Lesion-specific outcomes in neonates undergoing congenital heart surgery are related predominantly to patient and management factors rather than institution or surgeon experience: A Congenital Heart Surgeons Society Study
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Lesion-specific outcomes in neonates undergoing congenital heart surgery are related predominantly to patient and management factors rather than institution or surgeon experience: A Congenital Heart Surgeons Society Study

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Objective: To identify the role of institution and surgeon factors, including case volume and experience, on survival of neonates with complex congenital heart disease.

Methods: A total of 2421 neonates from 4 groups—transposition of the great arteries (n = 829), pulmonary atresia with intact ventricular septum (n = 408), Norwood (n = 710), and interrupted aortic arch (n = 474)—were prospectively enrolled from Congenital Heart Surgeons Society institutions. Multivariable analysis of risk-adjusted survival was performed for each group, entering each institution or surgeon into the multivariable analysis separately. Institutional performance was defined as [predicted survival – actual survival]. Neutralization of risk factors within each institution was evaluated using complex interaction terms. Institution and surgeon experience, defined by 5 domains (total case volume, total time each operation was performed, cases per year, rank-order of cases, case velocity), were also investigated.

Results: Institutional performance varied among all groups. Improved outcomes in Norwood and pulmonary atresia with intact ventricular septum were unrelated to any "experience" domains, whereas improved outcomes in transposition of the great arteries were significantly related to increased experience in most domains. No institution enrolling in all 4 studies ranked number 1 in performance for all groups. Neutralization of low birth weight as a risk factor contributed to decreased mortality after Norwood in one institution.

Conclusion: Survival of neonates with complex congenital heart disease is influenced more by patient and management factors than by institution or surgeon experience. Institutional excellence in managing some diagnostic groups does not indicate similar performance for all diagnostic groups. Weighted risk-adjusted comparisons could provide a mechanism to improve results in institutions with less than optimal outcomes. (J Thorac Cardiovasc Surg 2010;139:569-77)
operative risk, and the differential importance of patient and technical factors among diagnostic groups.\textsuperscript{11,14,15,18-20} We sought to use comprehensive diagnosis-based datasets (with the exception of the Norwood) derived from Congenital Heart Surgeons Society (CHSS) multi-institutional studies to overcome these problems and create risk-adjusted models to determine the role of institutional and surgeon experience on outcomes for neonates with complex CHD.

**MATERIALS AND METHODS**

**Patients and Institutions**

A total of 2421 neonates from 4 groups (transposition of the great arteries [TGA], Norwood, interrupted aortic arch [IAA], and pulmonary atresia with intact ventricular septum [PAIVS]) were prospectively enrolled from 24 to 33 CHSS institutions. Outcomes for all of these neonates, including the specific patient and procedural characteristics, have been reported.\textsuperscript{15,21-24} Participation in the study and submission of patient information was voluntary and confidential. Parental consent was obtained consistent with individual institutional policies. Ethics approval for the CHSS Data Center is obtained annually from the Hospital for Sick Children in Toronto. Enrollment period, institution, and surgeon characteristics for each group are shown in Table 1.

**Data Analysis**

Data are presented as frequency, median with range, or mean ± standard deviation as appropriate, with the number of missing values indicated. Percentages, hazard functions, and competing risk estimates are presented with confidence limits equivalent to 1 standard error (68\%\%). All data analyses were performed using SAS statistical software (version 9; SAS Institute Inc, Cary, NC). Multivariate parametric modeling of the hazard function\textsuperscript{16,17} and competing risks methodology\textsuperscript{22,25-29} were used to determine rates of transition to mutually exclusive time-related events and identify incremental risk factors associated with each transition rate as previously described.\textsuperscript{16,17,22,25-29} Transformations to linearize variables and to optimize calibration to risk for continuous predictors were considered in all multivariable analyses. Variable selection was primarily by bootstrap bagging, with those variables having greater than 50\% reliability included in the final models.\textsuperscript{17,22}

