Coronary artery bypass grafting (CABG) and surgical aortic valve replacement (AVR) are 2 of the most common cardiac surgical procedures in North America.1 Accurate risk models of perioperative mortality for CABG and AVR are not only useful for operative decision-making,2 but also valuable for quality improvement initiatives across surgeons and institutions.

In North America, the most widely used 30-day mortality risk score is the Society of Thoracic Surgeons (STS)–Predicted Risk of Mortality tool, derived from more than 1000 hospitals in the United States and encompassing more than 50 variables.3 An ideal risk model should be built and validated on the patient population in which it will be applied. Although the STS–Predicted Risk of Mortality tool was derived from a large surgical population, regional differences in patient sociodemographics and health care delivery systems may preclude this model from performing optimally in the health system where cardiac surgery is publicly funded. Furthermore, collecting more than 50 variables is resource intensive and is not feasible for all institutions. Similar limitations apply to the EuroSCORE II, which was derived from a population-based cohort in Europe.4 Given these limitations, we developed a more parsimonious model using readily available, linked clinical and administrative data sets in Ontario, Canada, to efficiently and accurately calculate risk-adjusted 30-day mortality rates for the purpose of province-wide quality improvement after CABG, AVR and combined CABG + AVR.

Research

Health services

Derivation and validation of predictive indices for 30-day mortality after coronary and valvular surgery in Ontario, Canada

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Abstract

Background: Coronary artery bypass grafting (CABG) and surgical aortic valve replacement (AVR) are the 2 most common cardiac surgery procedures in North America. We derived and externally validated clinical models to estimate the likelihood of death within 30 days of CABG, AVR or combined CABG + AVR.

Methods: We obtained data from the CorHealth Ontario Cardiac Registry and several linked population health administrative databases from Ontario, Canada. We derived multiple logistic regression models from all adult patients who underwent CABG, AVR or combined CABG + AVR from April 2017 to March 2019, and validated them in 2 temporally distinct cohorts (April 2015 to March 2017 and April 2019 to March 2020).

Results: The derivation cohorts included 13 435 patients who underwent CABG (30-d mortality 1.73%), 1970 patients who underwent AVR (30-d mortality 1.68%) and 1510 patients who underwent combined CABG + AVR (30-d mortality 3.05%). The final models for predicting 30-day mortality included 15 variables for patients undergoing CABG, 5 variables for patients undergoing AVR and 5 variables for patients undergoing combined CABG + AVR. Model discrimination was excellent for the CABG (c-statistic 0.888, optimism-corrected 0.866) AVR (c-statistic 0.850, optimism-corrected 0.762) and CABG + AVR (c-statistic 0.844, optimism-corrected 0.776) models, with similar results in the validation cohorts.

Interpretation: Our models, leveraging readily available, multidimensional data sources, computed accurate risk-adjusted 30-day mortality rates for CABG, AVR and combined CABG + AVR, with discrimination comparable to more complex American and European models. The ability to accurately predict perioperative mortality rates for these procedures will be valuable for quality improvement initiatives across institutions.
Methods

Study design and population
We conducted a retrospective analysis of patients aged 18 years and older who were identified in the CorHealth Ontario Cardiac Registry as having had CABG, AVR or combined CABG + AVR surgery between Apr. 1, 2015, and Mar. 31, 2020.\(^5,6\) CorHealth is a provincial organization with a mandate to collect health data from all patients undergoing cardiac procedures and to provide strategic leadership to improve cardiac, stroke and vascular care in Ontario. This mandatory registry contains demographic, clinical and perioperative information on all patients who undergo major cardiovascular procedures and related cardiac interventions in Ontario.\(^7-9\)

Our derivation cohort consisted of patients who underwent cardiac surgery between Apr. 1, 2017, and Mar. 31, 2019. Two temporally distinct validation cohorts included patients who underwent procedures between Apr. 1, 2015, and Mar. 31, 2017, and between Apr. 1, 2019, and Mar. 31, 2020. For each patient, we considered only the first surgical procedure in a given fiscal year. We confirmed surgical procedures performed using Canadian Classification of Health Interventions procedure codes, through linkage to the Canadian Institute for Health Information Discharge Abstract Database, which contains demographic, diagnostic and procedural information from the discharge abstracts of all acute care hospital admissions in Ontario; and the Ontario Health Insurance Plan Physician Claims Database, which contains information from nearly all physician encounters, diagnostic tests and outpatient laboratory services performed in Ontario. We excluded surgical procedures not recorded in the Discharge Abstract Database or Ontario Health Insurance Plan database, or for which CABG, AVR or combined CABG + AVR was performed concurrently with other cardiac procedures.

