Risk associated with anesthesia for noncardiac surgery in children with congenital heart disease

Taylor, Dan; Habre, Walid

How to cite

TAYLOR, Dan, HABRE, Walid. Risk associated with anesthesia for noncardiac surgery in children with congenital heart disease. In: Paediatric Anaesthesia, 2019, vol. 29, n° 5, p. 426–434. doi: 10.1111/pan.13595

This publication URL: https://archive-ouverte.unige.ch/unige:136871
Publication DOI: 10.1111/pan.13595

Received: 26 September 2018 | Revised: 9 January 2019 | Accepted: 22 January 2019

DOI: 10.1111/pan.13595

EDUCATIONAL REVIEW

WILEY Pediatric Anesthesia

Risk associated with anesthesia for noncardiac surgery in children with congenital heart disease

Dan Taylor[1] | **Walid Habre**[2]

[1]Department of Paediatric Anaesthesia, Evelina London Children's Hospital, Guy's and St Thomas' NHS Foundation Trusts, London, UK

[2]Paediatric Anaesthesia Unit, Department of Anaesthesiology, Pharmacology and Intensive Care, University Hospitals of Geneva, Geneva, Switzerland

Correspondence
Dr. Dan Taylor, Department of Paediatric Anaesthesia, Evelina London Children's Hospital, Guy's and St Thomas' NHS Foundation Trusts, London, UK.
Email: dan.taylor@gstt.nhs.uk

Funding information
No funding was provided for the writing of this article.

Section Editor: Philip Arnold

Summary

Database analysis has indicated that perioperative cardiac arrest occurs with increased frequency in children with congenital heart disease. Several case series and large datasets from ACS NSQIP have identified subgroups at the highest risk. Consistently, patients with single ventricle physiology (especially prior to cavopulmonary anastomosis), severe/supra-systemic pulmonary hypertension, complex lesions, and cardiomyopathy with significantly reduced ventricular function have been shown to be at increased risk for adverse events. Based on these results, algorithms for assessing risk have been proposed. How hospitals and health care systems apply these guidelines to provide safe care for these challenging patient groups requires the application of modern quality improvement techniques. Each institution should develop a system which reflects local expertise and resources.

KEYWORDS

adverse events, cardiac arrest, congenital heart disease, morbidity, quality improvement

1 | INTRODUCTION

Improvements in anesthesia management in the pediatric population are associated with reduced overall morbidity and mortality.[1,2] Despite this improvement, children with congenital and acquired heart disease (HD) still represent a population at increased risk when receiving anesthesia.[3] This fact is supported by a recent analysis of large databases from the American College of Surgeons (ACS) National Surgical Quality Improvement Program (NSQIP).[4,5]

As long-term survival improves in the group of patients with significant comorbidities, demand on anesthetic services increases. Diagnostic and noncardiac surgical interventions and regional techniques will often require general anesthesia (GA) or sedation.

Increased risk does not extend to all children with congenital HD (CHD), only to defined higher risk groups.[4,6] Recently, literature has focused on approaches to quantify the hazards involved,[7,8] predict levels of risk and develop approaches for high-risk cases.[9,10] This educational review assess the potential impact of this literature on our practice and suggests how we might work to achieve even better outcomes for all children with HD requiring anesthesia for noncardiac surgery (NCS).

2 | WHERE IS THE MAJOR RISK?

Clinicians are challenged in daily practice to identify children at moderate or high risk for major adverse events under anesthesia. Most publications consider major adverse events (cardiac arrest and death), but important information is also available on minor adverse events that may be the precursor of significant deterioration in cardiac function. Although many different definitions are used for these minor adverse events, it has become clear that some clinical scenarios represent higher risk for anesthesia and sedation for children with CHD.

One of the earliest series, published in 1998, looked at NCS in 276 children and adults with CHD treated by the Mayo Clinic Hospitals Group from 1988 to 1992.[11] The overall complication rate was 5.8%, with significantly higher incidence in children younger than 1 year old (15%). Moreover, patients with a diagnosis of pulmonary artery hypertension (PAH) had higher complication rates (15% vs 4.7%, in the CHD group with PAH excluded).

The other major risk factors associated with the occurrence of complications were identified as treatment for heart failure, cyanosis, inpatient procedures, and higher American Society of

Anesthesiologists (ASA) status. All children who suffered complications had one or more of these factors, or had procedures on the respiratory or neurological systems. The overall number of complications was small (15 in 276 procedures) and, whereas most were cardiac (n = 8), respiratory events, and seizures were also reported.

The increased risk associated with NCS in children with CHD has also been demonstrated by Baum et al[6] This group examined a hospital-consortium database of 191 261 procedures for patients less than 18 years of age. Mortality in children with CHD (n = 5967) was significantly higher than for those without (6% vs 1.8%; OR, odds ratio: 3.53; 95% CI, confidence interval: 3.15-3.95). CHD was broadly categorized as minor (patent ductus arteriosus, ventricular septal defect, atrial septal defect) and major (all more complex lesions), and 30-day mortality was significantly higher (11.3% vs 5.9%, OR 2.03, 95% CI: 1.47-2.8) in the major group. Outcomes were not controlled for age or physiological status and rates may have been high as this was an inpatient (not ambulatory) population.

