RACHS-ANZ: A Modified Risk Adjustment in Congenital Heart Surgery Model for Outcome Surveillance in Australia and New Zealand

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Background—Outcomes for pediatric cardiac surgery are commonly reported from international databases compiled from voluntary data submissions. Surgical outcomes for all children in a country or region are less commonly reported. We aimed to describe the bi-national population-based outcome for children undergoing cardiac surgery in Australia and New Zealand and determine whether the Risk Adjustment for Congenital Heart Surgery (RACHS) classification could be used to create a model that accurately predicts *in-hospital mortality* in this population.

Methods and Results—The study was conducted in all children's hospitals performing cardiac surgery in Australia and New Zealand between January 2007 and December 2015. The performance of the original RACHS-1 model was assessed and compared with an alternative RACHS-ANZ (Australia and New Zealand) model, developed balancing discrimination with parsimonious variable selection. A total of 14 324 hospital admissions were analyzed. The overall hospital mortality was 2.3%, ranging from 0.5% for RACHS category 1 procedures, to 17.0% for RACHS category 5 or 6 procedures. The original RACHS-1 model was poorly calibrated with death overpredicted (1161 deaths predicted, 289 deaths observed). The RACHS-ANZ model had better performance in this population with excellent discrimination (Az-ROC of 0.830) and acceptable Hosmer and Lemeshow goodness-of-fit (*P*=0.216).

Conclusions—The original RACHS-1 model overpredicts mortality in children undergoing heart surgery in the current era. The RACHS-ANZ model requires only 3 risk variables in addition to the RACHS procedure category, can be applied to a wider range of patients than RACHS-1, and is suitable to use to monitor regional pediatric cardiac surgery outcomes. (*J Am Heart Assoc.* 2019;8:e011390. DOI: 10.1161/JAHA.118.011390.)

Key Words: cardiac surgery • congenital heart disease • outcome and process assessment • pediatric • risk model

Congenital heart disease is the most frequently occurring congenital anomaly at birth and a leading cause of infant death from birth defects.[1] Many children with congenital heart disease require surgery, with some children needing multiple procedures during childhood. In order to monitor outcomes of hospitals performing pediatric cardiac surgery, methods of adjusting for procedural and patient risk are required. Three methods of scoring procedural complexity have been developed. The Aristotle Basic Complexity score[2] and the Risk Adjustment for Congenital Heart Surgery (RACHS-1) score[3] were developed based on expert opinion while the Society of Thoracic Surgeons–European Association for Cardiothoracic Surgery (STS-EACTS) Congenital Heart Surgery Mortality Score was developed more recently from empirical data

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Clinical Perspective

What Is New?

- This population-based study of a centralized system of providing pediatric cardiac services describes an overall hospital mortality for pediatric cardiac surgery of 2.3%.
- The modified Risk Adjustment for Congenital Heart Surgery - Australia and New Zealand (RACHS-ANZ) prediction model reported in the study is calibrated to the standard of care in Australia and New Zealand in the current era.
- Performance assessment of the model demonstrated excellent discrimination (Az-ROC of 0.830) and acceptable goodness-of-fit.

What Are the Clinical Implications?

- The infrastructure for surveillance of pediatric intensive care outcomes in Australia and New Zealand is well established.
- This study shows that simply by adding surgical procedure codes to the data collected, the existing infrastructure developed for regional monitoring of intensive care outcomes could also provide a system for regional monitoring of pediatric cardiac surgery outcomes.

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contained in 2 large international databases.[4] Procedure complexity categories, in combination with patient-level risk factors, have been used to develop outcome prediction models for congenital heart surgery.[3,4]

The Society of Thoracic Surgeons (STS) Congenital Heart Surgery Database and the European Association for Cardio-thoracic Surgery (EACTS) Congenital Heart Surgery Database enable participating cardiac surgical centers to benchmark risk-adjusted outcomes with international standards. Notwithstanding the importance of international comparisons, there are additional benefits from regional comparison of health outcomes, for example in our context, comparing outcomes across Australia and New Zealand (ANZ). Regional analyses allow outcomes to be compared in settings where health systems and healthcare resources are similar, and where the social determinants of health in the population are also similar. Individual pediatric cardiac services in ANZ benchmark institutional outcomes using international databases, however, the infrastructure for regional comparisons does not currently exist.

Methods for benchmarking pediatric intensive care, such as the Paediatric Index of Mortality,[5] estimate mortality risk at the time of admission to intensive care; however, to benchmark outcomes of surgical services where surgery, preoperative assessment, and postoperative care all potentially contribute to the outcome, it is important to use only preoperative risk factors and to assess outcome either at hospital discharge or a defined period such as 30 or 90 days after cardiac surgery.

In this study, we used the existing infrastructure of the ANZPIC Registry (Australian and New Zealand Paediatric Intensive Care Registry) to investigate the feasibility of developing a method for regional surveillance of pediatric cardiac surgery outcome. Because the registry receives patient records from all institutions performing cardiac surgery in children in ANZ, the study also provided a unique opportunity to describe population-based surgical outcomes. For surveillance of hospital performance, it is preferable to maximize the inclusion of cases managed by cardiac surgery programs in children's hospitals. The aim of the study was to develop and validate a modified and contemporary version of the RACHS model where surgery for acquired heart disease in children and congenital heart disease in adults could be included in addition to surgery for congenital heart disease in children.

Methods

The Stata code developed for the analysis may be obtained by contacting the first author at BrentM@adhb.govt.nz. Release of the data to researchers will be subject to the governance and confidentiality requirements of ANZICS CORE, as defined by the *ANZICS CORE Data Access and Publication Policy*. The policy and information request form are available at https://www.anzics.com.au/information-requests/.

Data Source

The ANZPIC Registry comprises records of all patients admitted to pediatric intensive care units (PICUs) in ANZ. Data were collected between January 1, 2007 and December 31, 2015. All 8 PICUs providing pre- and postoperative care to pediatric cardiac surgical patients in ANZ over this time period contributed data. Two neonatal intensive care units (NICUs) that routinely care for selected postoperative cardiac patients also contributed data between 2007 and 2010 inclusive.