Outcome
Our primary outcome was 30-day all-cause mortality, captured from Ontario’s Registered Persons Database. This is a registry maintained by the Ontario Ministry of Health, containing demographic information about every individual who has ever been registered for the Ontario Health Insurance Plan, including their eligibility and dates of death. Registration is required to access publicly funded health care services in the province.

Candidate variable selection
We identified potential variables to be included in our mortality model from a review of predictors in previously published models or those deemed clinically important by our co-author group.\(^4,10-13\) In addition to key demographic variables (age, sex and ethnicity), we developed a list of 63 variables and forwarded it to members of the CorHealth Ontario Cardiac Surgery Risk Adjustment Task Group for further selection through a modified Delphi process.\(^14,15\) The task group comprises clinical-, administrative- and system-level leadership, with representatives from cardiac surgery centres across the province. It serves to advise CorHealth Ontario on risk-adjustment models for key quality indicators and clinical variables to be used in the monitoring and reporting of quality of care and outcomes of cardiac surgery. We first asked respondents to rate each of the variables as important or not in the risk stratification process (Appendix 1, Supplemental Table 1, available at www.cmaj.ca/lookup/doi/10.1503/cmaj.202901/tab-related-content). If an organization had more than 1 representative in the task group, we asked that 1 electronic survey be returned on behalf of all its members. Respondents were also able to suggest variables not already on the list. We then reviewed a summary of results from responses received from 7 of 15 organizations (47% response rate) in a subsequent task group teleconference, where a final list of 57 candidate variables was created through consensus-based discussion. Further refinement to combine similar variables — for example, previous stroke with previous transient ischemic attack — resulted in 49 candidate variables for model development (48 for the CABG model, owing to exclusion of endocarditis) (Appendix 1, Supplemental Table 2).

Data sources
Data sources for candidate variables are provided in Appendix 1, Supplemental Table 2. We used the CorHealth Registry, the Discharge Abstract Database, the National Ambulatory Care Reporting System and the Ontario Health Insurance Plan database to obtain baseline demographics and comorbidities in addition to identifying our study population.\(^16,17\) Other data sources included the Ontario Laboratories Information System for laboratory information; the Canadian Institute for Health Information Same-day Surgery database for day procedure history; the Ontario Cancer Registry for cancer and radiation treatment history; and the Ontario Visible Minority Database for ethnicity.\(^18\) These data sets were linked using unique, encoded identifiers and analyzed at ICES (formerly Institute for Clinical Evaluative Sciences). Administrative codes and definitions used for variables, validation study results (where available) and variable formats are provided in Appendix 1, Supplemental Table 2.

Statistical analysis
In each model, we first performed unadjusted logistic regression to select potential predictors of 30-day mortality for each procedure of interest separately. We then entered candidate variables into a multivariable logistic regression model with backward selection and a significance threshold of $< 0.05$.\(^19\) Where missing, we imputed values using the procedure and sex-specific cohort mean (Appendix 1, Supplemental Table 2). We reviewed resulting models for face and content validity and selected final covariates based on statistical and clinical importance, as determined by the task group. For continuous variables, we examined their association with 30-day mortality using cubic spline analyses with 5 knots at the 5th, 27.5th, 50th, 72.5th and 95th percentiles. We entered linear variables (age, body surface area, hematocrit, leukocytes) into the models as continuous values, but treated nonlinear variables (Hospital Frailty Risk Score, body mass index, platelets) categorically based on their distribution in tertiles and clinically meaningful ranges.\(^20,21\) We report odds ratios, 95% confidence intervals (CIs) and $p$-values for final covariates in each model.
In both derivation and validation cohorts, we evaluated model discrimination using the c-statistic. For internal validation in the derivation sample, we computed optimism-corrected c-statistics using 250 bootstrap samples. We assessed calibration using the Hosmer-Lemeshow $\chi^2$ statistic, Brier score, calibration slope and a calibration curve, comparing observed versus expected mortality rates across deciles of expected risk. We also assessed the performance of the STS model in our derivation and validation cohorts. Roughly half of the hospitals were collecting STS data at the time, and these data were available to us. For all other hospitals, we mapped as many of the STS variables as possible to existing data sources at ICES. This was then used to estimate risk based on STS, ultimately including the entire cohort in the STS calculation. We conducted all analyses using SAS version 9.4 (SAS Institute, Cary NC).

**Ethics approval**

The use of these data was authorized under section 45 of Ontario’s *Personal Health Information Protection Act*, which does not require review by a Research Ethics Board.