Analysis of the Pediatric Perioperative Cardiac Arrest registry from 1994 to 2005 by Ramamoorthy[3] demonstrated 373 arrests, 127 occurring in children with HD. The data included cardiac surgical and catheter laboratory procedures; however, most (54%) of the arrests occurred during NCS in the general operating room. The children with HD were younger, sicker (assessed by ASA status), and more likely to require emergency surgery than their noncardiac cohort. Most reported arrests (70%) in children with HD occurred in those <2 years of age and were the consequence of cardiovascular events.

Though no denominator data were available, the congenital lesions associated with a particularly increased risk were aortic stenosis, cardiomyopathy, single ventricle lesions (especially unoperated and prior to cavopulmonary anastomosis), and the "failing Fontan" group classification. Children with HD were less likely to survive cardiac arrest than children without HD.

The incremental increase in mortality in children with "complex" CHD was demonstrated in a further single-center study from 2013.[7] This study analyzed 252 procedures for 71 children identified as high risk due to the presences of single ventricle physiology and to having undergone initial palliation with stage 1 of the Norwood procedure. Information on stage of palliation, age, ventricular function, medical therapy, and surgical complexity were also analyzed for their influence on operative course. The outcome measures were induction and maintenance instability, postoperative ventilation, and hospital length of stay (LOS). The authors identified the procedure being performed prior to cavopulmonary palliation and the use of angiotensin-converting-enzyme inhibitor as predictive of induction instability (which occurred in 73/173 cases), whereas the use of preoperative digoxin or inotrope was identified as predictive factors for maintenance instability (which occurred in 88/173 cases). Both were predicted by operative complexity. No clear predictors of postoperative ventilation were present; however, this observation is confounded by preoperative ventilation and nonstandardized indications. The multivariate analysis for prolonged hospital LOS again suggested digoxin and inotrope use were risk factors, as were preoperative LOS and moderate ventricular dysfunction (as defined by echocardiogram).

Although the series was small, the study focused on a high-risk group and, by the group's definition, perioperative-complication rates were high. Importantly, only one death (0.4%) and three arrests occurred (two of whom required emergent extracorporeal support).

Faraoni et al[4] further examined mortality using the ACS NSQIP database containing data from 51 008 children. Cases with HD were propensity matched with a group without HD, and an attempt was made to control for effects of age, physiological status, operative complexity, and emergency procedures. Rather than by specific lesion, children with HD were grouped by a standardized system based on residual lesion burden and functional status into minor, major, and severe CHD (Table 1). Most noteworthy was that children with minor CHD had no greater risk than the general population for overall mortality (1.2% vs 1.7%), cardiac arrest, or adverse events. Children with major or severe CHD had a higher mortality (OR 2.28, 95% CI: 1.37-3.79 and OR 7.32, 95% CI: 2.83-18.9, respectively) and were more likely to be re-intubated postoperatively.

The ACS NSQIP classification into major or severe categories offers a good approach for risk stratification in CHD children undergoing NCS. More recently, Lee's study[8] demonstrated that perioperative cardiovascular and respiratory events are common in these patients (11.7% and 4.5%, respectively). However, cardiac arrest was rare (0.16%), and the majority of these cardiovascular events were "inotrope usage" (11.4%), which may have been prophylactic or reactive. Higher ASA status, ACS NSQIP categories of major and severe, single ventricle physiology, and depressed ventricular function were identified as risk factors for the occurrence of perioperative cardiovascular events.

The potential impact of the type of surgical procedure on risk is not completely characterized. Lee's study suggested that some procedure groups (orthopedics, general surgery, neurosurgery, and pulmonary procedures) were associated with inotrope use. These procedures, however, were not graded by complexity. Some major procedures (eg, fundoplication, Ladd's procedure for intestinal malrotation) have been demonstrated to contribute to increased risk in children with CHD[12,13] and clearly the interplay between patient physiology and operative insult contributes to risk. This issue is confounded by variable indications for surgery both between institutions and between children with and without CHD.[14] Notably, the information about the risk status of children who were declined for surgery is missing. This information could be useful in building decision algorithms as to when to proceed with NCS in the higher risk group.

Finally the analysis of major NCS (and nonobstetric procedures) in grown up CHD (GUCH) patients listed in the US National Inpatient Sample (NIS, Healthcare Cost and utilization project) also give some insights of relevance.[15] This study examined 10 004 procedures performed with GUCH patients and demonstrated a significantly higher mortality than a matched cohort without CHD (4.1 vs 3.6% OR 1.13, 95% CI: 1.01-1.27). All complication rates measured (cardiac arrest, myocardial infarction, respiratory failure, stroke, deep

TABLE 1 ACS NSQIP Risk stratification for CHD presenting for NCS[10]

Classification	Definition
Minor CHD	Cardiac condition with or without medication and maintenance (eg, ASD, small to moderate VSD without symptoms) Repair of CHD with normal cardiovascular function and no medication
Major CHD	Repair of CHD with residual hemodynamic abnormality with or without medications (eg, TOF with free pulmonary regurgitation, HLHS including Stage 1 repair)
Severe CHD	Uncorrected cyanotic CHD Patients with documented pulmonary hypertension Patients with ventricular dysfunction requiring medication Listed for heart transplant

ACS, American College of Surgeons; ASD, atrial septal defect; CHD, congenital heart disease; HLHS, hypoplastic left heart syndrome; NCS, noncardiac surgery; NSQIP, National Surgical Quality Improvement Program; TOF, tetralogy of Fallot; VSD, ventricular septal defect.

vein thrombosis/pulmonary embolus, and renal failure) were higher in GUCH patients. An analysis of subgroups categorized by diagnosis revealed that a combined "complex" CHD group (essentially, left- or right-sided single ventricle lesions and truncus arteriosus) had the highest mortality rate at 7.8%. Simple lesions (atrial septal defect, aortic and mitral valve disease) had similar mortality rates as the control group. The database also confirmed that the number procedures in this patient group increased over time and that many of the procedures were performed outside of the teaching hospitals, where the patients likely received specialist services. The impact of this on outcome was not clear.