Data Validation

The data validation processes of the registry have been described previously.[6] An additional audit of cardiac surgical cases was performed in 2010. For each center, 5% of cases were randomly selected for audit with the random selection stratified by risk of death. A cardiologist from each site, blinded to the initial coding, reviewed the medical record and assigned a RACHS procedure category. The other variables in the RACHS-1 model were also recoded by independent data collectors. Survival to hospital discharge was confirmed with the medical records department of each hospital and hospitals were asked to check whether there were additional

intraoperative deaths of patients not admitted to PICU and therefore not registered.

Case Selection

Cardiac surgery was defined as surgery on the heart or intrathoracic great vessels. Children receiving extracorporeal life support were included if they underwent cardiac surgery during the hospital admission, while children receiving extracorporeal life support for indications other than support of cardiac surgery were not included. The initial data set contained all ICU admissions in which the patient had undergone a cardiac surgical procedure immediately before or during the stay in PICU or NICU. In the case of multiple PICU admissions during a single hospital admission, the information recorded for the admission during which the patient underwent the highest RACHS procedure category was used for analysis. Hospital admissions during which no cardiac surgical procedure had an applicable RACHS code were then excluded. As NICUs do not contribute to the ANZPIC Registry, staff from the 2 NICUs collected the information required for the study separately. The RACHS-1 model was not validated in patients with acquired heart disease or in patients over 18 years of age. These patients were excluded from recalibration of the RACHS-1 model and initial model development. Data from these excluded groups were subsequently reintroduced to each model under investigation and the effect of inclusion on discrimination and fit was assessed.

Model Development and Validation

Initially, the original RACHS-1 model was applied to the entire data set to assess calibration and fit. The standardized mortality ratio was calculated by dividing the number of deaths recorded by the number of deaths predicted when applying the original RACHS-1 model.

To build an alternative model, 33 patient variables were tested in combination with the RACHS procedure category in 93 logistic regression models using hospital mortality as the dependent variable. Continuous variables such as age, weight, and weight-for-age were added to a generalized additive model containing the RACHS procedure category and the plot of the smooth visually examined to determine whether transformation or division into categorical variables appeared appropriate. The risk variables can be found in Table S1 and logistic regression models in Table S2.

The fit of all models was compared using the Hosmer and Lemeshow goodness-of-fit (HL-GOF). A χ^2 test $P>0.1$ for the HL-GOF test was used to indicate acceptable fit. Discrimination of the models was compared using the area under the receiver operator characteristic plot (Az-ROC).[7]

For each model tested, the data were randomly divided into building and validation data sets in a 2:1 ratio. Out-of-sample performance was tested using 200 such random splits of the data. Fit statistics for each split were then computed, and the mean of the 200 HL-GOF statistics and Az-ROCs was recorded.
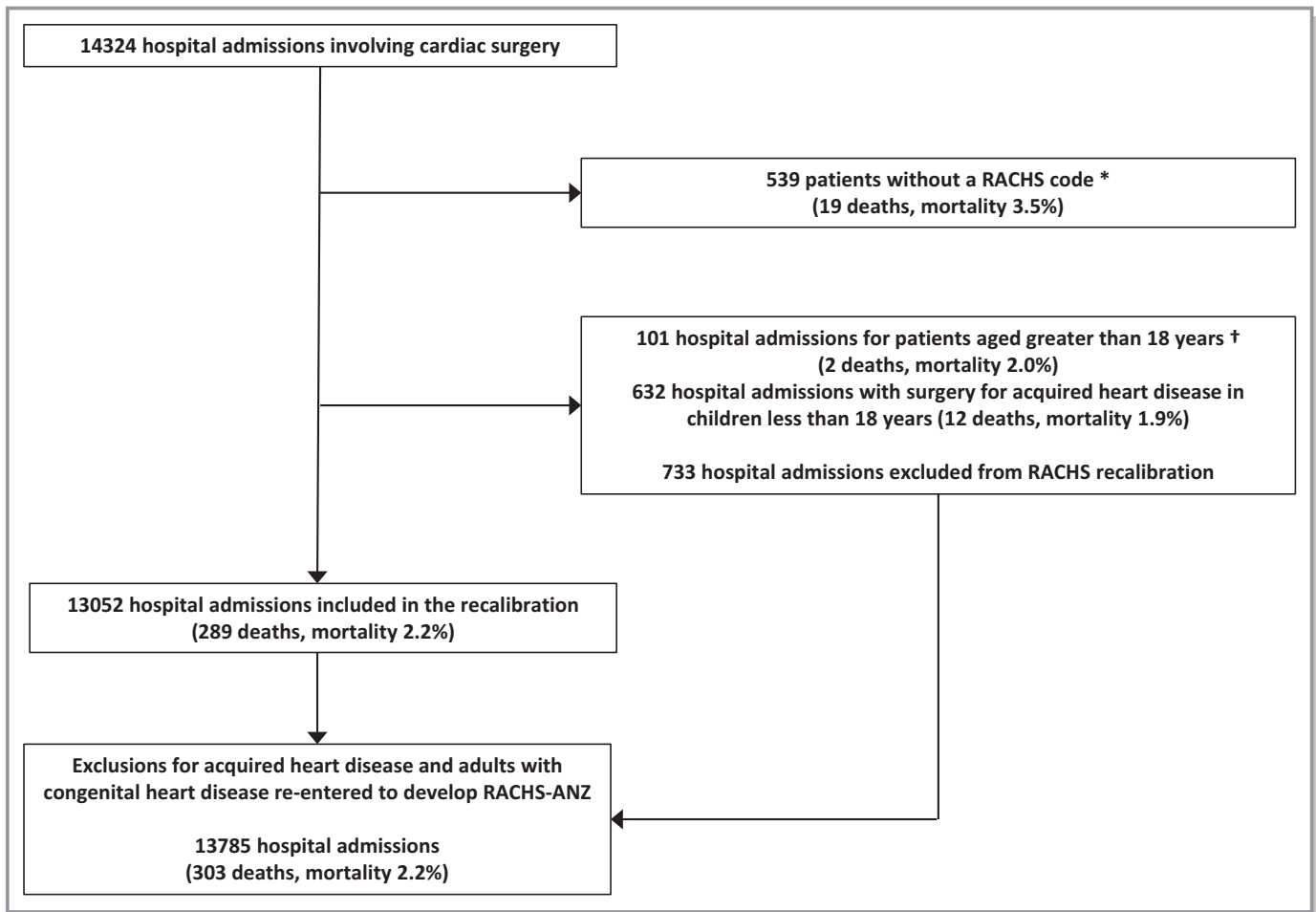
A final model was selected after excluding models with a mean HL-GOF χ^2 test $P\leq0.1$ and viewing the Az-ROC in descending order. The RACHS-ANZ model was selected by the authors, based on a compromise between model discrimination, ease and reproducibility of data collection, and parsimonious variable selection. The final coefficients for the selected model were then recalculated, including all data from the combined development and validation samples.[8]

Logistic regression and goodness-of-fit analyses were performed using Stata 13.1 for Windows. Generalized additive models and smoothed plots were generated using R 3.1.2. Two authors (B.M., A.S.) had full access to all the data in the study and take responsibility for its integrity and the data analysis. The human research ethics committee of the Children's Health Queensland, Brisbane, endorses the use of ANZPIC Registry data for research purposes. Consent was not required.

