## Title
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# Duration of Postoperative Mechanical Ventilation as a Quality Metric for Pediatric Cardiac Surgery

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## Abstract

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**Background—**Few metrics exist to assess quality of care at pediatric cardiac surgical programs, limiting opportunities for benchmarking and quality improvement. Postoperative duration of mechanical ventilation (POMV) may be an important quality metric because of its association with complications and resource utilization. We aimed to model case-mix adjusted POMV duration, and to explore hospital performance across POMV metrics.

**Methods—**Analysis of 4739 hospitalizations from 15 hospitals using the Pediatric Cardiac Critical Care Consortium clinical registry (10/2013–8/2015). All patients admitted to pediatric cardiac intensive care units after an index cardiac operation were included. We fitted a model to predict duration of POMV accounting for patient characteristics. Robust estimates of standard errors were obtained using bootstrap resampling. We created performance metrics based on observed-to-expected (O/E) POMV to compare hospitals.

**Results—**Overall, 3,108 patients (65.6%) received POMV; the remainder extubated intraoperatively. Our model was well-calibrated across groups; neonatal age had the largest effect on predicted POMV. These comparisons suggested clinically and statistically important variation in POMV duration across centers with three-fold difference observed in O/E ratios (0.6–1.7). We identified one hospital with better- and 3 hospitals with worse-than-expected performance ($p<0.05$) based on the O/E ratio.

**Conclusions—**We developed a novel case-mix adjusted model to predict POMV duration after congenital heart surgery. We report variation across hospitals on metrics of observed-to-expected duration of POMV that may be suitable for benchmarking quality of care. Identifying high-performing centers and practices that safely limit duration of POMV could stimulate quality improvement efforts.

## Classifications

CHD; Database; Outcomes; Pediatric; Postoperative Care; Quality Care; management

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Quality assessment in pediatric cardiac surgery suffers from a paucity of valuable metrics suitable for benchmarking. Mortality remains the predominant metric by which hospitals are compared, but many stakeholders have called for development of new quality measures that assess morbidity and resource utilization (1, 2). Duration of postoperative mechanical ventilation (POMV) may be one such important measure of quality care after pediatric cardiac surgery. While many children and adults undergoing surgery for congenital or acquired heart disease wean from mechanical ventilation early in the postoperative period, prolonged ventilation may be necessary for complex patients (3, 4). Data suggest that mechanical ventilation poses increased risk for infection, airway and lung injury, and failed extubation (3, 5, 6). Increased duration of POMV prolongs the critical care period and further exposes patients to potential risks (4, 7, 8), so it is reasonable to conclude that shortening POMV duration may represent higher quality, more cost-effective care. The National Quality Forum endorsed an adjusted prolonged mechanical ventilation hospital quality metric for coronary artery bypass surgery (9).

However, the heterogeneity of pediatric cardiovascular surgical procedures and case-mix differences across hospitals (10) create challenges in assessing duration of POMV as a measure of hospital performance. An ideal quality metric of POMV would account for the patient factors and operative complexity that differ across hospitals. Previous investigators used this approach to measure ventilation time for critically ill adults (11–13), but these models do not apply to children with congenital heart disease. Some factors associated with POMV duration in children with cardiac disease are known, but no validated tool exists to predict duration of POMV in this population (3, 4, 14–18). Metrics of adjusted POMV duration would allow hospitals to measure performance and benchmark against peer institutions. These data could motivate improvement initiatives via collaborative learning with high-performing centers.

In this context, we aimed to develop hospital performance metrics for duration of POMV after pediatric cardiac surgery using data from the Pediatric Cardiac Critical Care Consortium ($PC^4$) clinical registry. We developed and validated a model to predict duration of POMV, and then created several metrics based on observed-to-expected (O/E) duration of POMV. We describe differences in performance across hospitals for each metric and in aggregate.

## Patients and Methods

### Data Source

$PC^4$ is a voluntary quality improvement collaborative among hospitals across North America; 15 hospitals were submitting data at the time of the analysis. All cardiac intensive care unit (CICU) encounters at participant hospitals are submitted to the $PC^4$ clinical registry. Each case record includes demographics, patient comorbidities, data on cardiac surgical procedures and other interventions, critical care therapies, and complications, all with standardized definitions. The registry shares common terminology and definitions with the International Pediatric and Congenital Cardiac Code (19) and the Society of Thoracic Surgeons Congenital Heart Surgery Database as previously described (20); each site ensures that these data match across databases. Trained data managers who pass a certification exam abstract cases. We previously published results of the rigorous audit process demonstrating excellent data integrity within the registry (21). Submission of data to $PC^4$ is considered quality improvement activity and not subject to ongoing institutional review board oversight. The University of Michigan institutional review board oversees the $PC^4$ Data Coordinating Center; this study was approved with waiver of informed consent.