**Results**

The derivation cohorts included 13435 patients who underwent CABG, 1970 patients who underwent AVR, and 1510 patients who underwent combined CABG + AVR (Figure 1). The sample size, number of deaths and proportion of patients who died in the derivation and validation cohorts are shown in Table 1. The baseline characteristics were similar between the derivation and validation cohorts across all groups (Appendix 1, Supplemental Tables 3–5).

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**Figure 1:** Flow diagram for the derivation cohort. Note: AVR = aortic valve replacement, CABG = coronary artery bypass graft, CIHI DAD = Canadian Institute for Health Information Discharge Abstract Database, OHIP = Ontario Health Insurance Plan. Note: Owing to small cell sizes, some exclusion criteria have been collapsed.

**Table 1: Population size, number of deaths and proportion who died in the derivation and validation cohorts, by procedure category**

| Cohort        | CABG |                | AVR |                | CABG + AVR |                |
|---------------|------|----------------|-----|----------------|------------|----------------|
|               | Population size | No. (%) of patients who died within 30 days | Population size | No. (%) of patients who died within 30 days | Population size | No. (%) of patients who died within 30 days |
| Derivation cohort |
| FY2017        | 6734 | 105 (1.56)     | 966 | 22 (2.28)      | 759        | 23 (3.03)      |
| FY2018        | 6701 | 128 (1.91)     | 1004| 11 (1.10)      | 751        | 23 (3.06)      |
| Overall       | 13435| 233 (1.73)     | 1970| 33 (1.68)      | 1510       | 46 (3.05)      |
| Validation cohorts |
| FY2015–FY2016 | 13447| 208 (1.55)     | 1946| 26 (1.34)      | 1601       | 60 (3.75)      |
| FY2019        | 6430 | 89 (1.38)      | 777 | 10 (1.29)      | 555        | 20 (3.60)      |

Note: AVR = aortic valve replacement, CABG = coronary artery bypass graft, FY = fiscal year.
Predictors of 30-day mortality after isolated CABG

History of percutaneous coronary intervention and left ventricular ejection fraction were forced into the model on the basis of clinical significance. Of the candidate covariates evaluated, older age, female sex, Hospital Frailty Risk Score, renal insufficiency, thrombocytopenia, atrial arrhythmia, chronic lung disease, peripheral arterial disease, cerebrovascular disease, previous CABG, percutaneous coronary intervention within 1 day before surgical revascularization, thoracic aortic disease, preoperative cardiogenic shock, and moribund status were predictors of 30-day CABG mortality (Table 2).

The c-statistic was 0.888 in the derivation data set (optimism-corrected 0.866), indicating excellent discrimination, and the Hosmer-Lemeshow χ² statistic p value was 0.2, indicating that there was no lack of model fit. These metrics of performance remained robust in both validation cohorts (Table 3). Supplemental Figure 1a in Appendix 1 shows the calibration plot of observed versus expected rates of 30-day CABG mortality according to each decile of risk, and Table 3 shows the predicted probability for the derivation and validation samples. The observed and predicted numbers of deaths were similar across all except the highest risk decile, in which the model tended to overestimate mortality.

In comparison, when fitted to the derivation cohort, the c-statistic of the STS model was 0.816, and the Hosmer-Lemeshow χ² statistic p value was 0.6. The c-statistic of the STS model was 0.841 and 0.863 in each of the validation cohorts.

Predictors of 30-day mortality after isolated AVR

Sex was forced into the model on the basis of clinical significance. The multivariable predictors of 30-day mortality were frailty, leukocytosis, liver disease, and preoperative cardiogenic shock (Table 4).

The c-statistic was 0.850 in the derivation data set (optimism-corrected 0.762) and the Hosmer-Lemeshow χ² statistic p value was 0.08. These metrics of performance remained robust in both validation cohorts (Table 3). Supplemental Figure 1b (Appendix 1) shows the calibration plot of observed versus expected rates of 30-day AVR mortality according to each decile of risk. The observed and predicted numbers of deaths were similar across all risk deciles.

In comparison, when fitted to the derivation cohort, the c-statistic of the STS model was 0.861, and the Hosmer-Lemeshow χ² statistic p value was 0.3. The c-statistic of the STS model was 0.846 in the first validation cohort. There was an insufficient number of events to validate the STS model in the second validation cohort.

Predictors of 30-day mortality after combined CABG + AVR

Sex and a history of previous CABG were forced into this model on the basis of clinical significance. Other multivariable predictors of 30-day mortality were frailty, anemia, a history of previous CABG, and preoperative cardiogenic shock (Table 5).