Results

Details of the cases included and excluded are shown in Figure 1. A total of 14 324 hospital admissions involving cardiac surgery were available for analysis. The overall mortality rate was 2.3%, varying between 0.5% in patients undergoing a RACHS category 1 procedure and 17.0% in patients undergoing a category 5 or 6 procedure (Table 1). A total of 539 patients could not be assigned a RACHS procedure code (Table 2). Patients undergoing procedures for acquired heart disease and patients aged >18 years constituted 4.7% and 0.7% of cases, respectively. The organization of surgical services for adults with congenital heart disease varies across Australian states and New Zealand. In this study, 99 of the 107 patients aged over 18 years who received surgery in a children's hospital were managed in Victoria or New Zealand. Between 2007 and 2010, 153 cases, representing 2.4% of cases during this period, received postoperative care in a NICU. Collection of data in the 2 NICUs was not continued after 2010 because of the small number of cases per annum and because the overall project aim was to develop a benchmarking system based on data that are routinely available via the ANZPIC Registry. Mortality rates associated with selected risk factors are shown in Table 3.

Independent audit of 141 cases demonstrated agreement in RACHS category in 126 cases (89%), a higher code allocated by the auditor in 7 cases, and a lower category in 8

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│  │  14324 hospital admissions involving cardiac surgery │                          │
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│          │  539 patients without a RACHS code *                      │            │
│          │  (19 deaths, mortality 3.5%)                              │            │
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│          │  101 hospital admissions for patients aged greater than   │            │
│          │  18 years †  (2 deaths, mortality 2.0%)                   │            │
│          │  632 hospital admissions with surgery for acquired heart  │            │
│          │  disease in children less than 18 years (12 deaths,       │            │
│          │  mortality 1.9%)                                          │            │
│          │  733 hospital admissions excluded from RACHS recalibration │           │
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│  │  13052 hospital admissions included in the        │                            │
│  │  recalibration (289 deaths, mortality 2.2%)       │                            │
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│  │  Exclusions for acquired heart disease and adults │                            │
│  │  with congenital heart disease re-entered to      │                            │
│  │  develop RACHS-ANZ                                │                            │
│  │  13785 hospital admissions                        │                            │
│  │  (303 deaths, mortality 2.2%)                     │                            │
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Figure 1. Flow diagram for cases analyzed over 9 years. *Includes 6 patients aged over 18 years and 36 patients receiving surgery for acquired heart disease; †Includes 7 patients aged over 18 years receiving surgery for acquired heart disease. RACHS-ANZ indicates Risk Adjustment for Congenital Heart Surgery Score, Australia and New Zealand.

cases. The levels of agreement for prematurity, noncardiac structural anomaly, and combination procedure at the same operation were 97%, 91%, and 72%, respectively.

When applying the published RACHS-1 model and original coefficients[3] to the subset of patients for whom the original RACHS-1 model was validated, 1161 deaths were predicted

Table 1. RACHS-1 Risk Categories in All Patients and in Subgroups of Patients Aged >18 Years and Patients Who Received Surgery for Acquired Heart Disease

RACHS-1 Risk Category	All Cases		Surgery for Acquired Heart Disease		Age >18 Years	
	No. of Cases	No. of Deaths (%)	No. of Cases	No. of Deaths (%)	No. of Cases	No. of Deaths (%)
1	1758	8 (0.5)	8	1 (12.5)	13	0
2	5033	38 (0.8)	64	1 (1.6)	30	0
3	5207	104 (2.0)	537	7 (1. 3)	55	1 (1.8)
4	1388	85 (6.1)	28	3 (10.7)	3	1 (33)
5	23	6 (26.1)	0	. . .	0	. . .
6	376	62 (16.5)	2	0	0	. . .
Total	13 785	303 (2.2)	639	12 (1.9)	101	2 (2.0)

RACHS indicates Risk Adjustment for Congenital Heart Surgery Score.

Table 2. Cardiac Surgery Procedures in 539 Hospital Admissions Where a RACHS Procedure Code Could Not Be Assigned

Procedure	Cases	Deaths
Pacemaker insertion or replacement	191	2
Heart transplant	52	1
PDA surgery ≤30 d	43	1
Pulmonary venous stenosis repair	7	1
Fontan conversion	2	0
Cardiac surgery other	244	14
Total	539	19

PDA indicates patent ductus arteriosus.

while 289 deaths were observed, giving a standardized mortality ratio of 0.25 (95% CI 0.20–0.30) and a HL-GOF $P<0.05$. The within-sample Az-ROC was 0.815. Without altering the variables, the RACHS-1 model was recalibrated and tested on development and validation data sets, respectively. For the recalibrated model, the mean P value for the out-of-sample HL-GOF test was 0.250 and the mean Az-ROC was 0.814.

Model Selection

Because of the paucity of cases in RACHS category 5, RACHS categories 5 and 6 were grouped together as a single category for all models tested. Various age and weight categories were tested. The use of transformed variables such

Table 3. Risk Factors for Mortality

	No. of Cases*	No. of Deaths[†] (%)
RACHS procedure category 1	1758	8 (0.5)
RACHS procedure category 2	5033	38 (0.8)
RACHS procedure category 3	5207	104 (2.0)
RACHS procedure category 4	1388	85 (6.1)
RACHS procedure category 5	23	6 (26.1)
RACHS procedure category 6	376	62 (16.5)
Combination procedure	3681	118 (3.2)
Major noncardiac structural anomaly	939	45 (4.8)
ICU before surgery	1742	142 (8.2)
Age ≤30 d	2726	184 (6.8)
Age 31 d–1 y	5025	80 (1.6)
Weight ≤2.5 kg	383	46 (12.0)

ICU indicates intensive care unit; RACHS, Risk Adjustment for Congenital Heart Surgery Score.
*Inclusive of acquired heart disease and those aged over 18 years.
[†]Deaths during the same hospital admission the procedure occurred.

as "age in days <2 years" and "weight <4.0 kg" in many of the models was because of analysis of the smoothed generalized additive model plots (Figure 2).