3 | HIGH-RISK DIAGNOSES

3.1 | Single ventricle physiology—Before completion of Fontan

The presence of single ventricle physiology is consistently reported in higher risk groups. This was quantified by Torres et al[16] in a series for 2457 children less than 2 years old who were diagnosed with hypoplastic left heart syndrome (HLHS) and who have had NCS. Data were collected retrospectively from the NIS discharge database between 1988 and 1997. Overall, 147 children underwent noncardiac surgical intervention, with only 81% surviving to discharge. No improvement in survival was demonstrable over time (despite overall improvement in survival of these patients from cardiac surgery). Physiological status, surgical stage (pre or post cavopulmonary anastomosis), age, and cause of death related to NCS admission were not analyzed.

More recently, Christensen et al[17] reviewed 73 NCS procedures performed for 40 patients with HLHS in a single institution during 2002-2008. These children were older than Torres' group (only five were at Norwood 1 stage), and 36 had completed the Fontan procedure. The surgical procedures were also overall less complex (many were undertaken on an outpatient basis), but the outcomes were strikingly better: adverse events occurred in only 11 of the 73 procedures and there was no inpatient mortality.

The Boston group retrospectively reviewed outcomes in children with single ventricle physiology who underwent NCS between 2007 and 2014.[18] The review focused on the highest risk group prior to Glenn anastomosis, including children with HLHS who had completed Norwood stage 1 and those administered BT shunts and banded/hybrid approaches. This group reported on 121 NCS procedures performed for 70 patients (16.7% of the patient population). Many of the procedures were minor, such as line insertion (n = 23), gastroscopy or airway procedures (n = 38), and some of the cases involved sedation only. The majority of the cases were gastrointestinal, reflecting a relatively high frequency of gut perfusion, reflux, or feeding issues in this group.[19] The most frequent adverse events were bradycardia/arrhythmia in 12 cases, and there were two cardiac arrests (both survived, although one patient required extracorporeal support). The group experiencing adverse events could not be distinguished from those that did not with respect to their anatomy, their physiological status, the anesthetic technique, or the complexity of the surgical procedure. There was no mortality at 48 hours postoperation, the short follow-up being an attempt to focus on anesthesia-related issues.

The difference in outcomes between the studies may reflect a variety of factors. First, the observation that fewer operations and only minor surgery performed at or around Norwood 1 palliation may represent recognition that the children were in the highest risk group and only essential procedures were considered, as suggested by Watkins.[7] This was the stated case in Boston, where surgery is delayed if possible until after cavopulmonary anastomosis. Although smaller series have demonstrated good outcomes for babies with severe CHD who required emergency surgery prior to cardiac surgery,[20] surgery should be deferred wherever possible. Secondly, there is the possibility that highly specialist teams with concentrated expertise in this rare condition might have had an effect. The Torres series consisted of twice the number of cases as the Christensen study, but included procedures performed in hundreds of hospitals (exact number is not clear). These hospitals, although mostly large institutions, were not all teaching hospitals that have a full multidisciplinary pediatric cardiology team on site. It is known that case

numbers have a significant impact on cardiac surgical outcomes for this group,[21] and it seems very likely that the concentration of expertise and experience of the team contributes to good outcomes for NCS. Indeed, a study involving careful multidisciplinary assessment and care by experienced cardiac anesthesia staff has demonstrated the safety of laparoscopic procedures in this patient population.[22] In this series, 13 laparascopic procedures were carried out in a specialist cardiac center on children with HLHS (nine of which had completed Norwood stage 1 but had not received cavopulmonary connection). No major anesthesia-related critical incidents occurred and there was no mortality.

3.2 | Fontan circulations

Another group of concern is patients that have received total cavopulmonary connection (Fontan circulations). The largest series from the Mayo Clinic,[23,24] which maintains a database with data from over 1000 Fontan patients, analyzed complications in 39 anesthetic procedures performed for 31 patients and compared the outcomes with a group of patients over 16 year old receiving NCS from 1998 to 2009. In the Fontan circulation group, complications occurred in 31% of the procedures, including respiratory failure, hypotension, arrhythmias, and one death. In this small sample, only ventricular function (ejection fraction <30%) was identified as an independent risk factor for complications and longer hospital LOS.

In a second retrospective series,[24] CHD patients with Fontan circulations were matched for age and procedure with CHD patients with repaired biventricular circuits (CHD-BiV) and patients with no HD (NHD). From 1990 to 2005, 534 NCS were performed for 154 adults, and, of these, only 51 (9%) underwent GA. Almost half of the patients were under "monitored anesthetic care" and the rest under minimal sedation or regional or local anesthesia. Procedural complications occurred more frequently in the Fontan group (18% vs 5% in CHD-BiV and 1.4% in NHD group, $P = 0.001$), and arrhythmia, hypoxia, and hypotension were most common. The GA group was not analyzed separately, as GA was not identified as an independent risk factor for complications in multivariate analysis (although, notably, the only death was a GA patient). This analysis identified only baseline hypoxia (arterial $SpO_2 < 90\%$) as a significant predictor of complications. Type of Fontan circuit (intra- vs extra-cardiac), poor ventricular function, New York Heart Association functional status, and atrial arrhythmia were not identified as potential risk factors in this population.