The c-statistic was 0.84 in the derivation data set (optimism-corrected 0.764) and the Hosmer-Lemeshow χ² statistic p value was 0.7. These metrics of performance remained robust in both validation cohorts (Table 3). Supplemental Figure 1c in Appendix 1 shows the calibration plot of observed versus expected rates of 30-day combined CABG + AVR mortality according to each decile of risk. The observed and predicted numbers of deaths were similar across all except the middle risk decile, in which the model tended to overestimate mortality.

In comparison, when fitted to the derivation cohort, the c-statistic of the STS model was 0.828, and the Hosmer-Lemeshow χ² statistic p value was 0.3. The c-statistic of the STS model was 0.881 in the first validation cohort. There was an insufficient number of events to validate the STS model in the second validation cohort.

Interpretation

We found that multidimensional data sources consisting of readily available clinical registry and administrative health databases can be used to develop 30-day mortality risk models for CABG, AVR and combined CABG + AVR, with excellent performance. We found that the Ontario CABG model was the best-performing model with a c-statistic of 0.888, while those for AVR and combined CABG + AVR also predicted well, with c-statistics of 0.850 and 0.844, respectively, and performed consistently in the validation cohorts. By comparison, the STS CABG model did not perform as well in Ontario, with a c-statistic of 0.816, while its performance for AVR (c-statistic 0.861) and CABG + AVR (c-statistic 0.828) was comparable to the Ontario models in the derivation data set.

Several aspects of our models are novel, compared with existing perioperative mortality models. First, the incorporation of frailty in our models represents a major advance in the field. Indeed, cardiac surgery literature cites the exclusion of frailty as a major limitation of commonly used cardiac surgery risk scores. Second, the Ontario models achieved parsimony without sacrificing performance, which allows for efficient assessment of the quality of surgical care. Our CABG model included only 15 predictors as compared with more than 50 in the STS model, while our CABG + AVR and AVR models each included only 5 predictor variables. The large number of variables needed to risk-adjust using the STS model is a limitation, and only half of Ontario surgical hospitals participate in the STS data collection. Third, we were able to derive these models using routinely collected data that are readily available across all cardiac care institutions, without loss to follow-up. In contrast, collecting the data elements necessary for the STS model would require additional infrastructure, resources and personnel time to be put in place across all cardiac centres. Lastly, our models were developed by an interdisciplinary team with complementary expertise in cardiac surgery, cardiac anaesthesiology, cardiology and clinical administration, for the purpose of quality assessment across centres. This differs from the other risk scores, which were derived primarily for preoperative risk assessment and operative decision-making.

Our modelling methodology has additional unique strength. In contrast with other commonly used universal mortality prediction models, such as the EuroSCORE II and the American College of Surgeons National Surgical Quality Improvement
Table 2: Multivariable model after backward selection for predicting 30-day mortality in patients who underwent coronary artery bypass graft surgery

| Covariate                                                                 | Parameter | Standard error | OR (95% CI)     |
|---------------------------------------------------------------------------|-----------|----------------|-----------------|
| Intercept                                                                 | -8.8215   | 1.0805         | 0 (0)           |
| Age on procedure date                                                     | 0.04832   | 0.0087         | 1.05 (1.03–1.07) |
| Sex, female                                                               | 0.4509    | 0.1622         | 1.57 (1.14–2.16) |
| Hospital Frailty Risk Score                                               |           |                |                 |
| 0 to < 1.0                                                                |            |                |                 |
| 1.0 to 3.0                                                                | 0.6181    | 0.2840         | 1.86 (1.06–3.24) |
| > 3.0                                                                    | 1.3357    | 0.2571         | 3.80 (2.30–6.29) |
| Left ventricular ejection fraction                                         |           |                |                 |
| ≥ 35%                                                                     |            |                |                 |
| < 35%                                                                     | 0.3189    | 0.1979         | 1.38 (0.93–2.03) |
| Missing                                                                   | 0.5230    | 0.2762         | 1.69 (0.98–2.90) |
| Serum creatinine                                                          |           |                |                 |
| Missing or < 120                                                          |            |                |                 |
| 120–179                                                                   | 0.1629    | 0.2083         | 1.18 (0.78–1.77) |
| 180+                                                                     | 0.7859    | 0.2228         | 2.19 (1.42–3.40) |
| Platelet count                                                            |           |                |                 |
| < 130                                                                     |            |                |                 |
| 130–400                                                                   | -0.7033   | 0.2798         | 0.49 (0.29–0.86) |
| > 400                                                                    | -1.6244   | 0.6846         | 0.20 (0.05–0.75) |
| Atrial fibrillation or flutter                                            |           |                |                 |
| None                                                                      |            |                |                 |
| Recent onset (≤ 30 d)                                                      | 0.3801    | 0.2240         | 1.46 (0.94–2.27) |
| Remote (> 30 d)                                                           | 0.9369    | 0.2792         | 2.55 (1.48–4.41) |
| Chronic lung disease                                                      | 0.6986    | 0.2020         | 2.01 (1.35–2.99) |
| Peripheral artery or vascular disease                                     | 0.5658    | 0.2274         | 1.76 (1.13–2.75) |
| Previous stroke or transient ischemic attack                              | 0.5786    | 0.2323         | 1.78 (1.13–2.81) |
| History and timing of PCI                                                |           |                |                 |
| No previous PCI                                                           |            |                |                 |
| PCI within 1 day                                                          | 3.5112    | 1.2196         | 33.49 (3.07–365.63) |
| PCI > 1 day prior                                                         | -0.4232   | 0.2177         | 0.65 (0.43–1.00) |
| Previous CABG                                                             | 1.7743    | 0.3965         | 5.90 (2.71–12.83) |
| Number of diseased coronary vessels                                       |           |                |                 |
| Unknown                                                                   |            |                |                 |
| 1                                                                        | 0.7170    | 0.8820         | 2.05 (0.36–11.54) |
| 2                                                                        | -0.0829   | 0.8366         | 0.92 (0.18–4.74) |
| 3                                                                        | 0.3807    | 0.8230         | 1.46 (0.29–7.34) |
| Thoracic aorta disease                                                    | 1.6117    | 0.6746         | 5.01 (1.34–18.80) |
| Moribund*                                                                 | 0.7936    | 0.2182         | 2.21 (1.44–3.39) |
| Shock; preoperative ECMO, IABP or CBA; or resuscitation within 1 day on admission | 2.7808 | 0.1832 | 16.13 (11.27–23.10) |