When examining the RACHS categories without additional risk factors, the Az-ROC was 0.765 for the group excluding patients aged over 18 years and those with acquired heart disease, and the mean HL-GOF P value was 0.166. There was little difference in out-of-sample performance among the top-performing models. The highest out-of-sample Az-ROC when including all patients was 0.835, and when including only those patients for whom RACHS-1 was originally validated was 0.834. The chosen RACHS-ANZ model had an out-of-sample ROC of 0.830 (H-L GOF $P=0.216$) for the entire data set and 0.830 (H-L GOF $P=0.226$) for those in whom RACHS-1 was applicable. The final RACHS-ANZ model had the fewest variables of the top-performing models (3 variables in addition to the RACHS category) and avoided use of the "combination procedure" and "major noncardiac structural anomaly" variables described in the RACHS-1 model. Table 4 shows the results of logistic regression for the original model and for the final RACHS-ANZ model. "Days <2 years of age" refers to days of age at admission to PICU, with no correction for gestation, with anyone 730 days old or older on admission to PICU being coded as zero. "Weight <4.0 kg" refers to the patient weight on admission to PICU (or in the case of immediate postoperative admissions, the presurgery weight), with anyone weighing 4.0 kg or more being coded as zero. "ICU before surgery" was coded as 1 (yes) if the patient was managed in ICU immediately before surgery or 0 (no) if the patient was admitted to ICU for recovery following surgery. An example of using the model to calculate the risk of death is provided in Appendix S2.

Discussion

The data set used in this study is unique in that it represents all pediatric cardiac surgery and some selected representation of adult congenital cardiac surgery undertaken in the population of 2 countries during a 9-year period. The centralization of cardiac surgery services in ANZ results in pediatric cardiac surgery being undertaken at 1 institution in New Zealand, and in 4 Australian states. In New South Wales, surgery is undertaken in 2 hospitals that are now part of the same governance system (The Sydney Children's Hospitals Network). In Queensland there is a single pediatric cardiac service; however, the service was relocated to a different hospital twice during the study period. Pediatric cardiac surgery is not performed in 4 Australian states and territories. With all pediatric cases included, the study overcomes potential selection bias inherent in reports from voluntary registries or databases: when data submission is voluntary,
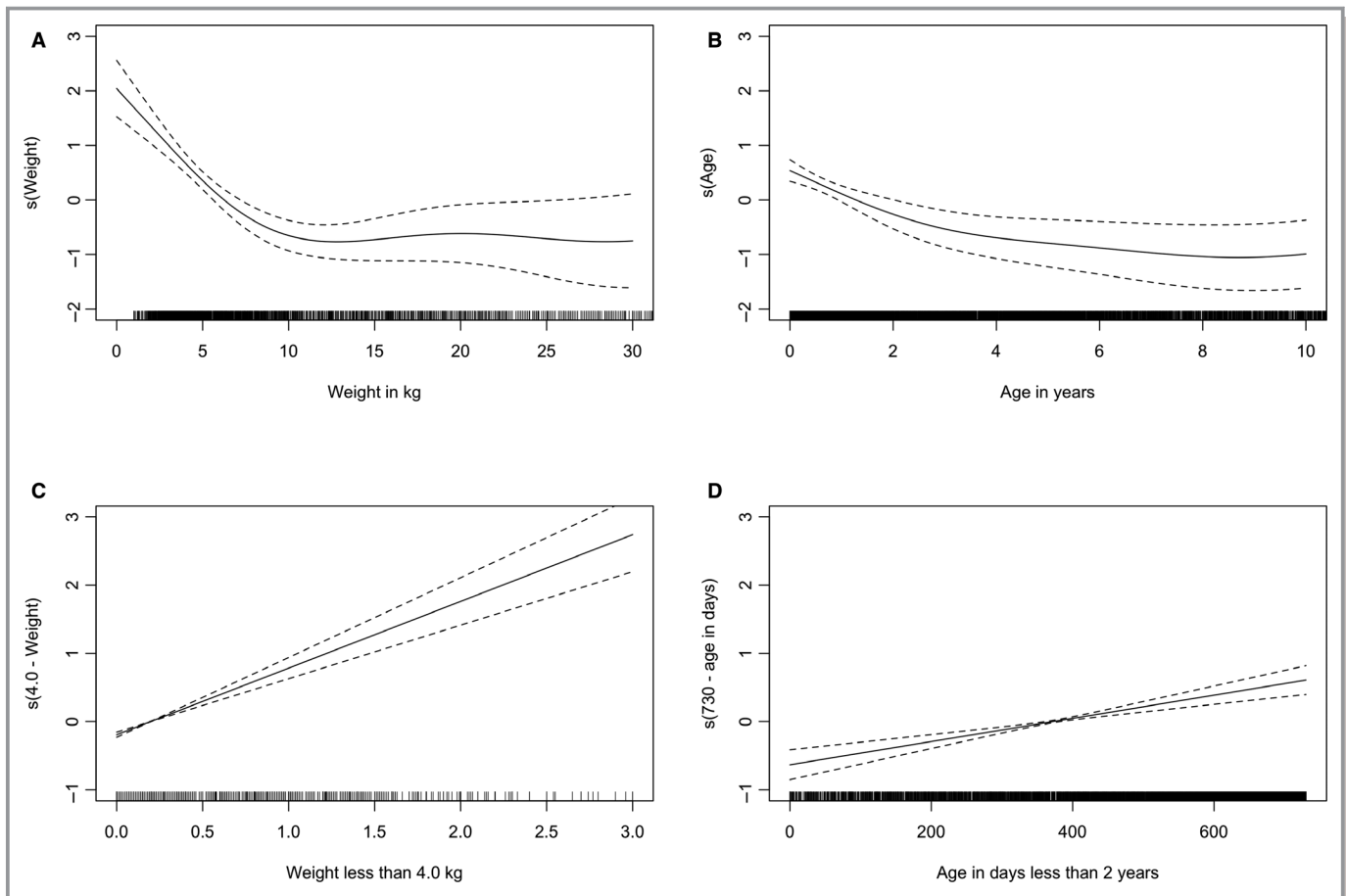
Figure 2. Four continuous variables plotted as smooths added to generalized additive models containing RACHS2-4, RACHS5 or 6, and ICU before surgery. Dashed lines represent 2 standard errors above and below the estimate of the smooth. **A**, Weight in kg. **B,** Age in years. **C,** Weight transformed as weight <4.0 kg. **D,** Age transformed as days <2 years. ICU indicates intensive care unit; RACHS, Risk Adjustment for Congenital Heart Surgery Score.

the case-mix and outcomes of contributing institutions may differ from those of institutions that do not contribute.