### Inclusion and Exclusion Criteria

We considered all surgical hospitalizations for patients admitted to $PC^4$ hospitals that included at least one CICU encounter between October 1, 2013 and August 31, 2015. Each hospitalization included an "index" surgical procedure as defined by the Society of Thoracic Surgeons (22). Though the unit of analysis is the surgical hospitalization we refer to these episodes as "patients" throughout the manuscript. We excluded those patients with a tracheostomy *in situ* at index operation, <2.5kg undergoing isolated patent ductus arteriosus repair, undergoing index operations not classifiable into one of the Society of Thoracic Surgeons-European Association for Cardiothoracic Surgery (STAT) mortality categories (23), or who died before postoperative day 7.

### Model Development: Outcomes and Predictor Variables

We developed a case-mix adjustment model to predict duration of POMV after congenital cardiac surgery. Total duration of POMV was the dependent variable in the model. We calculated duration of POMV by adding the length of each episode of mechanical ventilation after the index operation. The registry includes the exact start and stop time of each mechanical ventilation episode in the CICU, including episodes in other critical care areas. Patients extubated in the operating room after an index procedure who never require mechanical ventilation were included with a POMV duration of 0 hours. Duration of POMV was capped at 60 days to eliminate the impact of extreme outliers on the model.

Our aim was to create a *population-level* case-mix adjustment model. We did not attempt to predict duration of ventilation at the patient level. Thus, we explored candidate variables for our model present pre- or intra-operatively. We excluded postoperative variables that may be important for predicting the duration of mechanical ventilation for an individual patient such as vasoactive-inotropic score, complications, and critical care therapies; these variables could also reflect surgical or critical care quality, and therefore would not be appropriate for a case-mix adjustment model used in hospital quality assessment. Preoperative patient factors, comorbidities, and operative complexity variables that impact outcomes after congenital cardiac surgery were selected *a priori*. Patients were categorized as neonate (<30 days), infant (30–365 days), child (>365 days–18 years), or adult (>18 years). Other demographic variables included gender, prematurity (<37 weeks gestational age), and the presence of any extracardiac or chromosomal anomalies, syndromes, or airway anomalies (19). We recorded pre-operative mechanical ventilation only if it was present on CICU admission. STAT category and cardiopulmonary bypass (CPB) times were included as measures of surgical complexity.

### Model derivation and validation

We used zero-inflated negative binomial regression to model duration of POMV as a function of patient characteristics and operative complexity. Based on the generalized information criterion, zero-inflated negative binomial regression fit the data better than Poisson, negative binomial or zero-inflated Poisson models. Variables associated with duration of POMV at $p<0.05$ were retained in the final model. We derived bias-corrected confidence intervals for the regression coefficients based on 1000 bootstrap resamples.

To test goodness of fit, we separated the patients into equal rank-ordered groups (237 patients per group), and plotted the mean observed duration of mechanical ventilation within each group against the mean duration predicted by the model. Model discrimination was assessed using a pseudo C-statistic (see details of the method in the **Appendix**). Since the majority of patients had POMV <24 hours, we calculated this pseudo C-statistic for patients within subgroups of expected POMV ≤24 or >24 hours.

### Creating metrics of hospital performance using observed-to-expected duration of POMV

From the final model, we calculated O/E ratios of duration of POMV for each center. The O/E ratio was calculated by dividing total observed hours of mechanical ventilation by total expected hours. Expected hours were derived for each patient from our multivariable model.

For this analysis we excluded any patient with an expected duration of POMV >168 hours (~10% of the entire sample) because the model did not fit as well at the upper tail of the distribution (Figure 1). We empirically derived the 95% confidence intervals (CI) around the O/E ratio from our bootstrap resampling. Statistically better- or worse-than-expected performance was defined as an O/E ratio less than or greater than 1, respectively, with 95% CI not crossing 1.

While the O/E ratio is a clear performance metric, we explored alternative ways to express the data that might have value to clinicians and quality researchers. We created four additional metrics based on observed-to-expected duration of POMV (Table 1). Expected duration of POMV for each metric was determined from the model as described. Total days lost/saved per 100 patients is the O–E difference rather than ratio, which may be more easily interpretable for quality improvement initiatives. We took the difference of total days observed and total days expected at each hospital, and normalized the difference to per 100 hospitalizations. If observed was less than expected (difference <0), we considered those days of mechanical ventilation "saved." If the difference was >0, we considered those days "lost." We then ranked each hospital on every metric (1=best, 13=worst.); two hospitals that had recently joined the collaborative were dropped for these analyses because of low case numbers (N<50). Finally, we summed the ranks across each metric to determine an average hospital rank, weighing each metric equally.

## Results

The study included 4,739 hospitalizations at 15 participating CICUs. Overall, 3,108 patients (66%) required POMV. Fifty-three percent were infants and 22% had high complexity surgery (STAT categories 4 or 5). The median duration of POMV was 0.3 days ($10^{th}$–$90^{th}$ percentile range 0 – 5.9 days). The patient characteristics and all candidate predictor variables are shown in Supplemental Table 1.