Note: CABG = coronary artery bypass graft, CBA = catheter-based assist device, CI = confidence interval, ECMO = extracorporeal membrane oxygenation, IABP = intra-aortic balloon pump, OR = odds ratio, PCI = percutaneous coronary intervention, Ref. = reference category.

*Moribund is defined by American Society of Anesthesiologists (ASA) Physical Classification status 5, as a patient who is not expected to survive for > 24 hours with or without surgery.22
Table 3: Predicted probability of 30-day mortality in the derivation and validation cohorts, by procedure category

| Performance metric | CABG | AVR | CABG + AVR |
|--------------------|------|-----|------------|
| **Derivation cohort: FY2017 and FY2018** | | | |
| Predicted probability of 30-day mortality, % | 1.80 | 1.95 | 4.15 |
| C-statistic | 0.8882 | 0.8500 | 0.8400 |
| Optimism-corrected c-statistic | 0.8659 | 0.7618 | 0.7644 |
| Hosmer–Lemeshow $\chi^2$ statistic $p$ value | 0.2 | 0.08 | 0.7 |
| Brier score* | 0.0150 | 0.0136 | 0.0269 |
| Calibration slope | 0.8988 | 0.6932 | 0.6634 |
| **Validation cohort: FY2015–FY2016** | | | |
| Predicted probability of 30-day mortality, % | 1.35 | 0.95 | 3.80 |
| C-statistic | 0.8801 | 0.7882 | 0.7591 |
| Optimism-corrected c-statistic | Not applicable | Not applicable | Not applicable |
| Hosmer–Lemeshow $\chi^2$ statistic $p$ value | 0.2 | 0.06 | 0.001 |
| Brier score* | 0.0142 | 0.0145 | 0.0320 |
| Calibration slope | 0.9672 | 0.8426 | 0.9218 |
| **Validation cohort: FY2019** | | | |
| Predicted probability of 30-day mortality, % | 2.65 | 1.10 | 1.55 |
| C-statistic | 0.8587 | 0.9008 | 0.8175 |
| Optimism-corrected c-statistic | Not applicable | Not applicable | Not applicable |
| Hosmer–Lemeshow $\chi^2$ statistic $p$ value | 0.7 | 0.8 | 0.01 |
| Brier score* | 0.0136 | 0.0128 | 0.0309 |
| Calibration slope | 0.9491 | 0.9596 | 1.0061 |

Note: AVR = aortic valve replacement, CABG = coronary artery bypass graft, FY = fiscal year.
*The Brier score is the average squared prediction error, where lower values indicate better model performance.