If the original RACHS-1 model is applied to the data set, the standardized mortality ratio is 0.25 (0.20–0.30). That is, 75% of the children predicted to die in this study population, using standards developed in 1996 from 32 institutions in the United States, survived. Although RACHS-1 has been validated in a number of settings, most reports do not contain model coefficients to allow comparison of risk-adjusted outcomes for the entire surgical population; however, mortality rates within each RACHS-1 category have improved considerably since 1996.[9–12] The exact explanation for this is unknown, although the tendency for mortality prediction models to increasingly overpredict death over time has been noted previously.[12–17] It is possible that incremental gain has been achieved through advances in surgery, anesthesia, perfusion, and intensive care via the use of newer equipment, medications, and techniques. Both the recalibrated RACHS-1

model and the RACHS-ANZ model set a higher standard for benchmarking of cardiac surgical mortality.

During development of the modified prediction model, we examined alternative variable selection for patient specific factors, but we did not alter the system of categorizing procedures. The RACHS-ANZ model includes age as a continuous predictor up to 2 years of age, rather than the age categories from the original RACHS-1 model.[3] Of note, the age used in this analysis differs from RACHS-1 and STS-EACTS because it uses the age at admission to PICU, rather than age at operation, which was not available in the ANZPIC data set. It is likely that neonates with congenital heart disease that became clinically unstable during the first weeks of life were admitted to PICU for stabilization, although operative repair or palliation may not have occurred until the child was in a different RACHS-1 or STS-EACTS age category. Similarly the RACHS-ANZ model includes weight as a continuous predictor up to 4.0 kg rather than the category used in the harmonized

Table 4. Recalibrated RACHS-1 and RACHS-ANZ Models Applied to the Population Used for the Original Version of RACHS-1, and the Final RACHS-ANZ Model Applied to the Population Inclusive of Children With Acquired Heart Disease and Adults With Congenital Heart Disease

	Recalibrated RACHS-1*	RACHS-ANZ—Limited*	RACHS-ANZ—Final Model	
	OR (95% CI)	OR (95% CI)	OR (95% CI)	Coefficient (95% CI)
RACHS 1 (reference)	1.0	1.0	1.0	…
RACHS 2	1.20 (0.53–2.74)	1.38 (0.61–3.14)	1.23 (0.57–2.67)	0.2081 (−0.5666 to 0.9828)
RACHS 3	2.88 (1.31–6.34)	3.09 (1.41–6.76)	2.74 (1.32–5.69)	1.0071 (0.2747–1.7395)
RACHS 4	5.51 (2.42–12.54)	5.70 (2.54–12.76)	5.09 (2.39–10.87)	1.6280 (0.8704–2.3856)
RACHS 5	22.25 (6.41–77.16)			
RACHS 6	16.14 (6.94–37.55)			
RACHS 5 or 6		13.18 (5.76–30.20)	11.23 (5.14–24.55)	2.4189 (1.6371–3.2008)
Neonate	4.32 (2.84–6.56)			
Infant	2.07 (1.35–3.18)			
Premature	2.37 (1.72–3.28)			
Combination procedure	1.39 (1.08–1.80)			
Major noncardiac structural anomaly	2.46 (1.73–3.48)			
ICU before surgery†		2.21 (1.68–2.89)	2.29 (1.76–2.99)	0.8294 (0.5648–1.0940)
Weight <4.0 kg (per kg)‡		2.35 (1.89–2.92)	2.34 (1.89–2.89)	0.8482 (0.6352–1.0612)
Days <2 y (per d)§		1.0008 (1.0001–1.0014)	1.0008 (0.0002–1.0014)	0.000780 (0.000160–0.001399)
Constant				−5.7416 (−6.4577 to −5.0256)

ANZ indicates Australia and New Zealand; ICU, intensive care unit; OR, odds ratio; RACHS, Risk Adjustment for Congenital Heart Surgery Score.
*Limited to those aged 18 years or less without acquired heart disease.
†ICU before surgery: code as 1 if the patient was managed in ICU immediately before surgery or 0 if the patient was admitted to ICU for recovery following surgery.
‡Weight <4.0 kg=4.0—weight in kg. Code as zero if weight ≥4.0 kg.
§Days <2 years=730—age in days. Code as zero if age ≥730 days.

RACHS-1 method (500–2500 g).[18] With age and weight defined as continuous variables, rather than by categories, the effect of performing surgery near a defined cut point is reduced. Our analysis suggests that the risk of surgery in very young and low weight children reduces gradually over the first 2 years and as weight increases to 4 kg, rather than by stepwise reductions at specific ages or weights.

The RACHS-1 model includes the variable "combination procedure" defined as "2 or more distinct cardiac surgical procedures performed simultaneously." The final model does not include "combination procedure," because of the poor level of agreement between the coding of the data collectors and independent auditors. There was also variation between hospitals in the coding of the variable "major noncardiac structural anomaly." Dropping these variables resulted in only a small reduction in discrimination, while inclusion of physiological data for patients admitted to PICU before surgery or substituting weight-for-age z-score for weight resulted in only minor improvements in discrimination. Therefore, these variables were not included in the final model. Patients receiving intensive care immediately before surgery had an increased risk of mortality. Preoperative patient factors that indicate a requirement for intensive care, such as shock or the need for mechanical ventilation, have previously been associated with increased mortality risk in congenital heart surgery.[19]

Recent international efforts to standardize congenital heart disease nomenclature and risk assessment are commendable for many reasons. The publication of a validated STS-EACTS mortality prediction model, developed from pooled data from databases in Europe and the United States, represents a landmark achievement in this field. A revised RACHS-1 model, described as a harmonization of 2 similar methods developed to benchmark congenital heart surgery in the United States, has recently been published.[18] Similar to our study, this report allowed population-based estimates of outcome as the database captured ≈95% of pediatric hospital admissions in the United States.