**Statistical Models**

Overall risk-adjusted parametric mortality models were constructed on the basis of the total experience of all institutions, accounting for patient, demographic, and procedural factors that influence mortality for the entire diagnostic group. The overall mortality models for each group were specified a priori, meaning that we used the previously reported overall mortality model for each diagnostic group\textsuperscript{15,21-24} (Table E1). However, the importance of risk factors affecting overall outcomes may or may not apply equally to each individual institution. We addressed this problem using the following methods to account for potential variation within each institution: (1) Each institution was forced into the overall model for each diagnostic group (ie, to determine whether that particular institution conferred an increased or decreased risk); (2) interaction terms were then created with each risk factor within the overall model to determine whether improved or reduced institutional performance could be explained by neutralization of known risk factors for the entire cohort; (3) institutional “experience” was then incorporated as an explanatory variable to define whether these factors improved performance discrimination; and (4) actual institutional performance at an individual institution was compared with the expected risk-adjusted mortality at that institution on the basis of all identified risk factors. Institutional “experience” was evaluated using the following 5 separate domains:

1. total case volume (the total number of patients enrolled at each institution during the entire study enrollment period).
2. total time period (years) in which each institution was performing a particular procedure (the difference in years between the date of the last procedure and the date of the first procedure during the study enrollment period; for example, if institution “X” enrolled their first patient with an arterial switch operation in 1985 and enrolled their last patient with an arterial switch in 1989, this value would be 4 years);
3. cases per year (the total number of patients enrolled by each institution divided by the number of years in which that institution enrolled patients in each study);
4. rank order of cases (the first case through the last case in consecutive order); and
5. case velocity over time (the rank order of each case divided by the time interval (number 2 above) in which a particular procedure was performed).

Surgeon “experience” was likewise evaluated using the same 5 domains but was considered only in Norwood and TGA, the only 2 groups with available surgeon-level data. The effect of era was considered by incorporating the date at which each institution or surgeon enrolled their first patient undergoing a particular procedure as an explanatory variable.

**RESULTS**

**Impact of Institutional Experience Factors on Mortality**

Impact of institution “experience” factors on risk-adjusted overall 5-year mortality after admission is shown in Table 2. In complex procedures, such as the Norwood, there was no apparent survival benefit conferred by increased institution “experience” in any of the 5 domains investigated (Figure 1). Improved results in management of neonates with PAIVS were also not significantly related to increased institution experience (Table 2).

However, in TGA, improved 5-year survival is significantly associated with increasing institutional experience in 4 of the 5 domains investigated (Table 2). Lower annual TGA case volume, with a threshold value of less than 50 cases per year, resulted in significantly increased mortality (Figure 2, A). The improvement in mortality, though, was due to improved outcomes for the arterial switch (n = 516) rather than for the atrial switch (n = 276), in which the risk did not change significantly (Figure 2, B). For the arterial switch, increased case velocity over time was associated with decreased mortality (parameter estimate: −0.06 ± 0.13 per case; P < .001). Similarly, mortality was inversely related to increased total procedure time that each institution had with the arterial switch (parameter estimate: −0.24 ± 0.10 per year; P = .01). However, for the atrial switch, there was no significant survival benefit conferred by any of the experience domains considered.

**Institutional Performance**

There was considerable variation in institutional performance among the different lesion sets (Figure 3, A–D). No
clear relationship between volume and performance was evident, but wide overlapping confidence intervals indicate poor discrimination except between those institutions performing at both extremes. Institutional excellence in managing some groups of neonates did not translate into equally superior performance in their management of other groups (Figure 4).

Impact of Surgeon Factors and Learning Curve Dynamics

Increasing surgeon “experience” was related to improved survival for the TGA cohort (Table 3). Outcomes for the arterial switch improved significantly with increased