Each of the 15 hospitals contributing data to this analysis performs the full spectrum of congenital heart surgery (complex neonatal repairs, STAT 5 procedures) and the range of annual index operations across the hospitals is 206–601 per year. Every hospital has a dedicated cardiac intensive care unit, and all but four have a 24/7 intensivist coverage model.

### Model performance

Table 2 shows the final predictor variables in our case-mix adjustment model. Independent predictors of longer duration of POMV were age, prematurity, extracardiac/genetic anomalies, underweight, preoperative mechanical ventilation, higher STAT category, and CPB time. Neonate status had the largest effect on duration of POMV (incidence rate ratio 3.8 versus child, 95% CI 2.9–4.8). The goodness of fit plot showed a well-fitted model predicting mean duration of POMV for groups of patients (Figure 1). The pseudo C-statistic for this model was 0.73 for patients with expected duration of POMV <24 hours, and 0.63 for patients with expected duration >24 hours.

### Hospital performance on metrics of case-mix adjusted duration of POMV

Figure 2 shows O/E ratios of duration of POMV for each hospital (N=13). One hospital had better-than-expected performance (O/E ratio 0.59, 95% CI 0.4–0.8), and three hospitals had worse-than-expected (O/E >1). Figures 3–5 demonstrate the variation in hospital performance on each metric of adjusted POMV described in Table 1. For the total days lost-saved per 100 hospitalizations metric (Figure 5), the top-ranked hospital saved 173 days of POMV compared to the lowest-ranked hospital. The aggregate rankings for each hospital on all four metrics are reported in Table 3 (1=best). The average rankings suggested two positive outliers (average rank 1.75), a middle group (average rank 4.5–7.25), and five hospitals in a lower group with average rank 8.25–10.75 and ranking >10 on two or more metrics.

## Comment

We developed a case-mix adjusted model to predict duration of POMV in pediatric cardiac surgical patients using a parsimonious set of easily collected predictor variables. The model was well-calibrated to predict duration of POMV across groups of patients, a characteristic that aligns with our aim to use this model to assess hospital performance. We also created a novel set of quality metrics based on O/E duration of POMV. Analysis of hospital performance on these metrics suggested clinically important variation across 13 hospitals. To our knowledge this is the first such analysis in pediatric cardiac surgical outcomes research.

Efforts to reduce duration of POMV probably represent high quality care so long as this is accomplished with low reintubation rates, avoidance of periextubation complications such as cardiac arrest, and low mortality. Strategies for POMV practices differ across hospitals; in some cases, early extubation is not feasible due to unique microsystem features of each hospital such as need for operating room turnover or ICU staffing (5, 24), though we can only speculate on whether that is more or less true among hospitals in this cohort. These performance metrics may reflect those practice differences rather than differences in quality of care. Further, it will be important to understand how adjusted duration of POMV correlates with other resource utilization such as adjusted intensive care and hospital length of stay. Despite these caveats, our POMV metrics could provide actionable information to hospitals for determining whether improvement initiatives are warranted.

Mahle and colleagues from the Pediatric Heart Network (25) demonstrated the value of understanding duration of POMV for quality improvement efforts in pediatric cardiac surgery. These investigators successfully reduced POMV after two infant cardiac surgical procedures through collaborative learning. A critical aspect of this process involved presenting POMV metrics to the participating study teams. Comparative reports - though not adjusted - across the hospitals helped to identify positive and negative outliers, and the key practices at higher-performing hospitals were identified and implemented at hospitals with longer duration of POMV.

This prior experience illustrates how we hope $PC^4$ hospitals will use the metrics developed in the current study. The rigorous case-mix adjustment method allows meaningful crosshospital comparison. Transparent data sharing within the $PC^4$ collaborative facilitates identification of top performers and discussions about practice differences that could lead to collaborative learning approaches to reduce duration of POMV across a wider patient population (25, 26).

We created metrics that assess performance of the entire perioperative team, and therefore only included quality-independent *preoperative* factors. Determining the relative contributions of surgical and CICU care to adjusted duration of POMV metrics represents the next key step in this investigation. To do so will require addition of postoperative severity of illness variables to the model to isolate and measure the quality of CICU care (4, 15, 17). Assessing the drivers of prolonged POMV – surgical vs. CICU quality – will help hospitals to identify the key levers for improvement.

Our analytic strategy works well for assessing duration of POMV for groups of pediatric cardiac surgical patients and for hospital quality assessment. The model fit across groups of patients demonstrates that our modeling approach achieves the stated aim for population-level case-mix adjustment. The model was not created or optimized to predict duration of POMV for individual patients. As such, the c-statistic for our model is low relative to other risk-adjustment models (27) commonly used in this population because of our approach.