One reason in favor of using RACHS-1 is that the simpler procedure categorization may result in more accurate data. In our study the discrimination of the procedure category alone, without patient-specific covariates, was 0.77, only marginally lower than that reported for the STS-EACTS score without covariates (0.79).[4] With the addition of patient covariates, the

discrimination of our model (0.83) was similar to that reported for an equivalent STS-EACTS model (0.82) and similar to that reported for the original and updated versions of the RACHS-1 models (0.81 and 0.82).[3,18] A direct comparison of the RACHS and STS-EACTS systems for categorizing surgical procedures was beyond the scope of this study and could be investigated in the future.

The final RACHS-ANZ model has 3 additional patient covariates that are easy to define and collect. The performance of the model was unchanged when patient groups not previously included in RACHS-1 were introduced to the model (children in whom surgery was for acquired heart disease or adults in whom surgery was for congenital heart disease). The aim was to maximize cases included for benchmarking of hospital mortality.

This study has a number of limitations. The sample size for the data quality audit was small relative to size of the study; the audit indicated only 90% agreement in coding of some variables; however, there was not a systematic bias in the inconsistencies. Reports of this information are unusual and could be seen as a strength of the study. Exclusion of 3.8% of patients in whom a RACHS-1 category could not be assigned is a limitation. The results justify inclusion of adults with congenital heart disease in the analysis of the overall population of patients receiving cardiac surgery in children's hospitals. However, because of the small number of adult patients in the study, the model should not be considered a robust predictor of mortality in the population of adult patients with congenital heart disease.

We developed a method for assessing the risk-adjusted outcome of cardiac surgery in children's hospitals in ANZ. There are clear benefits from international benchmarking achieved by participation in large international databases. Additional complementary information is obtained by benchmarking at a regional level, because background variation from a number of sources is reduced. Compared with the diverse range of healthcare systems contributing to international databases, there is greater homogeneity in the systems for delivering complex pediatric specialty care in ANZ. The centralized system of care and full participation reduces potential selection bias, while a local registry further aids consistency by providing standardized training of data collectors and methods for maintaining data quality.

Conclusion

The original RACHS-1 model overpredicts mortality in children undergoing congenital heart surgery in the current era. RACHS-ANZ uses the minimum number of variables needed to achieve acceptable model performance, and out-of-sample validation demonstrated acceptable fit and excellent

discrimination. The new model can be applied to a wider range of patients than RACHS-1, including adults undergoing surgery for congenital heart disease and children having surgery for acquired heart disease. Many regions already collect the data needed to monitor PICU performance; collecting just 1 extra variable, the cardiac surgery procedure code, adds the ability to monitor regional pediatric cardiac surgery outcomes using RACHS-ANZ.

Author Contributions

Slater was responsible for project inception, design, and format of data collection variables, supervision, and final edit. Alexander coordinated the project data collection, assisted in data validation steps, as well as assisted in the literature search and editing of the manuscript. McSharry wrote software for data validation and patient audits, audited NZ data, performed the statistical analysis, assisted in the coordination of all centers, produced all tables and graphs, and wrote the manuscript draft. Shann, Winlaw, and Gentles provided opinions as to how to analyze data and edited the manuscript.

Disclosures

None.

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Supplemental Material

Appendix S1.

The Australian and New Zealand Intensive Care Society Paediatric Study Group Management Committee Members:

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Appendix S2.

Sample calculation of the predicted risk of death using the RACHS-ANZ model.

Consider a 7-day-old baby undergoing insertion of a systemic to pulmonary artery shunt for pulmonary atresia; the weight is 2.2 kg; the baby has not required admission to intensive care prior to surgery. The risk variables are RACHS category 3[a]; ICU prior to surgery = 0[b]; weight less than 4.0 kg = 1.8[c]; days less than 2 years = 723[d]. Using the coefficients in Table 4 for the RACHS-ANZ model derived from the entire study sample, the RACHS-ANZ logit =$(1.0071 \times 1)^a$ + $(0.8294 \times 0)^b$ + $(0.8482 \times 1.8)^c$ + $(0.\,0.000780 \times 723)^d$ − 5.7416 = −2.6438.

The predicted risk of death = $e^{logit}/(1+e^{logit})$ = $2.7183^{-2.6438}/ (1+2.7183^{-2.6438})$ = 0.0664, or 6.6%

Table S1. The risk variables tested during the development of an alternative logistic regression model.

Risk variable	Abbreviated variable name	Comment
RACHS-1 procedure categories	RACHS1 – RACHS6	As defined by Jenkins *et al* [1]
Combination procedure	cp_sop	
Major non-cardiac structural anomaly	nc_stan	
Age ≤ 30 days	neonate	
Age 31 days – 1 year	infant	
Premature		
Systolic blood pressure	sbpa	Physiological variables measured within the first hour of ICU admission only included if the patient had been admitted to ICU prior to undergoing surgery. For patients who did not require ICU admission prior to surgery, pre-operative physiological data were not available and normal values were used as default. Transformations of physiological variables tested were as per those used in the PIM3 model [2]
Base excess	bea	
100 x FiO_2/PaO_2	fpratio	
Lactate	lactate	
ICU prior to surgery	icu_prior	Code as 1 if the patient was managed in ICU immediately prior to surgery or 0 if the patient was admitted to ICU for recovery following surgery
Interhospital transfer	transacute	Hospital admission following interhospital transfer
Multiple operations	multipleops	Multiple ICU admission during the same hospital admission where cardiac surgery was performed immediately prior to or during the ICU admission
Elective ICU admission	elective	ICU admission after elective surgery or for an elective procedure
Endocarditis	endocarditis	
Rheumatic	rheumatic	
Other acquired heart disease	acquiredother	
Chromosomal Anomaly	chromanom	
Velo Cardio Facial Syndrome	vcf	
Days less than 2 years	daysless2years	(730–age in days) if age < 730 days, 0 if age ≥ 730 days
Days less than 7 days	daysless7	(7–age in days) if age < 7 days, 0 if age ≥ 7 days
Days less than 2 years if age ≥ 7days	daysless2to7	(730–age in days) if age ≥ 7 days & < 730 days, 0 if age < 7days or ≥ 730 days
Corrected gestational age	cga	Gestation + age in weeks
Still preterm	stillpremature	Corrected gestational age < 37 weeks
Weight ≤ 2.5 kg	smallwt	
Weight ≤ 2.0 kg	wtless2	
Weight for age z score	ukzweight	Royal College of Paediatrics and Child Health [3]. Age corrected for gestation if the child was born <37 weeks completed gestation and less than 2 years of age on admission to PICU
Weight less than 5.0 kg	wtlessthan5.0	5.0–wt if wt<5.0 kg, 0 if wt ≥ 5.0kg
Weight less than 4.5 kg	wtlessthan4.5	4.5–wt if wt<4.5 kg, 0 if wt ≥ 4.5kg
Weight less than 4.0 kg	wtlessthan4.0	4.0–wt if wt<4.0 kg, 0 if wt ≥ 4.0kg
Weight less than 3.5 kg	wtlessthan3.5	3.5–wt if wt<3.5 kg, 0 if wt ≥ 3.5kg
Weight less than 3.0 kg	wtlessthan3.0	3.0–wt if wt<3.0 kg, 0 if wt ≥ 3.0kg
Weight less than 2.5 kg	wtlessthan2.5	2.5–wt if wt<2.5.0 kg, 0 if wt ≥ 2.5kg
Weight less than 2.0 kg	wtlessthan2.0	2.0–wt if wt<2.0 kg, 0 if wt ≥ 2.0kg