### TABLE 1. Institution and surgeon characteristics for each diagnostic group

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Norwood</td>
<td>Enrollment period: 1994–2000&lt;br&gt;Total no. of patients: 710&lt;br&gt;No. of institutions: 29&lt;br&gt;Total cases (median and range): 6 (1–155)&lt;br&gt;Cases per year (median and range): 14 (1–40)&lt;br&gt;Total No. of surgeons: 56&lt;br&gt;No. of surgeons per institution (median and range): 1 (1–10)&lt;br&gt;Total cases: 5 (1–130)&lt;br&gt;Cases per year (median and range): 3 (1–36)</td>
</tr>
<tr>
<td>II. TGA</td>
<td>Enrollment period: 1995–1989&lt;br&gt;Total no. of patients: 829&lt;br&gt;No. of institutions: 24&lt;br&gt;Total cases (median and range): 53 (1–169)&lt;br&gt;Arterial switch (median and range): 52 (1–146)&lt;br&gt;Atrial switch (median and range): 21 (1–31)&lt;br&gt;Cases per year (median and range): 12 (1–60)&lt;br&gt;Arterial switch per year (median and range): 17 (1–52)&lt;br&gt;Atrial switch per year (median and range): 5 (1–15)&lt;br&gt;No. of surgeons: 50&lt;br&gt;No. of surgeons per institution (median and range): 1 (1–10)&lt;br&gt;Total cases per surgeon (median and range): 38 (1–87)&lt;br&gt;Cases per surgeon per year (median and range): 9 (1–28)&lt;br&gt;Atrial switch per surgeon per year: 3 (1–12)</td>
</tr>
<tr>
<td>III. IAA</td>
<td>Enrollment period: 1987–1997&lt;br&gt;Total no. of patients: 474&lt;br&gt;No. of institutions: 33&lt;br&gt;Total cases (median and range): 9 (1–57)&lt;br&gt;Cases per year (median and range): 3 (1–10)</td>
</tr>
<tr>
<td>IV PAIVS</td>
<td>Enrollment period: 1987–1997&lt;br&gt;Total no. of patients: 408&lt;br&gt;No. of institutions: 33&lt;br&gt;Total cases (median and range): 17 (1–41)&lt;br&gt;Cases per year (median and range): 3 (1–9)</td>
</tr>
</tbody>
</table>

### TABLE 2. Impact of institution “experience” factors on risk-adjusted mortality

<table>
<thead>
<tr>
<th>Factor</th>
<th>Parameter estimate ± SE</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased total case volume*</td>
<td>Norwood (per case): −0.002 ± 0.001</td>
<td>.17</td>
</tr>
<tr>
<td>Increased total cases per year</td>
<td>Norwood (per case): −0.02 ± 0.01</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Increased cases per year</td>
<td>IAA (per case): 0.02 ± 0.01</td>
<td>.07</td>
</tr>
<tr>
<td>Increased rank order</td>
<td>PAIVS (per case): 0.02 ± 0.01</td>
<td>.001</td>
</tr>
<tr>
<td>Increased total procedure time</td>
<td>TGA (per case): −0.02 ± 0.01</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

IAA, Interrupted aortic arch; TGA, transposition of the great arteries; PAIVS, pulmonary atresia with intact ventricular septum. *Total number of patients enrolled at each institution during the entire study enrollment period. | Rank order of cases, indicating a potential learning curve (Figure 5).

Conversely, there was no influence of surgeon “experience” on outcomes after the Norwood procedure (Table 3). Risk-adjusted 5-year mortality was not significantly improved despite increasing surgeon annual case volume (Figure 6).

Neutralization of Risk: Management Paradigms as Reasons for Improved Outcomes

Institution-specific models using the interaction terms revealed one potential reason for improved institutional performance in the Norwood series. Risk factors for mortality identified from the overall model of all 710 neonates included the patient-specific factor lower birth weight. However, one institution that enrolled 43 patients (total volume range for all institutions: 3–155) achieved the best performance because birth weight had little impact on survival within this institution. The favorable results in this institution may derive not from volume, but from their...
management of a patient characteristic, ‘‘low birth weight,’’ which was a risk factor for all other institutions, but has been neutralized in this institution (Figure 7).

Institutional protocols rather than volume or technical expertise per se are also implicated as the underlying reason for improved outcomes in the PAIVS cohort. The institution with the best results in PAIVS enrolled only 20 patients but used a balanced management protocol based on morphology. The morphologically driven protocol allowed this institution to achieve comparably excellent survival, with a high prevalence of biventricular repair and Fontan operation, and few patients remaining unrepaired at age 5 years (Figure 8).

**DISCUSSION**

Defining the impact of institution and surgeon experience on outcomes in neonatal CHD is crucial in the current climate of extensive public scrutiny. The potential that parallel initiatives similar to those spearheaded by the Leapfrog Group may be advocated in pediatric cardiac surgery further highlight the importance of the establishment of a precise and valid measure of performance. We report results from the first study to use an academic database with a comprehensive variable set to examine the influence of institution and surgeon experience on outcomes for neonates beyond hospital discharge. We have shown that risk adjustment with data-derived risk factors to ‘‘level the playing field’’ provides an accurate method to compare and explain institutional performance. Institution and surgeon experience are not the primary determinants of survival, but experience is more important in some diagnostic groups than others.