These Mayo Clinic series[23,24] are important as they represent the experience of one of the world's largest centers and show that NCS can be performed safely in centers with expertise and relevant support services. The first series described the safe performance of laparoscopic procedures, the use of which has been a concern for this patient group. Although the best approach appears to be the judicious use of GA, which is always performed by the cardiac anesthesia team, details about the decision-making process were not provided. The second series included patients with evidence of "failing Fontan" (poor functional status, worsening cyanosis, atrial arrhythmias, cirrhosis, and protein-losing enteropathy), but is unclear which procedures had been performed and which anesthetic techniques were used. There is no doubt GA confers a higher risk for this subgroup of patients, and good perioperative management requires thorough knowledge of Fontan physiology.[25,26]

3.3 | Pulmonary hypertension

The anesthetic management of patients with pulmonary hypertension is reviewed in a further article in this edition of the journal. The potential to induce a pulmonary hypertensive crisis and cardiac failure is a concern in the perioperative management of patients with PAH. The dangers for this diagnostic group arise from the stress response to surgery as well as anesthesia-induced changes in pulmonary and systemic vascular resistance (PVR and SVR) and cardiac function.

This potential risk was examined in a large retrospective single-center series by Carmosino et al,[27] in which 256 NCS procedures were performed on 156 patients with PAH from 1999 to 2004; 78% of these patients were under GA. Adults and children were included with a wide range of age, from 4 days to 30 years (median 4 years). Importantly, 55% of the procedures were cardiac catheterizations, of which 68% involved diagnostic manipulations of PVR. The series included other potentially high-risk procedures, including airway interventions, thoracic, and major abdominal surgery.

Major complications occurred with seven patients, all of whom received cardiac catheterization. Transient arrest occurred in a child with a device closure of ventricular septal defect (VSD). An additional six patients experienced pulmonary hypertensive crises, two of whom died as a result. The presence of supra-systemic pulmonary artery pressure at baseline was the only risk factor identified in multivariate analysis. Etiology of PAH (56% patients had idiopathic PAH), type of anesthesia (volatile vs intravenous), occurrence of significant desaturation, and duration of procedure were not significant predictors.

In a later retrospective series,[28] an entirely pediatric population with different diagnostic categories was examined over an 8-year period. PAH was secondary to bronchopulmonary dysplasia (BPD) in 46.8%, with only 28.6% was related to CHD. Seventy-seven patients with PAH underwent 141 procedures. In this study as well, cardiac catheterizations were included in NCS (39.2% of cases, 84.4% of which included diagnostic manipulations of PVR), with gastrointestinal procedures being the next most common (29.1%). Major perioperative events reported were cardiac arrest (2.7% intraoperative, 4.7% postoperative), pulmonary hypertensive crisis (2%), and failed extubation (5.6%) with an overall mortality of 1.4%. Severe PAH (supra-systemic PA pressure) was identified as a risk factor. A quarter of the children in this group had a major complication. No individual PAH etiology was predictive of major adverse events. A subgroup analysis of children with non-BPD-associated PAH also suggested functional status (reported as an ASA score) and type of

surgery were indicative of increased risk, with thoracic surgery possibly an area of increased concern.

These series are important in summarizing data from centers with significant experience in PAH, where decision-making and perioperative management have been refined over many years. It is noteworthy that many of the major events occurred for children with PAH receiving manipulations of PVR, which were intentionally performed in the cardiac catheter lab. Outside of this area, critical incidents seem rarer. Experience outside such institutions will be limited and case numbers small, so we should be cautious in considering the risk as low outside tertiary referral centers.

3.4 | William's syndrome

The anesthetic management of patients with William's syndrome is reviewed in a further article in this edition of the journal. William's syndrome is a complex developmental disorder associated with a genetic abnormality in the synthesis if the elastin protein. The microdeletion causes a variety of congenital cardiac lesions, including classically supravalvar aortic stenosis as well as supravalvar pulmonary stenosis, obstructive coronary artery disease and diffuse aortic stenosis (in addition to extra-cardiac vascular anomalies). This complex of lesions predisposes to myocardial ischemia, and this complication has occurred under GA and sedation.[29] Patients with William's syndrome often have significant developmental delay and, along with cardiac issues, dental, and gastrointestinal/feeding problems that require investigation or treatment under anesthesia.

In addition to the article in this edition, an excellent review highlights the issues faced when treating children with William's syndrome and suggests an approach for assessment and management of anesthesia.[30] In addition to the imbalance in oxygen supply (reduced coronary perfusion pressure) and increased demand (increased ventricular wall tension and myocardial oxygen consumption) that can lead to ischemia in any patient with left ventricular outflow tract obstruction, William's syndrome children face additional threats. Noncompliant elastin-deficient vessels, ostial stenosis, and coronary arteriopathy may all be present.

All children with William's syndrome should be thoroughly assessed and risk stratified (Table 2). The multidisciplinary team should perform a risk-benefit analysis for any procedure. Matisoff[30] provides a detailed approach based on risk-level assessment that emphasizes careful attention to balance of myocardial oxygen supply and demand throughout the perioperative period and appropriate use of specialist teams and high-dependency care (including provision of extracorporeal support if necessary).