Table S2. Alternative logistic regression models tested. Discrimination (Az-ROC) and goodness-of-fit (HL-GOF p value) assessed in all patients and after excluding patients aged under 18 years and patients in whom surgery was performed for acquired heart disease. The final RACHS-ANZ model is highlighted.

	Mean ROC Area		Mean HL-GOF p	
	All	Under 18 years & congenital	All	Under 18 years & congenital
	n = 13785	n = 13052	n = 13785	n = 13052
1 RACHS2-RACHS6 neonate infant nc_stan premature cp_sop	0.80999313	0.81403654	0.24606197	0.25036968
2 RACHS2-RACHS4 RACHS5or6	0.75815066	0.76452915	0.16756443	0.16610442
3 RACHS2-RACHS4 RACHS5or6 acquired	0.75706436	0.76452915	0.20130153	0.16610442
4 RACHS2-RACHS4 RACHS5or6 acquiredother	0.75729924	0.76452915	0.18825729	0.16610442
5 RACHS2-RACHS4 RACHS5or6 rheumatic	0.76483826	0.76452915	0.16093173	0.16610442
6 RACHS2-RACHS4 RACHS5or6 endocarditis	0.76038197	0.76452915	0.17262518	0.16610442
7 RACHS2-RACHS4 RACHS5or6 endocarditis rheumatic acquiredother	0.76612704	0.76452915	0.17850034	1.66E-01
9 RACHS2-RACHS4 RACHS5or6 icu_prior	0.79768878	0.79964105	0.20313531	0.18427976
11 RACHS2-RACHS4 RACHS5or6 neo infant	0.7926024	0.79704824	0.18978584	0.19158169
12 RACHS2-RACHS4 RACHS5or6 smallwt	0.77440406	0.78056404	0.18172837	0.1771104
13 RACHS2-RACHS4 RACHS5or6 neo infant smallwt	0.79898881	0.80366099	0.17954153	0.19016724
14 RACHS2-RACHS4 RACHS5or6 daysless7	0.77632824	0.78310198	0.17081243	0.19001342
15 RACHS2-RACHS4 RACHS5or6 daysless2years	0.79984635	0.80283968	0.28992042	0.26961558
16 RACHS2-RACHS4 RACHS5or6 daysless7 daysless2years	0.79895893	0.8024157	0.30967012	0.28744142
17 RACHS2-RACHS4 RACHS5or6 daysless7 daysless2to7	0.79587214	0.79955489	0.30615045	0.31381467
18 RACHS2-RACHS4 RACHS5or6 daysless2years gestation	0.80487469	0.80819604	0.28382151	0.28885141
19 RACHS2-RACHS4 RACHS5or6 daysless2years cga	0.77827344	0.78204755	0.22999645	0.23323936
20 RACHS2-RACHS4 RACHS5or6 daysless2years premature	0.80398399	0.80695319	0.30449291	0.3016733
21 RACHS2-RACHS4 RACHS5or6 daysless2years stillpremature	0.80419634	0.80792191	0.30570491	0.27950516
22 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt	0.80398813	0.80754718	0.2857867	0.2967124
24 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight	0.80325028	0.80556313	0.25159391	0.26410946
25 RACHS2-RACHS4 RACHS5or6 gestation daysless2years ukzweight	0.81146939	0.8140477	0.26092545	0.25013926
26 RACHS2-RACHS4 RACHS5or6 nc_stan	0.7691693	0.77566423	0.18030981	0.16232471
27 RACHS2-RACHS4 RACHS5or6 cp_sop	0.76685398	0.77334943	0.22721697	0.21830484

