, skull thickness, and the size of the cerebrospinal fluid layer, compared to the regional oxygenation saturation index generated by the monitor produced by Somanetics.

Regardless of which device is used, monitoring with Near Infrared Reflectance Spectroscopy can help to guide optimal delivery of oxygen continuously in the peri-operative period and to acutely minimize surgical complications, such as the malposition of arterial or venous cannulas that might impede cerebral circulation.[19,36–41] Case reports also document the utility of monitoring with Near Infrared Reflectance Spectroscopy in determining abnormal states of flow, such as a partially occluded Blalock-Taussig shunt,[42] or early detection of necrotizing enterocolitis in congenital cardiac patients during non-cardiac surgery. Monitoring with Near Infrared Reflectance Spectroscopy, both intra-operatively and post-operatively in the Intensive Care Unit, is now a common practice in many cardiac centres providing care for children. One report documents its use in evaluating patients in an outpatient setting with univentricular physiology.[43] Unfortunately, it is still very difficult to determine the sensitivity and specificity of the monitors of Near Infrared Reflectance Spectroscopy, and they are best used presently as a monitor of trends in a given patient, rather than as an absolute value, because of the wide range of baseline values.[44] Schwarz and colleagues have published a "Near Infrared Reflectance Spectroscopy Matrix" for evaluation and treatment strategies for events resulting in a decrease in the cerebral saturation readings from baseline[45] (Table 2). Although developed for their neuroendovascular suite, the algorithm presented is equally applicable to the congenital cardiac operating suites and intensive care unit.

The use of multi-modal neurophysiologic monitoring for cardiac surgery has been advocated to reduce the high rate of neurocognitive complications in these patients.[19,46,47] These strategies include the use of electroencephalography and transcranial Doppler ultrasound in addition to Near Infrared Reflectance Spectroscopy.[48] The idea is to induce clinical interventions as early as possible to prevent

Table 2. Near Infrared Reflectance Spectroscopy Matrix.

COS	Key variable	Associated parameters	Interpretation	Intervention
↓	Hgb ↓	MAP, SaO_2, pCO_2, temp (≡)	↓O_2 transport, blood loss hemodilution	Blood product transfusion
↓	MAP ↓	Hgb, SaO_2, pCO_2, temp (≡)	Hypotension	Optimize blood pressure
↓	SpO_2 ↓	Hgb, MAP, pCO_2, temp (≡)	Hypoxygenation	Optimize ventilation and oxygenation
↓	pCO_2 ↓	Hgb, MAP, SaO_2, temp (≡)	CBF ↓	Optimize ventilation (normoventilation)
↓	Temp ↑	Hgb, MAP, SaO_2, pCO_2 (≡)	$CMRO_2$ ↑	Correct to normothermia or mild hypothermia
↓	Cannulation	Hgb, MAP, SaO_2, pCO_2, temp (≡)	Malposition of arterial or venous cannulas, CBF ↓	Reposition cannulas
↓	Inadequate anaesthesia	MAP ↑; Hgb, SaO_2, pCO_2, temp (≡)	$CMRO_2$ ↑	Deepen anaesthesia

Adapted from Schwarz et al., Neurol Res 2005: 27: 423–428.
(≡) – within physiologic limits/unchanged; ↓/↑ – decrease/increase from physiologic limits.
COS – cerebral oxygen saturation; Hgb – haemoglobin; MAP – mean arterial pressure; CBF – cerebral blood flow; $CMRO_2$ – cerebral oxygen consumption.

adverse neurological outcomes, but adoption of multiple simultaneous monitoring modalities has not been as widespread as monitoring of Near Infrared Reflectance Spectroscopy alone. Monitoring of Near Infrared Reflectance Spectroscopy is currently limited to assessing cerebral oxygenation only in the frontal lobes of the brain, and does not provide information about Middle or Posterior Cerebral Arterial flow. As a result, embolic phenomena to the Middle Cerebral Artery resulting ischaemia and/or permanent brain injury may be missed with Near Infrared Reflectance Spectroscopy alone. Monitoring with Transcranial Doppler on the other hand provides excellent information about cerebral blood flow in the Middle Cerebral Artery and emboli, but does not quantify oxygenation. Hence, the combination of the two may provide additional assurances about neurologic protection.

Though large randomized prospective trials are still unavailable for the paediatric and congenital cardiac population, current literature suggests that some form of neurophysiologic monitoring, either solely or in combination, when combined with a treatment algorithm, reduces post-operative length of stay and neurocognitive complications in patients undergoing surgery involving cardiopulmonary bypass or carotid manipulation.[49] Murkin and colleagues recently demonstrated a significant decrease in length of stay in the intensive care unit and in the score for "Major Organ Morbidity and Mortality" of The Society of Thoracic Surgeons in adult patients undergoing primary coronary artery bypass grafting who were randomized to the treatment arm of a study using Near Infrared Reflectance Spectroscopy aimed at keeping the value from Near Infrared Reflectance Spectroscopy within 75% of baseline.[50] A comparable paediatric or congenital cardiac study currently does not exist. Other techniques that may minimize morbidity related to anaesthesia and improve outcomes for patients are more difficult to elucidate, but might include the introduction of more sophisticated ventilators into the operating room and the adoption of dedicated teams for congenital cardiac anaesthesia that specialize in the care of these complex children and adults on a routine basis.

Summary

Patients undergoing congenital cardiac surgery remain at a higher risk even after full surgical correction. It is recognized now that there is no such thing as a "cured" congenital cardiac patient, and that all of these patients should be treated with particular care as they remain at a higher risk for cardiac arrest compared to their peers. Morbidity and mortality related to anaesthesia remains an important challenge for patients with underlying congenital cardiac disease. The successful management of these patients requires an understanding of the disease process, the surgical and cardiology interventions that have occurred, and their effects on patient physiology. As more and more of these patients survive and move into adulthood, it will be critical to identify them and arrange for support from a team of anaesthesiologists that is familiar with their pathophysiology.

Newer monitoring modalities may give an early warning to disturbances in cardiac and neurologic function and prevent adverse outcomes. Currently efforts are underway to provide an accurate estimate of the incidence of complications in this patient population. This achievement will allow for a more realistic discussion with our patients and surgical colleagues.

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