3.5 | Cardiomyopathy

Congenital HD patients with cardiomyopathy (of any etiology) and severe ventricular dysfunction should be considered at high risk, as confirmed by a review of 34 procedures (largely defibrillator placement and imaging) performed on 26 patients in the Boston database.[31] Eighteen complications occurred in twelve children, of whom 83% had severe ventricular dysfunction. The most frequent complication comprised hypotension, requiring inotropic support and high-dependency care. However, 30-day mortality was low, with only one death. Murphy et al[32] also investigated a particularly high-risk group of inpatients with decompensated heart failure requiring noncardiac procedures. Of the 21 cases identified (median age 21 months), 13 had cardiomyopathies, five had structural HD, two who had neonatal infarcts in structurally normal hearts, and one had a failing transplant. Of the 28 procedures performed, most were line insertions for treatment (n = 18) or catheters for assessment (n = 6) with two emergency laparotomies. The authors describe a balanced technique involving ketamine, opiate, muscle relaxant, volatile anesthesia at subminimum alveolar concentrations, and managed good procedural outcomes in most cases. Two children suffered cardiac arrest under GA but both were resuscitated. Overall, six patients died in admission due to underlying diagnosis but none directly related to anesthesia.

4 | RISK STRATIFICATION OF HIGH-RISK CASES

In the development and validation of the Pediatric Respiratory Assessment Measure[5] for predicting mortality in the general pediatric population, multivariate analysis showed CHD (without further

TABLE 2 Classification of risks in William's syndrome[30]

Low risk	Moderate risk	High risk
Normal ECG	Mild stenosis of branch pulmonary artery stenosis	Severe SVAS
Normal echocardiogram	Hypertension	Symptoms or ECG consistent with ischemia
Minimal extra-cardiac anomalies	Mild to moderate SVAS (<40 mmHg)	Coronary disease demonstrated on imaging
	Other mild cardiac anomalies (eg, VSD)	Severe left ventricular hypertrophy
	Repaired SVAS or SVPS without residual gradients	Biventricular outflow tract disease
	Mild left ventricular hypertrophy	Prolonged QTc on ECG
	Mild to moderate SVPS in isolation	
	Significant extra-cardiac disease (eg, difficult airway or severe GORD)	

ECG, electrocardiogram; GORD, gastro-esophageal reflux disease; QTc, corrected QT interval; SVAS, supravalvar aortic stenosis; SVPS, supravalvar pulmonary stenosis; VSD, ventricular septal defect.

definition or stratification) to be an independent predictor. Other markers of critical illness, such as ventilation and inotropic support, which may be more frequent in the CHD population, also had an additive effect in the score. In the recent European multicenter observational study, APRICOT (Anaesthesia PRactice In Children Observational Study), children receiving cardiac catheterization were at high risk for severe cardiovascular critical events (Risk ratio [RR] 3.2; 95% CI 1.7-5.8).[33] Although no differentiation was made between children with CHD and those with other congenital diseases, a history of any handicap (including CHD) was associated with higher incidence of severe critical events.

Risk stratification systems for CHD have been proposed by several experts.[34] Two important recent studies have attempted to further develop such systems using outcome data.

Saettle et al[9] prospectively applied a locally developed risk stratification to their population of 100 children with CHD having NCS. Patients were placed into low-, medium-, or high-risk categories, according to diagnostic category (Table 3). Additionally, physiological and functional information was included, and the presence of systemic or supra-systemic PAH, decreased cardiac index and "severe" heart failure were placed in the high-risk category regardless of the anatomical diagnosis. In addition, patients with an age less than 1 year, additional comorbidities or high-risk surgery were assigned to a higher risk category. The system was used in the 2 years prior to publication to tailor assessment, perioperative care and postoperative placement on an individual basis.

Of the 100 children with CHD who had received NCS included in the study period (4.5% of total operations), 23 were low risk, 66 moderate risk, and 11 high risk. No major complications occurred. Minor complications (mostly respiratory and one occurrence of transient electrocardiographic ST-segment changes) occurred in 8% of the low- and medium-risk cases and 9% of the high-risk cases. Importantly, all high-risk cases (and many of the lower risk cases) were managed by pediatric cardiac anesthetists. This small, single tertiary center study describes an elegant way of managing this patient group that appears to reduce complication rates. The applicability of the method to different contexts, such as hospitals without pediatric cardiac anesthetists and larger populations, is untested.

Faraoni et al[10] used the ACS NSQIP data pediatric database to analyze CHD patients under 18 years old of age who had received NCS for the years 2012 and 2013 (the derivation cohort). The scoring system was then validated in a 2014 cohort. Having previously demonstrated[4] that low-risk children (as defined by the ACS database) were at similar risk of death as children without CHD, the low-risk children were excluded from the analysis. The remaining cases were distributed into in the derivation cohort (4375 cases) and the validation cohort with major or severe CHD (2869 cases). Mortality was 4.7% in the derivation cohort and 4.0% in the validation cohort. Children who died were younger, had higher ASA scores and more comorbidities and many had single ventricle physiology. Complex, emergency, and gastrointestinal procedures were also found to increased risk for mortality, whereas laparoscopic procedures were associated with reduced risk.