28 RACHS2-RACHS4 RACHS5or6 cp_sop nc_stan	0.77669147	0.78303728	0.22426883	1.97E-01
29 RACHS2-RACHS4 RACHS5or6 ad_stan	0.77041758	0.77691835	0.18016492	1.89E-01
30 RACHS2-RACHS4 RACHS5or6 lactate	0.76627138	0.7725111	0.18810627	0.20514603
31 RACHS2-RACHS4 RACHS5or6 bea	0.7861259	0.79142649	0.18176676	0.15391855
32 RACHS2-RACHS4 RACHS5or6 sbpa sbp2	0.78783653	0.78906671	0.14667672	0.13308153
33 RACHS2-RACHS4 RACHS5or6 sbp_120	0.78484331	0.78826091	0.19297942	0.16271586
34 RACHS2-RACHS4 RACHS5or6 fpratio	0.7716418	0.77791852	0.2006692	0.20353839
36 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan cp_sop	0.8285175	0.82917175	0.19873586	0.22723753
37 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa	0.83312321	0.83446351	0.20999263	2.31E-01
38 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight cp_sop	0.82412688	0.82397967	0.25801853	0.28380042
39 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan	0.82766647	0.8279884	0.15868926	1.68E-01
40 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight	0.82334561	0.82280123	0.22147939	0.24505218
46 RACHS2-RACHS4 RACHS5or6 nc_stan sbp2 sbpa	0.79679233	0.79882891	0.18531075	0.16807531
47 RACHS2-RACHS4 RACHS5or6 nc_stan cp_sop sbp2 sbpa	0.8016776	0.80375791	0.22378999	0.23354368
48 RACHS2-RACHS4 RACHS5or6 elective nc_stan cp_sop sbp2 sbpa	0.81416952	0.81408113	0.20147552	0.23879124
49 RACHS2-RACHS4 RACHS5or6 elective icu_prior nc_stan cp_sop sbp2 sbpa	0.81652273	0.8164611	0.19870724	0.25920522
50 RACHS2-RACHS4 RACHS5or6 elective icu_prior ukzweight nc_stan cp_sop sbp2 sbpa	0.82560296	0.82386013	0.31033296	0.31770411
51 RACHS2-RACHS4 RACHS5or6 elective icu_prior daysless2years ukzweight nc_stan cp_sop sbp2 sbpa	0.83196697	0.83122412	0.20684146	0.21856726
52 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt premature	0.80640162	0.80940683	0.32656102	0.2992131
53 RACHS2-RACHS4 RACHS5or6 daysless2years zscorewt smallwt	0.81145077	0.81452059	0.30273858	0.30702483
54 RACHS2-RACHS4 RACHS5or6 daysless2years zscorewt premature	0.81395431	0.81660634	0.2697322	0.28423125
55 RACHS2-RACHS4 RACHS5or6 daysless2years zscorewt smallwt premature	0.8142234	0.81695549	0.27916221	0.29192286
56 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight smallwt	0.80637791	0.80891781	0.27513127	0.27355883
57 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight premature	0.8106324	0.81280579	0.26390901	0.26012797
58 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight smallwt premature	0.81139995	0.81372575	0.28183801	0.25793994
65 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years smallwt nc_stan	0.82570775	0.82698475	0.19864217	0.21694539
66 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years smallwt nc_stan cp_sop	0.82937034	0.83013004	0.27622419	0.31173183
67 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years smallwt cp_sop	0.82627196	0.82632366	0.29338899	0.30913918
72 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa endocarditis rheumatic acquiredother	0.83497361	0.83446351	0.24221184	0.23144395
73 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa endocarditis	0.83434428	0.83446351	0.23466595	0.23144395

74 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa rheumatic	0.83463477	0.83446351	0.21085437	0.23144395
75 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa acquiredother	0.83229383	0.83446351	0.22072923	0.23144395
76 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight nc_stan bea sbp2 sbpa	0.8324837	0.83343827	0.1729061	0.18064269
77 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight cp_sop bea sbp2 sbpa	0.82829255	0.82886094	0.25473139	0.27146024
78 RACHS2-RACHS4 RACHS5or6 icu_prior daysless2years ukzweight bea sbp2 sbpa	0.82766394	0.82778848	0.2486828	0.27803462
81 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop	0.80904931	0.81172544	0.27389432	0.26721718
86 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop ad_stan	0.80898599	0.81206832	0.3228738	0.32295333
87 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop chromanom	0.80799654	0.81034478	0.27420581	0.28607567
88 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop premature	0.81054895	0.81302697	0.27870773	0.29012487
89 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop transacute	0.81109695	0.81427324	0.36472976	0.35091738
90 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight cp_sop	0.80592262	0.8084899	0.26267642	0.22672589
91 RACHS2-RACHS4 RACHS5or6 daysless2years wtless2 cp_sop	0.80886511	0.81200509	0.26525079	0.26370165
92 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop nc_stan	0.81187253	0.81535474	0.32085147	0.29777851
93 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop vcf	0.8084774	0.81109543	0.26245831	0.26096428
94 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop nonchromsynd	0.81234218	0.81552645	0.28940791	0.28602899
95 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt cp_sop multipleops	0.81190597	0.81445434	0.25171095	0.21935902
96 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt elective	0.8221793	0.82107754	0.20029598	0.21970441
97 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan cp_sop	0.8103944	0.81378142	0.24192255	0.23259627
98 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa	0.8279001	0.83068811	0.25227964	0.22133227
99 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa endocarditis rheumatic acquiredother	0.83064734	0.83068811	0.25438887	0.22133227
100 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa endocarditis	0.83008377	0.83068811	0.22459766	0.22133227
101 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa rheumatic	0.82934004	0.83068811	0.26310346	0.22133227
102 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan cp_sop bea sbp2 sbpa acquiredother	0.8270725	0.83068811	0.25547147	0.22133227
103 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight nc_stan bea sbp2 sbpa	0.82650416	0.82906718	0.21149169	0.17288506
104 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight cp_sop bea sbp2 sbpa	0.82241125	0.82451403	0.31459358	0.29984334
105 RACHS2-RACHS4 RACHS5or6 daysless2years ukzweight bea sbp2 sbpa	0.82099319	0.82279645	0.31722571	0.28083264
108 RACHS2-RACHS4 RACHS5or6 daysless2years smallwt nc_stan	0.80730356	0.81166765	0.31914216	0.31000707
109 RACHS3 RACHS4 RACHS5or6 icu_prior daysless2years smallwt nc_stan	0.82684733	0.82790131	0.21643332	0.24362193
110 RACHS2-RACHS6	0.75815737	0.76453542	0.16791372	0.16622298
111 RACHS3 RACHS4 RACHS5or6	0.75473019	0.76026717	0.16013612	0.16384547

112 RACHS2-RACHS4 RACHS5or6 daysless2years wtless2 icu_prior	0.82154615	0.82250555	0.22119322	0.24083816
113 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior smallwt	0.81973212	0.82037375	0.2017829	0.20687307
114 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan5.0	0.82749239	0.82860169	0.18954993	0.16985117
115 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan4.5	0.8288699	0.82912204	0.22192658	0.22575685
116 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan4.0	0.8298434	0.8301229	0.21588963	0.22641165
117 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan3.5	0.82891337	0.82920891	0.18503502	0.20506086
118 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan3.0	0.82644415	0.82703188	0.2044364	0.22706082
119 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan2.5	0.82366971	0.82434817	0.21474731	0.24678694
120 RACHS2-RACHS4 RACHS5or6 daysless2years icu_prior wtlessthan2.0	0.82087494	0.82131032	0.20532338	0.22251896

Supplemental References:

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