**Previous Models for Risk Stratification**

Recent methods of risk stratification in CHD surgery, including the RACHS-1 and Aristotle Basic and Comprehensive scores, have been proposed as useful methods for comparing inter-institutional outcomes. However, although these scores may be statistically useful when applied to a large group of patients with shared characteristics, they lack precision in estimating risk for individual patients. Furthermore, candidate risk factors used in these systems have been consensus based rather than data derived. Other problems with both the Aristotle and RACHS systems, including procedure ‘‘groups’’ that are not accommodated by the scoring systems, ambiguous or redundant nomenclature, and insufficient variables to permit
complete risk factor adjustment, have hampered widespread acceptance of either system. Previous studies evaluating outcomes have used “early death” in an attempt to simplify and standardize analysis. However, “early” is arbitrary, being variously defined as operative mortality (death within 30 days of operation and before hospital discharge), in-hospital mortality (death occurring after operation and during the same hospital admission as that operation), or 30-day mortality (death occurring within 30 days of operation regardless of hospital status). None of the former recognize that the risk of death after operation changes over time. Typically the risk is high at the time of operation but decreases rapidly to a lower risk that is constant but not zero, and much later, the risk...
increases in a third phase. Risk factors that influence outcome, either positively or negatively, in one phase may or may not affect outcome in any of the other phases. The early hazard phase of risk is unaffected by either the first 30-day period after operation or by hospital discharge. The CHSS report of outcomes in 710 neonates after the Norwood operation, for example, documented an early phase mortality that persisted beyond both hospital discharge and the 30-day definition.\textsuperscript{15} Other CHSS studies, using techniques described by Blackstone and others,\textsuperscript{15-24} used parametric hazard function analysis to define both the phases of risk and those factors that influence risk during a given phase of follow-up.

**Impact of Institutional and Surgeon Factors on Outcome**

We have shown that survival of neonates with complex CHD is influenced more by patient and management factors than institution or surgeon experience. Despite similar complexity, however, experience is clearly more important in some lesions and procedures (the arterial switch for TGA) than others (the Norwood procedure). In agreement with our finding, Checchia and colleagues\textsuperscript{1} also found that outcomes after the Norwood operation were independent of surgeon volume. What reasons underlie this disparate influence? First, outcomes may be more dependent on experience for the arterial switch because operative technique is the defining factor for the arterial switch operation, whereas for the Norwood operation, the technical issues are overshadowed by the comparatively more complicated preoperative and postoperative care. A patient who has had a technically successful arterial switch operation, therefore, does well with little requirement for critical postoperative care. In contrast, an arterial switch operation that is technically compromised (eg, coronary stenosis) results in a high risk of death irrespective of postoperative care. Second,

**FIGURE 4.** There were 6 CHSS institutions that contributed patients to all 4 diagnostic groups and had more than 10 patients within each group. These institutions were ranked out of a total number of 31 institutions based on the magnitude of difference between the predicted mortality at that institution after risk adjustment and the actual mortality at that institution. Institutions with the largest differential were ranked from lowest to highest, with a lower number indicating superior performance. The institution number is listed along the horizontal axis. Each geometric shape represents the individual institution’s performance within a particular diagnostic group. Institutional excellence in managing certain diagnostic groups does not translate into excellence in managing all diagnostic groups. Note that institution 18 has excellent performance in the Norwood and IAA groups, but has the worst performance in the PAIVS group. PAIV/S, Pulmonary atresia with intact ventricular septum; TGA, transposition of the great arteries; IAA, interrupted aortic arch.

**TABLE 3. Impact of surgeon “experience” factors on mortality**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Parameter estimate</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norwood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased total case volume</td>
<td>-0.001 (\pm) 0.001</td>
<td>.40</td>
</tr>
<tr>
<td>Increased cases per year</td>
<td>-0.004 (\pm) 0.007</td>
<td>.49</td>
</tr>
<tr>
<td>Increased rank order</td>
<td>-0.002 (\pm) 0.002</td>
<td>.91</td>
</tr>
<tr>
<td>Increased case velocity</td>
<td>-0.006 (\pm) 0.001</td>
<td>.70</td>
</tr>
<tr>
<td>Increased procedure time</td>
<td>-0.04 (\pm) 0.03</td>
<td>.26</td>
</tr>
<tr>
<td>TGA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased total case volume (per case)</td>
<td>-0.01 (\pm) 0.004</td>
<td>.002</td>
</tr>
<tr>
<td>Increased cases per year (per case)</td>
<td>-0.04 (\pm) 0.01</td>
<td>.002</td>
</tr>
<tr>
<td>Increased rank order (per case)</td>
<td>-0.01 (\pm) 0.06</td>
<td>.009</td>
</tr>
<tr>
<td>Increased case velocity (per case)</td>
<td>0.004 (\pm) 0.002</td>
<td>.09</td>
</tr>
<tr>
<td>Increased procedure time (per year)</td>
<td>-0.13 (\pm) 0.08</td>
<td>.10</td>
</tr>
<tr>
<td>Arterial switch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased rank order (per case)</td>
<td>-0.04 (\pm) 0.01</td>
<td>.001</td>
</tr>
<tr>
<td>Atrial switch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased rank order (per case)</td>
<td>-0.03 (\pm) 0.03</td>
<td>.41</td>
</tr>
</tbody>
</table>