Multivariable logistic regression modeling retained eight variables in the final model (Table 4) from which a score of 1-10 was derived. This model showed good discrimination for prediction of in-hospital mortality (area under curve [AUC] 0.837, 95% CI: 0.806-0.868). In the derivation cohort, scores of ≤3 were associated with low risk of mortality (OR 1.54, 95% CI: 0.78-3.04), scores of 4-6 with medium risk (OR 4.19, 95% CI: 2.56-6.87), and scores of ≥7 with high risk (OR 22.15, 95% CI: 15.06-32.59). This association emphasizes the importance of markers for critical illness and the functional severity of the disease as well as reinforcing single ventricle physiology as major area of concern. Of note, surgical complexity was not found to be significance in this analysis. The validation cohort

TABLE 3 Examples of specific cardiac lesions with associated risk[9]

	Low risk	Moderate risk	High risk
Conduction abnormalities		Wolff-Parkinson-White syndrome Long QT syndrome Pacemaker dependence	
Structural lesions	Repaired atrial or ventricular septal defect Mild regurgitation or stenosis of a single valve	Simple unrepaired lesions, such as atrial or ventricular septal defect Complex cardiac defects with full repair Single ventricle with Glenn or Fontan palliation	Unrepaired complex cardiac lesions Systemic arterial to pulmonary arterial shunts Severe valvular disease
Pulmonary hypertension		New York Heart Association functional class 1 Normal cardiac index	Pulmonary artery pressure equal to or higher than systemic Decreased cardiac index Severe heart failure
Miscellaneous		Heart or lung transplant	Ventricular assist devices William's syndrome Hypertrophic obstructive cardiomyopathy

was analyzed carefully, with statistical attempts to correct for the tendency to "overfit" when deriving AUC.[35] The score showed good discrimination in the validation cohort (AUC 0.831, 95% CI: 0.787-0.875). There was good calibration and high concordance when comparing predicted vs observed mortality.

This scoring system is a significant step forward in our knowledge. Practical application of the score to everyday practice is hampered by lack of data about the professionals performing the surgery (cardiac specialist or general pediatric anesthetist) and where the surgery was performed (teaching vs peripheral, large vs small hospital). The system does, however, clearly confirm the need to combine knowledge of diagnosis and physiological status when assessing children for NCS.

5 | HOW DO WE IMPROVE OUTCOMES?

5.1 | Define the local and national practice

The first step in refining our practice is to understand where and by whom children with CHD are currently being anesthetized for NCS. Most of the data regarding outcome were provided from large US datasets that do not provide the details of perioperative management for these patients.[4] It is possible these details are important factors in outcomes. The series reporting low complication rates in specialist centers indicate that the use of multidisciplinary decision-making and planning and involvement of pediatric cardiac anesthetists are crucial to achieving these low rates.[20,28]

However, local arrangements can be created to provide safe care by centers that do not have full cardiac and cardiothoracic services on site. In a series of 240 NCS procedures[36] in one such institution (including 36 high-risk cases), mortality and morbidity rates were described that compare well with the published literature. The study emphasizes the importance of adequate pediatric cardiology involvement in planning and perioperative care and the need for onsite intensive care facilities for looking after these children postoperatively.

In terms of anesthetic care, no international standard exists for the training of pediatric cardiac anesthetists, and standards may vary within one country.[37] The American Quality Improvement Program introduced guidelines and a threshold based on age for managing anesthesia in children (regardless of the presence of CHD).[38] Such basic recommendations are still lacking in Europe.[39] Creation and adoption of some national or international guidance for the anesthetic care of children with CHD having NCS is an important starting point and will allow us to benchmark any quality improvement process.

5.2 | Collect and analyze outcome data

Deployment of an international anesthesia-incident reporting system is an essential starting point for harmonizing risk stratification and perioperative anesthesia management for children with CHD who will have NCS. The US is leading in this area with NSQUIP and the Congenital Cardiac Anesthesia Society (CCAS). In fact, pediatric cardiac disease has been described as a role model for the development of anesthesia databases.[40] Data from children with CHD are often included in diagnostic and interventional databases, which have an established legal framework for data protection and funding in place. The CCAS database, for instance, was developed as an extension to the Society of Thoracic Surgeon's Congenital Heart surgery database and has collected data since 2010. This database provides benchmark data that can be used as a starting point for comparing practice elsewhere.

Clear definitions are essential to meaningful data analysis and sharing. Diagnostic categories have internationally accepted frameworks[41] but, as mentioned in this review, there is

TABLE 4 Multivariate risk stratification score to predict postoperative mortality[10]

Variables	B (SE)	OR	95% CI	*P*	Risk score
Emergency procedure	0.50 (0.17)	1.66	1.19-2.31	0.003	+1
Severe CHD	0.50 (0.19)	1.65	1.15-2.39	0.007	+1
Single ventricle physiology	0.61 (0.26)	1.83	1.10-3.06	0.020	+1
Surgery within 30 days	0.70 (0.18)	2.01	1.40-2.89	<0.001	+1
Inotropic support	0.72 (0.19)	2.05	1.40-3.01	<0.001	+1
Preoperative CPR	0.90 (0.32)	2.46	1.32-4.57	0.004	+2
Acute or chronic kidney injury	1.48 (0.40)	4.42	2.00-9.75	<0.001	+3
Mechanical ventilation	2.05 (0.18)	7.80	5.42-11.21	<0.001	+4

Data are from multiple logistic regression and are presented as regression coefficient (B), SE, OR, 95% CI, and Wald test *P* value.