Beyond those already mentioned, there are important limitations to consider. Our investigation was limited to candidate variables included in the clinical registry, and there may be other important predictors not measured. For instance, at the time of this analysis prior operations was not a variable collected in the database. The database has since been expanded, and we will have the opportunity to refine our model in future analyses. This analysis was performed at 15 hospitals performing over 200 index operations per year and all with dedicated CICUs; it is unclear whether the model would include different variables if derived from a larger, more diverse set of hospitals. It is important to note that our model allows a hospital to understand how their observed duration of ventilation compares to what would be expected based on case-mix. Our methods, like all those that use indirect standardization approaches, do not facilitate direct comparisons of quality between hospitals that may have different case-mix. Finally, other potential metrics of hospital quality related to limiting POMV may exist (16, 28). While the quality metrics we evaluated provide insight into hospital performance, we analyzed these out of context to other important quality indicators.

## Conclusion

We developed a case-mix adjusted model to predict duration of POMV after congenital heart surgery accounting for baseline patient and operative characteristics. We used this model to derive several novel metrics of hospital performance pertaining to duration of POMV, and highlight differences across centers. Identifying high-performing hospitals that safely limit duration of POMV is a necessary step to elucidate key practices that underlie better outcomes. We aim to translate this knowledge into quality improvement initiatives and reduce duration of POMV across hospitals through collaborative learning within $PC^4$.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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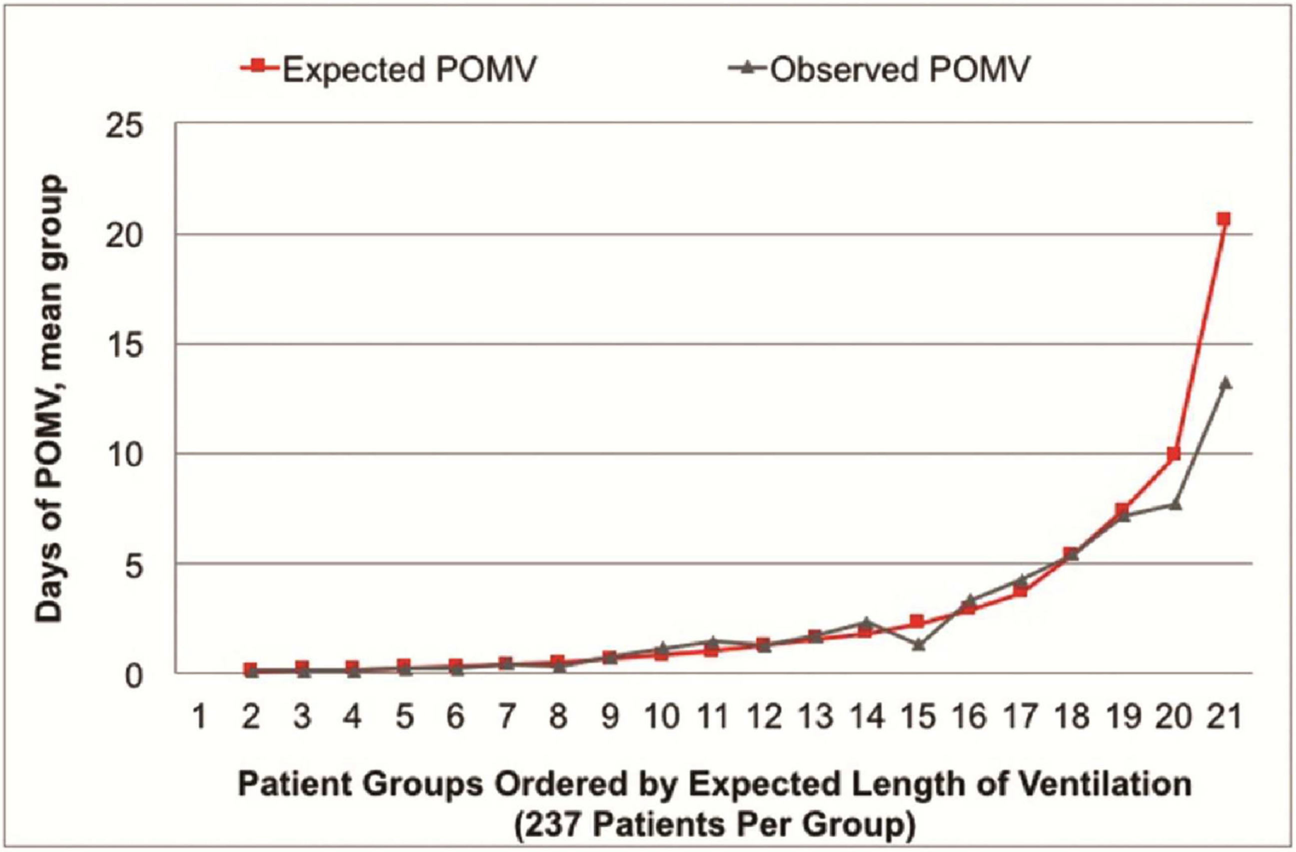


**Figure 1.**
plot of mean expected duration of postoperative mechanical ventilation (POMV) in equal rank ordered groups (red squares) vs. mean observed duration within group (black triangles).