\textit{SE}, Standard error; TGA, transposition of the great arteries.

**FIGURE 5.** There was a significant positive association between increased surgeon experience and improved outcomes for the TGA cohort that was specific for the arterial switch operation. This nomogram shows a decline in risk-adjusted 5-year mortality as a function of increasing case rank-order per surgeon stratified by procedure type. Although mortality declines for both procedures, there was a significant decrease in mortality only for the arterial switch.
the relatively narrow morphologic spectrum of TGA compared with the wider morphologic spectrum of hypoplastic left heart syndrome is also likely to increase the relative importance of experience. Third, the TGA cohort circumscribed an earlier time period (1980s vs late 1990s for the Norwood series) that included the introduction of a new technique. It is probable that the strong influence of increased experience in TGA outcomes is due to capturing a learning curve for the arterial switch, which was missed in the Norwood cohort.

Concordant with these findings, Birkmeyer and colleagues found that the importance of hospital volume varied markedly according to procedure type. They found that hospital mortality for pancreatectomy and esophagectomy was highly correlated with increasing caseload, whereas volume had little impact on mortality after coronary artery bypass grafting or carotid endarterectomy.

Our results are in contrast with those reported by others who have examined the impact of volume on in-hospital or 30-day mortality, but they confirm the findings of other recently published studies using large administrative databases. Jenkins and colleagues reported significantly decreased in-hospital mortality among those centers performing greater than 300 cases annually in their analysis of 2833 congenital heart operations performed at 37 centers. Hannan and colleagues reached similar conclusions whereby the odds ratio for hospital death was 1.42 in low-volume institutions (annual volume <100 cases) when compared with high-volume centers (annual volume >100 cases). They also found that increased annual surgeon caseload (>75) significantly improved survival to hospital discharge. Similarly, Allen and colleagues found that evidenced-based referrals from a small volume (<50 cases per year) to large volume (>300 cases per year) resulted in a reduction in mortality after congenital heart surgery.

Different findings reported in our study are related to the different end point used for comparison and our analytic methods. We have used parametric time-related analysis for mortality rather than logistic regression models fit for an arbitrary end point: hospital or ‘‘early’’ death. Further, the statistical models were risk adjusted on the basis of data-derived variables derived from an academic database rather than risk stratified on the basis of consensus-based
scores. Recognizing that volume may not be the singular best metric for “experience,” we used 5 different measures for both institution and surgeon experience. Finally, the relationship between volume and outcome may be different given the considerable improvement in surgical outcomes in the contemporary era. By using a measure of memory loss termed “exponentially weighted moving average,” deLeval and colleagues showed that mortality estimates can be influenced when remote experiences are down-weighted compared with more current experience.

Welke and colleagues used a large administrative database, the Nationwide Inpatient Sample, to demonstrate the inherent flaws in using case volume alone as a discriminator of mortality. The relationship between hospital pediatric surgical volume and in-hospital mortality was examined using data from more than 55,000 pediatric cardiac surgical operations performed at more than 300 hospitals, using grouped volume categories. These authors found that very small hospitals (those performing ≤20 cases per year) had equivalent mortality to that of large hospitals (those performing >200 cases per year). Model discrimination using volume was poor (c-statistic of 0.5), indicating that predictive ability was no better than a coin flip. A subsequent analysis exploring volume–outcome relationships revealed, using simple power calculations, that an annual volume threshold of 525 operations would be required to detect a doubling of the baseline mortality within the Nationwide Inpatient Sample database (from 4.2% to 8.4%) with a 20% type II error rate.