Table 4: Multivariable model after backward selection for predicting 30-day mortality in patients who underwent aortic valve replacement

| Covariate | Parameter | Standard error | OR (95% CI) |
|-----------|-----------|----------------|-------------|
| Intercept | −6.4791 | 0.6230 | 0 (0.00–0.01) |
| Sex, female | 0.3500 | 0.4091 | 1.42 (0.64–3.16) |
| Hospital Frailty Risk Score | | | |
| 0 to < 1.0 | Ref. | | |
| 1.0 to 3.0 | 0.0775 | 0.7554 | 1.08 (0.25–4.75) |
| > 3.0 | 1.4117 | 0.5332 | 4.10 (1.44–11.67) |
| Leukocytes, per 10³ | 0.1191 | 0.0459 | 1.13 (1.03–1.23) |
| Liver disease | 1.8277 | 0.7377 | 6.22 (1.46–26.41) |
| Shock; preoperative ECMO, IABP or CBA; resuscitation within 1 day or on admission; or ventricular tachycardia or fibrillation within 30 days | 3.3448 | 0.4437 | 28.36 (11.88–67.66) |

Note: CBA = catheter-based assist device, CI = confidence interval, ECMO = extracorporeal membrane oxygenation, IABP = intra-aortic balloon pump, OR = odds ratio, Ref. = reference category.
Our research was motivated by a province-wide initiative to improve cardiac surgery quality that includes the provision of outcomes reports on key quality indicators for all cardiac centres in Ontario. Although these reports are not released to the public, each cardiac surgery program sees the outcomes of all other surgical centres in an identifiable manner. It should be noted that the practice of public reporting is controversial, as the observed outcomes are influenced by practice variations in patient selection, as well as the fact that even a small excess of adverse events could have a large impact on rates of rare outcomes. Interestingly, a population-based cluster randomized trial by Tu and colleagues showed that the public release of hospital-specific quality indicators did not improve outcomes after acute myocardial infarction and congestive heart failure. Conversely, in the setting of the Michigan Society of Thoracic and Cardiovascular Surgeons Quality Collaborative, where 33 hospitals participated in quarterly presentation of unblinded data for the purpose of quality improvement through enhanced feedback, a substantial reduction in the rate of postoperative pneumonia was shown after intervention. Further studies are needed to determine whether an enhanced feedback system could reduce operative mortality after cardiac surgery.

**Limitations**

Our study has several limitations. First, important sociodemographic risk factors such as low socioeconomic status are difficult to capture using administrative data sets. Although we included neighbourhood income as a surrogate measure for socioeconomic status, we did not adjust for other determinants of socioeconomic status in this analysis. Second, certain physiological details, such as specific lesion locations and exact percentage stenoses of coronary lesions, were unavailable in the

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**Table 5: Multivariable model after backward selection for predicting 30-day mortality in patients who underwent combined coronary artery bypass graft surgery and aortic valve replacement**

| Covariate                                      | Parameter | Standard error | OR (95% CI) |
|-----------------------------------------------|-----------|----------------|-------------|
| Intercept                                     | –1.5823   | 1.3567         | 0.21 (0.01–2.94) |
| Sex                                           | 0.1718    | 0.3568         | 1.19 (0.59–2.39) |
| Hospital Frailty Risk Score 0 to < 1.0        | 0.8814    | 0.7403         | 2.41 (0.57–10.30) |
| > 3.0                                         | 2.0618    | 0.6146         | 7.86 (2.36–26.22) |
| Hematocrit, per 10%                           | –0.9301   | 0.3026         | 0.39 (0.22–0.71) |
| Previous CABG                                 | 0.9574    | 0.6593         | 2.60 (0.72–9.48) |
| Shock; preoperative ECMO, IABP, or CBA; resuscitation within 1 day or on admission; or ventricular tachycardia or fibrillation within 30 days | 2.2722 | 0.4094 | 9.70 (4.35–21.64) |

Note: CABG = coronary artery bypass graft, CBA = catheter-based assist device, CI = confidence interval, ECMO = extracorporeal membrane oxygenation, IABP = intra-aortic balloon pump, OR = odds ratio, Ref. = reference category.
data sets used. There is evidence that the inclusion of coronary anatomic complexity may improve mortality risk prediction. Third, we relied on administrative data and physician billing codes to derive covariates of interest, but the data sources used in this study and associated codes have been previously validated or published. Fourth, our models apply to the 3 most commonly performed cardiac surgery procedures, and the incremental risk of concomitant procedures — such as aortic root enlargement ascending aorta replacement — was not captured. Fifth, the low event rates for AVR and combined CABG + AVR precluded us from entering a large number of covariates during the modelling process. Despite this, our models performed well in 2 separate validation cohorts. Sixth, our study is limited by a lack of validation outside Ontario. Future opportunities to evaluate the ability of these models to benchmark national cardiac surgery performance are warranted, using data sources such as the Canadian Institute for Health Information. Lastly, continuous model updates are also warranted, to accommodate evolving patient demographics and indications for CABG and AVR.