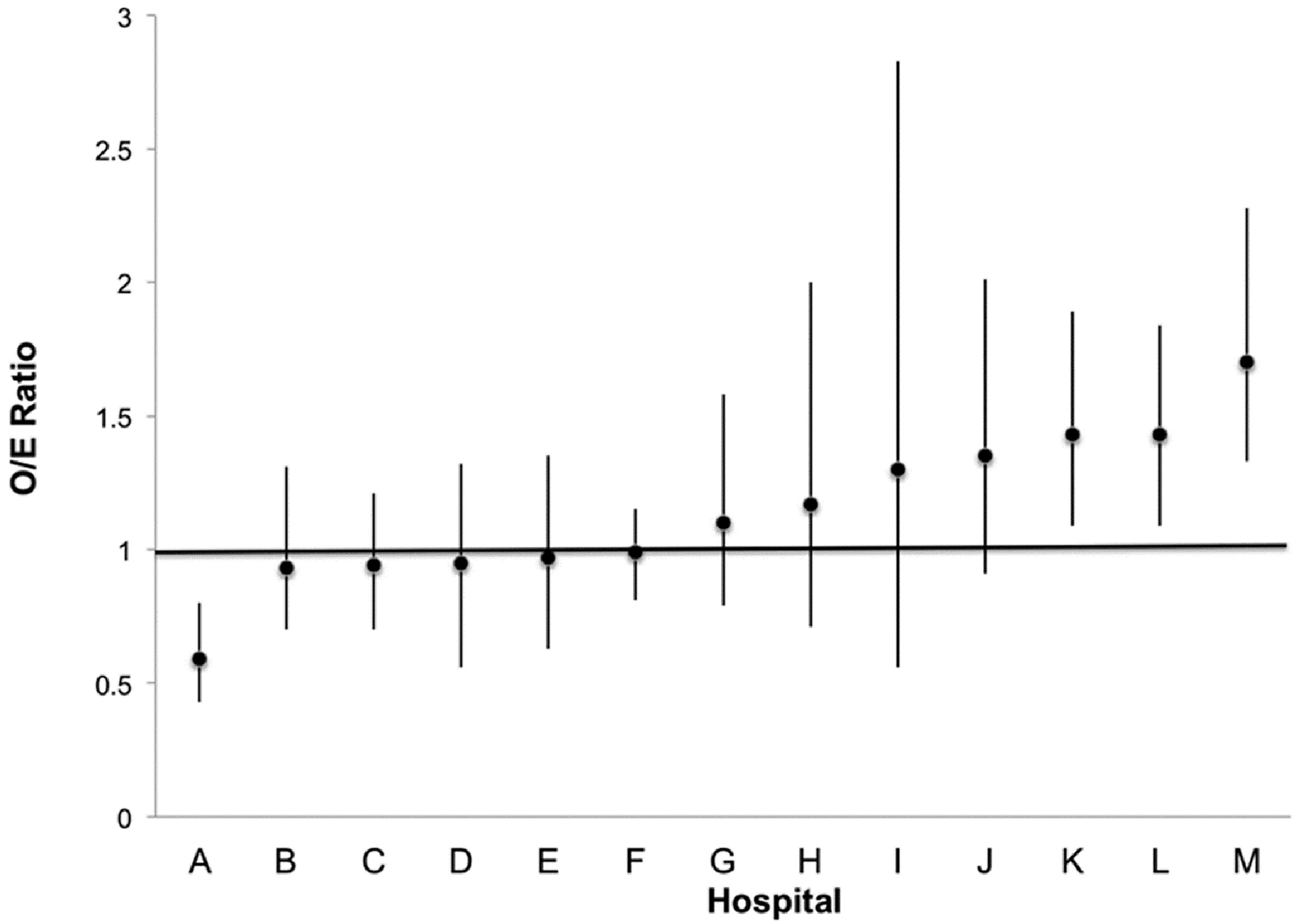


**Figure 2.**

observed-to-expected (O/E) ratio of duration of postoperative mechanical ventilation (POMV). Hospitals are rank ordered with A=lowest O/E and M=highest. Hospital A has statistically-significant less than expected duration of POMV, while hospitals K–M have significantly greater than expected POMV.