CHD, congenital heart disease; CI, confidence interval; CPR, cardiopulmonary resuscitation; OR, odds ratio; SE, standard error.

no standard and accepted stratification for low-, medium-, and high-risk NCS cases. The NSQUIP classification[4] is simple and has been validated on the largest studies. The classification certainly distinguishes well between low- and high-risk groups, although it is difficult to stratify higher risk cases, perhaps because the HLHS is included in "major" CHD and all pulmonary hypertension in "severe". More complex scoring systems may be developed, but currently Faraoni's, based on the NSQUIP database, is the best validated.[10]

5.3 | Apply learning from these outcomes to develop practice and reduce complication rates

For outcome data to be meaningful, large (at least national scale) amounts are necessary. Nonetheless, each hospital or network caring for children with CHD will need to develop its own guidance. This guidance will depend on the expertise of the multidisciplinary team and how facilities (particularly critical care) are structured in each geographical area.

The rarity of CHD and the low overall rate of complications demand a national or international approach to facilitate learning and improve outcomes. CCAS and ACS NSQUIP have provided models that countries outside the US might find helpful. Only by sharing our experience and knowledge can we learn from these rare but devastating complications and continue to contribute to improved outcomes for children with CHD.

Reflective questions

- What are the adverse events and outcomes for children with CHD in your hospital? If no data are available, how might it be collected?
- What risk assessment guidelines are used at your institution for patients with CHD presenting for NCS?
- How should the care of children with CHD presenting with NCS best be planned and delivered where you work?

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

ORCID

Dan Taylor https://orcid.org/0000-0002-6763-4812
Walid Habre https://orcid.org/0000-0002-6521-5091

REFERENCES

1. Murat I, Constant I, Maud'huy H. Perioperative anaesthetic morbidity in children: A database of 24 165 anaesthetics over a 30-month period. *Pediatr Anesth*. 2004;14:158-166.
2. Bhananker SM, Ramamoorthy C, Geiduschek JM, et al. Anesthesia-related cardiac arrest in children: Update from the pediatric perioperative cardiac arrest registry. *Anesth Analg*. 2007;105:344-350.
3. Ramamoorthy C, Haberkern CM, Bhananker SM, et al. Anesthesia-related cardiac arrest in children with heart disease: Data from the pediatric perioperative cardiac arrest (POCA) registry. *Anesth Analg*. 2010;110:1376-1382.
4. Faraoni D, Zurakowski D, Vo D, et al. Post-operative outcomes in children with and without congenital heart disease undergoing noncardiac surgery. *J Am Coll Cardiol*. 2016;67:793-801.
5. Nasr VG, DiNardo JA, Faraoni D. Development of a pediatric risk assessment score to predict perioperative mortality in children undergoing noncardiac surgery. *Anesth Analg*. 2017;124:1514-1519.
6. Baum VC, Barton DM, Gutgesell HP. Influence of congenital heart disease on mortality after noncardiac surgery in hospitalized children. *Pediatrics*. 2000;105:332-335.
7. Watkins SC, McNew BS, Donahue BS. Risks of noncardiac operations and other procedures in children with complex congenital heart disease. *Ann Thorac Surg*. 2013;95:204-211.
8. Lee S, Reddington E, Koutsogiannaki S, et al. Incidence and risk factors for perioperative cardiovascular and respiratory adverse events in pediatric patients with congenital heart disease undergoing noncardiac procedures. *Anesth Analg*. 2018;127:724-729.
9. Saettele AK, Christensen JL, Chilson KL, Murray DJ. Children with heart disease: risk stratification for non-cardiac surgery. *J Clin Anesth*. 2016;35:479-484.
10. Faraoni D, Vo D, Nasr VG, Dinardo JA. Development and validation of a risk stratification score for children with congenital heart disease undergoing noncardiac surgery. *Anesth Analg*. 2016;123:824-830.
11. Warner MA, Lunn RJ, O'Leary PW, Schroeder DR. Outcomes of noncardiac surgical procedures in children and adults with congenital heart disease. *Mayo Clin Proc*. 1998;73:728-734.
12. Short HL, Travers C, McCracken C, Wulkan ML, Clifton MS, Raval MV. Increased morbidity and mortality in cardiac patients undergoing fundoplication. *Pediatr Surg Int*. 2017;33:559-567.
13. Putnam LR, Anderson KT, Tsao KJ, et al. The impact of cardiac risk factors on short-term outcomes for children undergoing a Ladd procedure. *J Pediatr Surg*. 2017;52:390-394.
14. Sulkowski JP, Cooper JN, McConnell PI, et al. Variability in noncardiac surgical procedures in children with congenital heart disease. *J Pediatr Surg*. 2014;49:1564-1569.
15. Maxwell BG, Wong JK, Kin C, Lobato RL. Perioperative outcomes of major noncardiac surgery in adults with congenital heart disease. *Anesthesiology*. 2013;119:762-769.
16. Torres A, DiLiberti J, Pearl RH, et al. Noncardiac surgery in children with hypoplastic left heart syndrome. *J Pediatr Surg*. 2002;37:1399-1403.
17. Christensen RE, Gholami AS, Reynolds PI, Malviya S. Anaesthetic management and outcomes after noncardiac surgery in patients with hypoplastic left heart syndrome: a retrospective review. *Eur J Anaesthesiol*. 2012;29:425-430.
18. Brown ML, DiNardo JA, Odegard KC. Patients with single ventricle physiology undergoing noncardiac surgery are at high risk for adverse events. *Pediatr Anesth*. 2015;25:846-851.
19. Jeffries HE, Wells WJ, Starnes VA, Wetzel RC, Moromisato DY. Gastrointestinal morbidity after Norwood palliation for hypoplastic left heart syndrome. *Ann Thorac Surg*. 2006;81:982-987.
20. Walker A, Stokes M, Moriarty A. Anesthesia for major general surgery in neonates with complex cardiac defects. *Pediatr Anesth*. 2009;19:119-125.
21. Pasquali SK, Li JS, Burstein DS, et al. Association of center volume with mortality and complications in pediatric heart surgery. *Pediatrics*. 2012;129:e370-e376.