**Conclusion**

Accurate computation of 30-day mortality risk for CABG, AVR and combined CABG + AVR can be achieved parsimoniously using routinely collected multidimensional administrative and clinical registry data sets, with comparable performance to more complex models derived from large, clinical data-derived US and European registries. The parsimonious Ontario cardiac surgery risk scores are a product of province-wide interdisciplinary collaboration among cardiac surgeons, cardiac anesthesiologists, cardiologists and clinical administrators. Hybridization (using a hybrid of clinical registry and administrative data sources) of routinely collected multidimensional data sources represents an efficient approach to data collection that has utility in system-wide quality of care evaluation and reporting.

**References**

1. El Bardissi AW, Aranki SF, Sheng S, et al. Trends in isolated coronary artery bypass grafting: an analysis of the Society of Thoracic Surgeons adult cardiac surgery database. *J Thorac Cardiovasc Surg* 2012;143:273-81.
2. Tam DY, Bakaean F, Feldman DN, et al. Modality selection for the revascularization of left main disease. *Can J Cardiol* 2019;35:983-92.
3. Shahian DM, Jacobs JP, Badhwar V, et al. The Society of Thoracic Surgeons 2018 Adult Cardiac Surgery Risk Models: Part 1 – Background, design considerations, and model development. *Ann Thorac Surg* 2018;105:1411-8.
4. Nashef SA, Roques F, Sharples LD, et al. EuroSCORE II. *Eur J Cardiothorac Surg* 2012;41:734-44, discussion 744-5.
5. Johnston A, Mesana TG, Lee DS, et al. Sex differences in long-term survival after major cardiac surgery: a population-based cohort study. *J Am Heart Assoc* 2019;8:e013260.
6. Tam DY, Dharra C, Rocha R, et al. Long-term survival after surgical or percutaneous revascularization in patients with diabetes and, ullevist coronary disease. *J Am Coll Cardiol* 2020;76:1153-64.
7. Sun LY, Spence SD, Benton S, et al. Age, not sex, modifies the effect of frailty on long-term outcomes after cardiac surgery. *Ann Surg* 2020 June 11 [Epub ahead of print]. doi: 10.1097/SLA.0000000000004060.
8. Sun LY, Bader Eddeen A, Ruel M, et al. Derivation and validation of a clinical model to predict intensive care unit length of stay after cardiac surgery. *J Am Heart Assoc* 2020;9:e017847.
9. Sun LY, Gaudino M, Chen RJ, et al. Long-term outcomes in patients with severely reduced left ventricular ejection fraction undergoing percutaneous coronary intervention vs coronary artery bypass grafting. *JAMA Cardiol* 2020;5:631-41.
10. Hannan EL, Szypulski Farrell L, Wechsler A, et al. The New York risk score for in-hospital and 30-day mortality for coronary artery bypass graft surgery. *Ann Thorac Surg* 2013;95:46-52.
11. Hannan EL, Racz M, Cullford AT, et al. Risk score for predicting in-hospital/30-day mortality for patients undergoing valve and valve/coronary artery bypass graft surgery. *Ann Thorac Surg* 2013;95:1282-90.
12. O’Brien SM, Feng L, He X, et al. The Society of Thoracic Surgeons 2018 Adult Cardiac Surgery Risk Models: Part 2 – Statistical considerations and results. *Ann Thorac Surg* 2018;105:1419-28.
13. Ristovic V, de Roock S, Mesana TG, et al. The impact of preoperative risk on the association between hypotension and mortality after cardiac surgery: an observational study. *J Clin Med* 2020;9:2057.
14. Sun LY, Rodger J, Duffett L, et al. Derivation of patient-defined adverse cardiovascular and noncardiovascular events through a modified Delphi process. *JAMA Netw Open* 2021;4:e203205.
15. Lee DS, Tran C, Flintoft V, et al.; Canadian Cardiovascular Outcomes Research Team/Canadian Cardiovascular Society Heart Failure Quality Indicator Panel. CCORT/CCS quality indicators for congestive heart failure care. *Can J Cardiol* 2003;19:357-64.
16. Hayatsu Y, Ruel M, Bader Eddeen A, et al. Single versus multiple arterial revascularization in patients with reduced renal function: long-term outcome comparisons in 23,406 CABG patients from Ontario, Canada. *Ann Surg 2020 June 24 [Epub ahead of print]. doi: 10.1097/SLA.0000000000003908.
17. Sun LY, Tu J, Bader Eddeen A, et al. Prevalence and long-term survival after coronary artery bypass grafting in men and women with heart failure and preserved vs reduced ejection fraction. *J Am Heart Assoc* 2018;7:e008992.
18. Shah BR, Chiu M, Amin S, et al. Surname lists to identify South Asian and Chinese ethnicity from secondary data in Ontario, Canada: a validation study. *BMC Med Res Methodol* 2010;10:42. doi: 10.1186/1472-6963-10-42.
19. Harrell FE Jr, Lee KL, Mark DB. Multivariable prognostic models: issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors. *Stat Med* 1996;15:361-87.
20. Gilbert T, Neuberger J, Krandijer J, et al. Development and validation of a Hospital Frailty Risk Score focusing on older people in acute care settings using electronic hospital records: an observational study. *Lancet* 2018;391:1775-82.
21. Clinical laboratory tests: adult normal values. Ottawa: Medical Council of Canada; 2020. Available: https://www.mcc.ca/objectives/normal-values/ (accessed 2021 Oct. 18).
22. Hurwitz EE, Simon M, Vinta SR, et al. Adding examples to the ASA-physical status classification improves correct assignment to patients. *Anesthesiology* 2017;126:614-22.
23. Mandrekar JN. Receiver operating characteristic curve in diagnostic test assessment. *J Thorac Oncol* 2010;5:1315-6.
24. Otto CM, Nishimura RA, Bonow RO, et al. 2020 ACC/AHA guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association joint committee on clinical practice guidelines. *Circulation* 2021;143:e72-227.
25. Tran DTT, Tu JV, Dupuis JY, et al. Association of frailty and long-term survival in patients undergoing coronary artery bypass grafting. *J Am Heart Assoc* 2018;7:e008882.
26. Bilimoria KY, Liu Y, Paruch JL, et al. Development and evaluation of the universal ACS NSQIP surgical risk calculator: a decision aid and informed consent tool for patients and surgeons. *J Am Coll Surg* 2013;217:833-42.e1-3.
27. Tam DY, Freams SE. Commentary: One size doesn’t always fit all. *J Thorac Cardiovasc Surg* 2020;160:180-1.
28. Ad N, Holmes SD, Patel J, et al. Comparison of EuroSCORE II, original EuroSCORE, and the Society of Thoracic Surgeons Risk Score in cardiac surgery patients. *Ann Thorac Surg* 2016;102:573-9.
29. Mori M, Shahian DM, Huang C, et al. Surgeons: buyer beware—does “universal” risk prediction model apply to patients universally? *J Thorac Cardiovasc Surg* 2020;160:176-9.e2.
30. Neumann FJ, Sousa-Uva M, Ahlsson A, et al. 2018 ESC/EACTS guidelines on myocardial revascularization. *EuroIntervention* 2019;14:1435-534.
31. Tu JV, Sykora K, Naylor CD. Assessing the outcomes of coronary artery bypass graft surgery: how many risk factors are enough? Steering Committee of the Cardiac Care Network of Ontario. J Am Coll Cardiol 1997;30:1317-23.