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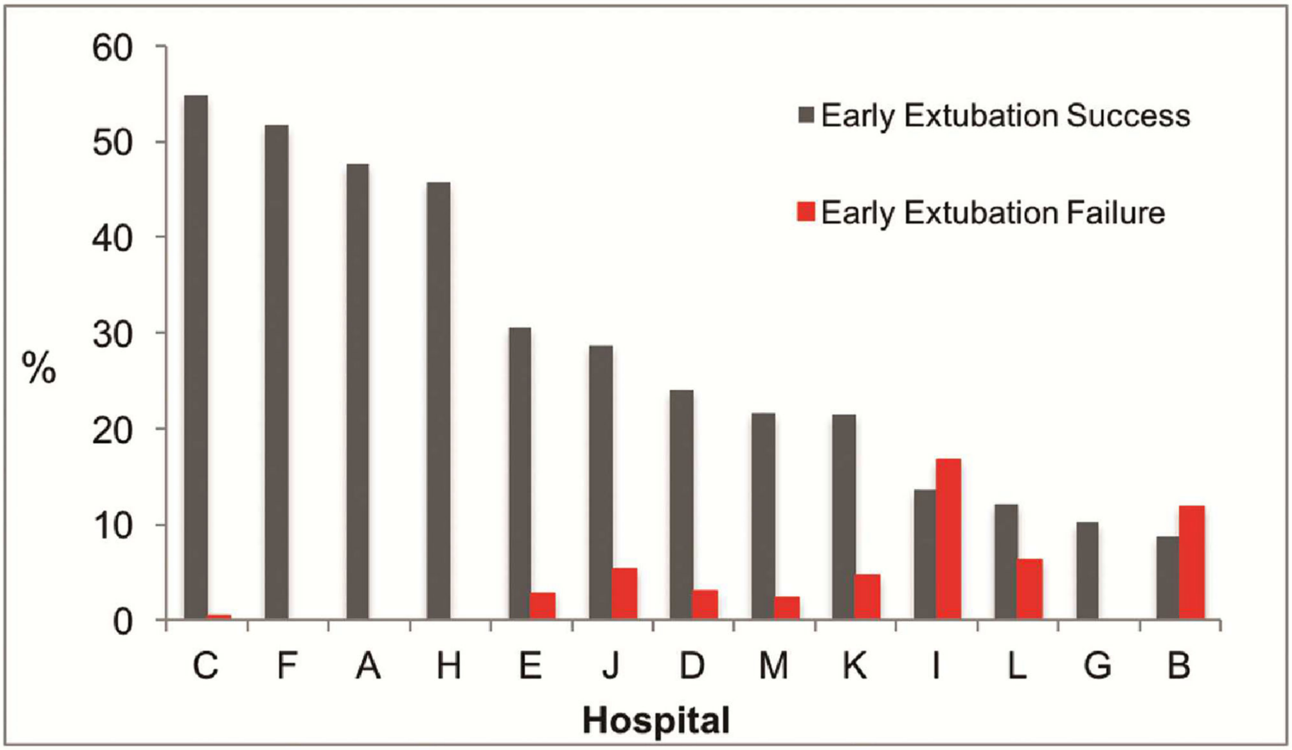


**Figure 3.**

percentage of patients with expected postoperative mechanical ventilation (POMV) >12 hours who had observed POMV <6 hours (Success, black), and those with an expected duration of POMV <6 hours who had observed POMV >12 hours (Failure, red).