We found considerable ranked performance variation among institutions within each of 4 groups, with most institutions falling within the 95% confidence intervals of predicted survival. Difficulty achieving reasonable performance discrimination between individual institutions because of wide confidence intervals was also noted by Stark and colleagues in their review of all operations performed in the United Kingdom between 1999 and 1998.

Our study also found that variation in performance among different diagnostic groups occurred within an individual institution. Excellent performance in one diagnostic group did not indicate similar performance in all other groups. Implications for evidence-based referral highlight the importance of defining the institutional distribution of specific expertise.

Management Paradigms in Complex Congenital Heart Disease

Institution-specific management paradigms rather than increasing volume or other measures of “experience” may provide solutions to such critically important problems as the treatment of low birth weight neonates or refining the selection criteria for specific repair pathways. We showed that the institution with the best results in the Norwood operation had neutralized an important risk factor that still confounds other institutions. Likewise, selection of neonates for a single or biventricular repair pathway in one institution based on a morphologic protocol led to superior results in PAIVS. In support of this contention, Checchia and colleagues demonstrated a significant 1-year survival benefit (50% vs 10%, P < .0001) for infants after the Norwood operation by following the adoption of a preoperative selection protocol that triaged infants to either Norwood or transplantation on the basis of a weighed risk score.

LIMITATIONS

Hierarchic models that account explicitly for within-subject correlation among patients treated at one institution and that introduce surgeon-level factors as random effects (general estimating equations and mixed models) can be easily applied for use in non-timed event analyses such as logistic regression. Hierarchic models may improve discrimination among institutions by reducing variance between each institution. However, software that integrates fixed and random effects within multiphase parametric models is not presently available.

CHSS member institutions represent a select group of hospitals, and submission of data was voluntary for these studies. It is possible, therefore, that the lack of a clear volume–outcome relationship in this study may be due to selection bias, and the results may not be applicable to non-CHSS institutions.

We were unable to quantitate accurately the total operative experience of each individual surgeon because of several factors. These 4 CHSS studies spanned several decades in which migration of surgeons to different institutions over time presumably occurred. Further, formal certification in congenital heart surgery has not existed until 2007, making it impossible to determine with certainty a definitive end point for training.

CONCLUSIONS

Institution and surgeon experience is not the only factor influencing outcomes in complex CHD. Experience cannot be singularly defined as volume and should be evaluated as a composite measure. Considerable overlap in ranked performance exists among institutions, and discrimination is likely to further decline with the overall improvement in outcomes and the “shrinking” margin of error. Excellent institutional performance in managing one diagnostic group does not indicate similar performance for all other diagnoses. Valid comparisons of institution and surgeon outcomes could provide a mechanism to improve results in institutions with less favorable outcomes.

References


### TABLE E1. Multivariable models for overall mortality

**Norwood**
- Birth weight (kg)
- Age at operation (d)
- Circulatory arrest time (min)
- Ascending aortic dimension (mm)
- Reimplantation of the ascending aorta (yes/no)
- Shunt origin from the aorta (yes/no)
- Interaction term between ascending aortic diameter and ascending aortic diameter

**Interrupted aortic arch**
- Date of birth (squared transformation)
- Weight at repair (inverse transformation)
- Truncus arteriosus (yes/no)
- IAA type B or C (yes/no)
- VSD not large (yes/no)
- Absence of malalignment of the VSD (yes/no)
- No augmentation of the aortic arch at IAA repair (yes/no)
- Main pulmonary artery-aorta anastomosis performed at IAA repair (yes/no)

**Pulmonary atresia with intact ventricular septum**
- Graded spectrum of right ventricular size (square transformation)
- Tricuspid valve Z-score
- Higher left ventricular pulse pressure (mm Hg)
- Birth weight (kg)

**Transposition of the great arteries**
- Birth weight (kg)
- Age at repair (d)
- Female gender (yes/no)
- Major associated cardiac anomalies (yes/no)
- Major associated noncardiac anomalies (yes/no)
- Number of pre-repair procedures
- Simple TGA (yes/no)
- Moderate or large VSD (yes/no)
- Multiple VSDs (yes/no)
- Degree of pulmonary stenosis
- Repair type
  - Arterial switch
  - Atrial switch
- Rastelli
- Use of circulatory arrest (yes/no)
- Circulatory arrest time (min)
- CrossClamp time (min)

**IAA, Interrupted aortic arch; VSD, ventricular septal defect; TGA, transposition of the great arteries.**


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