22. Slater B, Rangel S, Ramamoorthy C, Abrajano C, Albanese CT. Outcomes after laparoscopic surgery in neonates with hypoplastic heart left heart syndrome. *J Pediatr Surg*. 2007;42:1118-1121.
23. Rabbitts JA, Groenewald CB, Mauermann WJ, et al. Outcomes of general anesthesia for noncardiac surgery in a series of patients with Fontan palliation. *Pediatr Anesth*. 2013;23:180-187.
24. Egbe AC, Khan AR, Ammash NM, et al. Predictors of procedural complications in adult Fontan patients undergoing non-cardiac procedures. *Heart*. 2017;103:1813-1820.
25. Pitkin AD, Wesley MC, Guleserian KJ, Baum VC, Burch TM, Janelle GM. Perioperative management of a patient with failed Fontan physiology. *Semin Cardiothorac Vasc Anesth*. 2013;17:61-65.
26. Windsor J, Townsley MM, Briston D, Villablanca PA, Alegria JR, Ramakrishna H. Palliation for single-ventricle physiology: perioperative management for noncardiac surgery and analysis of outcomes. *J Cardiothorac Vasc Anesth*. 2017;31:2296-2303.
27. Carmosino MJ, Friesen RH, Doran A, Ivy DD. Perioperative complications in children with pulmonary hypertension undergoing noncardiac surgery or cardiac catheterization. *Anesth Analg*. 2007;104:521-527.
28. Bernier ML, Jacob AI, Collaco JM, McGrath-Morrow SA, Romer LH, Unegbu CC. Perioperative events in children with pulmonary hypertension undergoing non-cardiac procedures. *Pulm Circ*. 2018;8:1-10.
29. Burch TM, McGowan FX, Kussman BD, Powell AJ, Dinardo JA. Congenital supravalvular aortic stenosis and sudden death associated with anesthesia: what's the mystery? *Anesth Analg*. 2008;107:1848-1854.
30. Matisoff AJ, Olivieri L, Schwartz JM, Deutsch N. Risk assessment and anesthetic management of patients with Williams syndrome: a comprehensive review. *Pediatr Anesth*. 2015;25:1207-1215.
31. Kipps AK, Ramamoorthy C, Rosenthal DN, Williams GD. Children with cardiomyopathy: complications after noncardiac procedures with general anesthesia. *Pediatr Anesth*. 2007;17:775-781.
32. Murphy T, Smith JH, Ranger M, Haynes SR. General anaesthesia for children with severe heart failure. *Pediatr Cardiol*. 2011;32:139-144.
33. Habre W, Disma N, Virag K, et al. Incidence of severe critical events in paediatric anaesthesia (APRICOT): a prospective multicentre observational study in 261 hospitals in Europe. *Lancet Respir*. 2017;2600:1-14.
34. White MC, Peyton JM. Anaesthetic management of children with congenital heart disease for non-cardiac surgery. *Contin Educ Anaesthesia, Crit Care Pain*. 2012;12:17-22.
35. Smith G, Seaman SR, Wood AM, Royston P, White IR. Correcting for optimistic prediction in small data sets. *Am J Epidemiol*. 2014;180:318-324.
36. Ng SM, Jin X, Yates R, Kelsall A. Outcome of noncardiac surgery in children with congenital heart disease performed outside a cardiac center. *J Pediatr Surg*. 2016;51:252-256.
37. Baehner T, Dewald O, Heinze I, et al. The provision of pediatric cardiac anesthesia services in Germany: current status of structural and personnel organization. *Pediatr Anesth*. 2017;27:801-809.
38. Peterson MB, Houck CS, Deshpande JK, Flick RP. The American College of Surgeons Children's Surgery Verification and Quality Improvement Program: what anesthesiologists need to know now. *Anesth Analg*. 2018;126:1624-1632.
39. Habre W. Pediatric anesthesia after APRICOT (Anaesthesia PRactice in Children Observational Trial): Who should do it? *Curr Opin Anaesthesiol*. 2018;31:292-296.
40. Vener DF, Pasquali SK, Mossad EB. Anesthesia and databases: pediatric cardiac disease as a role model. *Anesth Analg*. 2017;124:572-581.
41. Béland MJ, Jacobs JP, Tchervenkov CI, Franklin R. Report from the executive of the International Working Group for mapping and coding of nomenclatures for paediatric and congenital heart disease. *Cardiol Young*. 2002;12:425-430.

How to cite this article: Taylor D, Habre W. Risk associated with anesthesia for noncardiac surgery in children with congenital heart disease. *Pediatr Anesth*. 2019;29:426–434. https://doi.org/10.1111/pan.13595