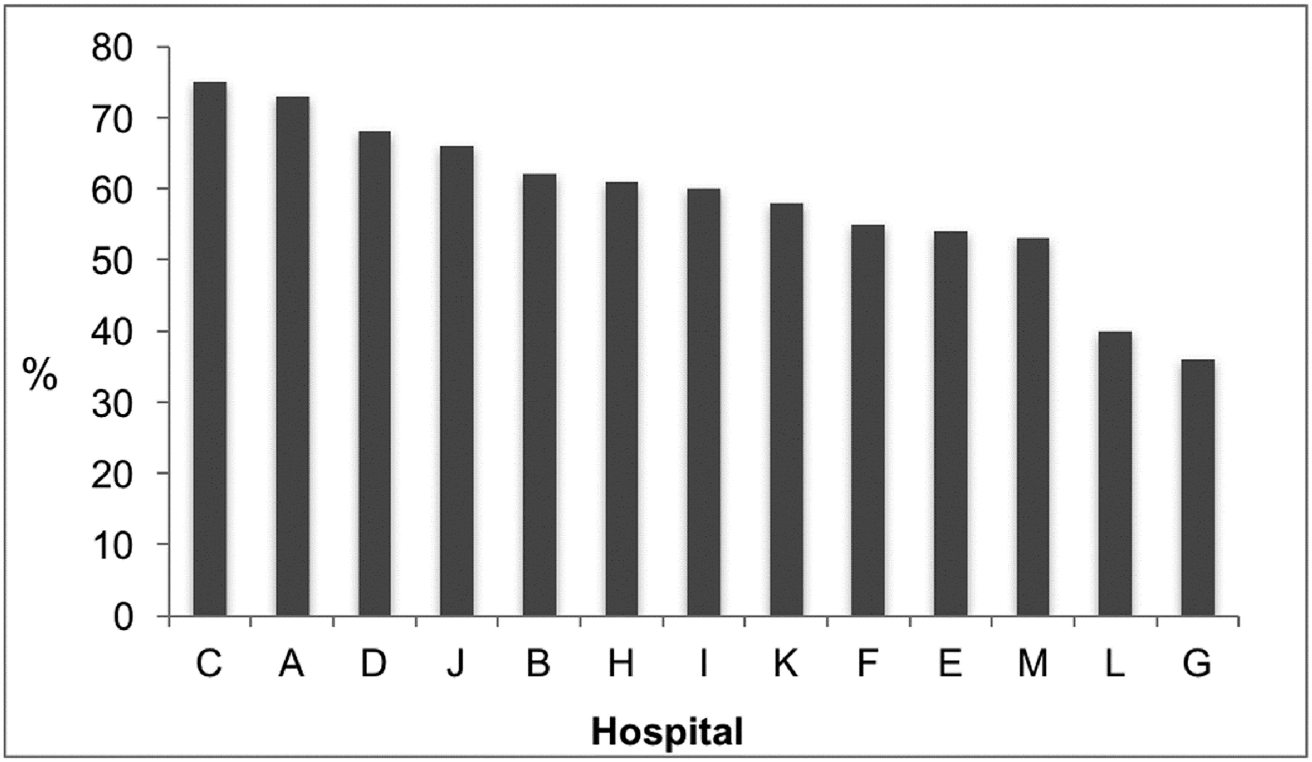


**Figure 4.**
percentage of patients by hospital whose observed duration of postoperative mechanical ventilation (POMV) was <50% expected duration of POMV.

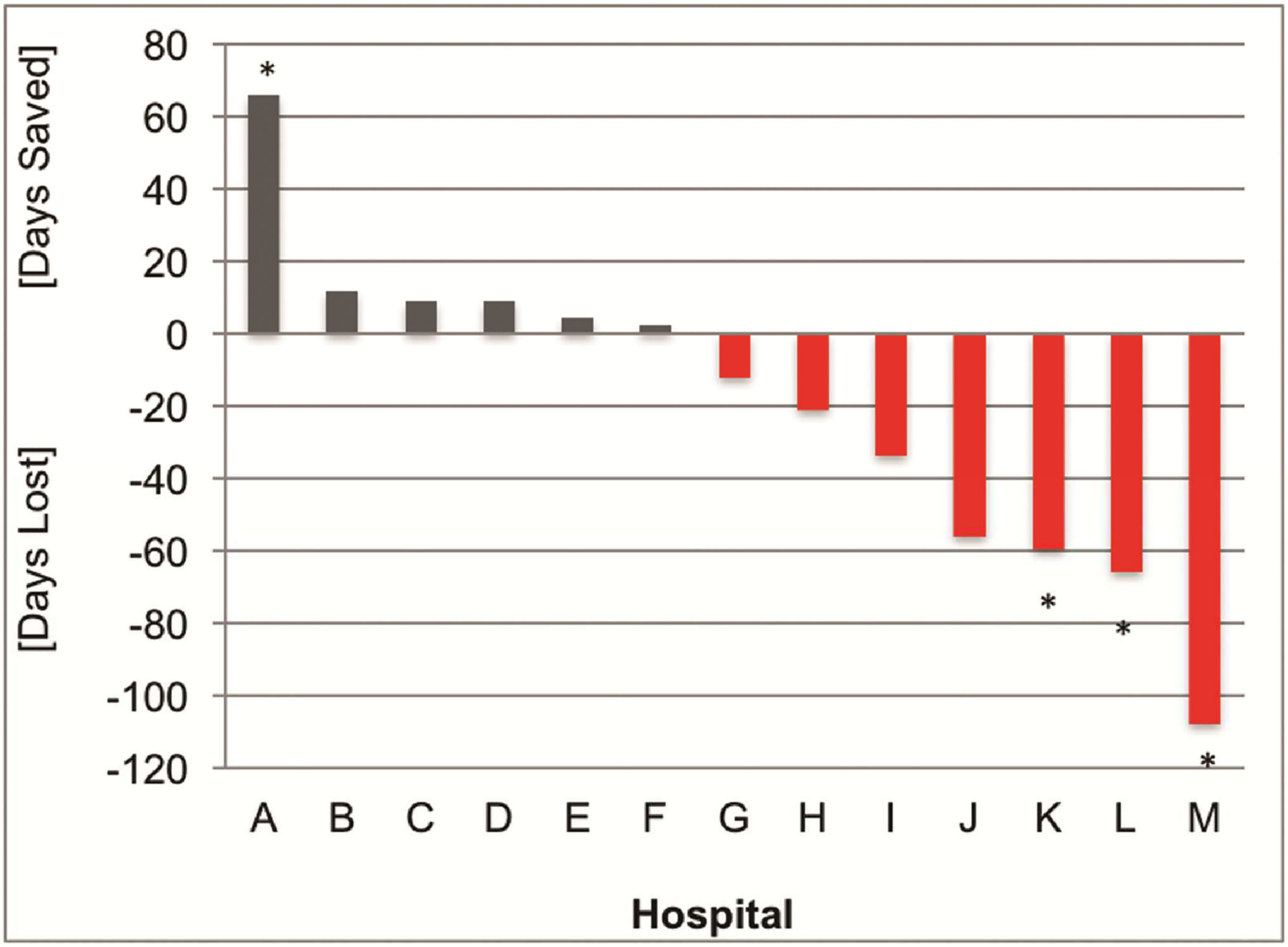


**Figure 5.**
total days of postoperative mechanical ventilation (POMV) saved (black) or lost (red) at each center, per 100 hospitalizations. Hospitals are rank ordered with A=best performance (days saved) and M=worst performance (days lost). * denotes hospitals with statistically significant days saved/lost ($p<0.05$).