32. Guru V, Anderson GM, Frenses SE, et al.; Canadian CABG Surgery Quality Indicator Consensus Panel. The identification and development of Canadian coronary artery bypass graft surgery quality indicators. J Thorac Cardiovasc Surg 2005;130:1257.

33. Jha AK. Public reporting of surgical outcomes: Surgeons, hospitals, or both? JAMA 2017;318:1429-30.

34. Tu JV, Donovan LR, Lee DS, et al. Effectiveness of public report cards for improving the quality of cardiac care: the EFFECT study—a randomized trial. JAMA 2009;302:2330-7.

35. Likosky DS, Harrington SD, Cabrera L, et al. Collaborative quality improvement reduces postoperative pneumonia after isolated coronary artery bypass grafting surgery. Circ Cardiovasc Qual Outcomes 2018;11:e004756.

36. Farooq V, van Klaveren D, Steyerberg EW, et al. Anatomical and clinical characteristics to guide decision making between coronary artery bypass surgery and percutaneous coronary intervention for individual patients: development and validation of SYNTAX score II. Lancet 2013;381:639-50.

37. Tam DY, Fang J, Tran A, et al. A clinical risk scoring tool to predict readmission after cardiac surgery: an Ontario administrative and clinical population database study. Can J Cardiol 2018;34:1655-64.

38. Braga JR, Austen PC, Ross HJ, et al. Importance of nonobstructive coronary artery disease in the prognosis of patients with heart failure. JACC Heart Fail 2019;7:493-501.

39. Englum BR, Ganapathi AM, Schechter MA, et al. Changes in risk profile and outcomes of patients undergoing surgical aortic valve replacement from the pre- to post-transcatheter aortic valve replacement eras. Ann Thorac Surg 2016;101:110-7.

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