**Table 1**

Metrics of hospital performance on duration of postoperative mechanical ventilation

| Metric | Numerator | Denominator | Unit |
|---|---|---|---|
| Early Extubation Success | Hospitalizations with observed MV <6 hours | Hospitalizations with predicted MV >12 hours | % |
| Early Extubation Failure | Hospitalizations with observed MV >12 hours | Hospitalizations with predicted MV <6 hours | % |
| Positive Deviance in Reduction of MV | Hospitalizations with observed MV <50% predicted duration | All hospitalizations | % |
| Total Days of MV Lost/Saved | (Total days observed – Total days predicted) | All Hospitalizations with predicted MV <7 days | Days lost/saved per 100 hospitalizations |

MV, mechanical ventilation

## Table 2

Multivariable model predicting duration of postoperative mechanical ventilation. N=4,739

| Characteristic | Frequency (%) or Median (IQR) | IRR[a] (95% CI)[b] | p-value[c] |
|---|---|---|---|
| **Male Gender** | 2,602 (55%) | 1.10 (0.92–1.30) | 0.046 |
| **Age Group** | | | |
| **Neonate** | 1,007 (21%) | 3.81 (2.87–4.79) | <0.001 |
| **Infant** | 1,528 (32%) | 1.87 (1.40–2.38) | <0.001 |
| **Child** | 1,925 (41%) | REF | |
| **Adult** | 279 (6%) | 1.35 (0.60–2.57) | 0.014 |
| **Weight Category** | | | |
| **Underweight**[d] | 1,070 (23%) | 1.19 (0.96–1.49) | 0.005 |
| **Normal Weight** | 3,515 (74%) | REF | |
| **Overweight**[e] | 159 (3%) | 0.52 (0.35–0.76) | <0.001 |
| **Prematurity (<37 weeks)** | 509 (11%) | 1.26 (1.02–1.57) | 0.002 |
| **Airway anomaly** | 145 (3%) | 2.76 (2.03–3.61) | <0.001 |
| **Extracardiac or genetic anomaly** | 1,307 (28%) | 1.44 (1.19–1.73) | <0.001 |
| **Pre-operative mechanical ventilation** | 355 (7%) | 1.88 (1.45–2.39) | <0.001 |
| **STAT category 1 – 3** | 3,595 (76%) | REF | |
| **STAT category 4 – 5** | 1,030 (22%) | 1.96 (1.62–2.39) | <0.001 |
| **CPB Time, mins** | 78 (43–124) | 1.00 (1.00–1.01) | <0.001 |

[a] IRR, Incidence rate ratios

[b] Bias corrected confidence intervals derived from 1000 bootstrap resamples.

[c] P-values from zero-inflated negative binomial regression.

[d] Weight-for-age Z-score <−2 (age ≤ 20 years old) or Body Mass Index <18.5 (age >20 years old)

[e] Weight-for-age Z-score >2 (age ≤ 20 years old) or Body Mass Index >30 (age >20 years old)

CPB, cardiopulmonary bypass; IQR, interquartile range; REF, reference group; STAT, Society of Thoracic Surgeons-European Association for Cardiothoracic Surgery.

**Table 3**

Aggregate hospital ranking across metrics (1=best)

| Center | EE Success | EE Failure | POMV Reduction | Days POMV Saved/Lost | Average Rank |
|---|---|---|---|---|---|
| **A** | **3** | **1** | **2** | **1** | **1.75** |
| **C** | **1** | **2** | **1** | **3** | **1.75** |
| **F** | **2** | **1** | **9** | **6** | **4.5** |
| **D** | **7** | **5** | **3** | **4** | **4.75** |
| **H** | **4** | **1** | **6** | **8** | **4.75** |
| **E** | **5** | **4** | **10** | **5** | **6** |
| **J** | **6** | **7** | **4** | **10** | **6.75** |
| **B** | **13** | **9** | **5** | **2** | **7.25** |
| **G** | **12** | **1** | **13** | **7** | **8.25** |
| **K** | **9** | **6** | **8** | **11** | **8.5** |
| **M** | **8** | **3** | **11** | **13** | **8.75** |
| **I** | **10** | **10** | **7** | **9** | **9** |
| **L** | **11** | **8** | **12** | **12** | **10.75** |

Hospitals are designated A–M to correspond with Hospital designation in Figures 2–5

EE, early extubation; POMV, postoperative mechanical ventilation