Advanced artificial intelligence–guided hemodynamic management within cardiac enhanced recovery after surgery pathways: A multi-institution review

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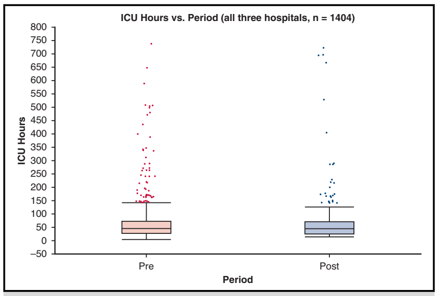
ABSTRACT

Objective: The study objective was to report early outcomes of integrating Hypotension Prediction Index–guided hemodynamic management within a cardiac enhanced recovery pathway on total initial ventilation hours and length of stay in the intensive care unit.

Methods: A multicenter, historical control, observational analysis of implementation of a hemodynamic management tool within enhanced recovery pathways was conducted by identifying cardiac surgery cases from 3 sites during 2 time periods, August 1 to December 31, 2019 (preprogram), and April 1 to August 31, 2021 (program). Reoperations, emergency (salvage), or cases requiring mechanical assist were excluded. Data were extracted from electronic medical records and chart reviews. Two primary outcome variables were length of stay in the intensive care unit (using Society of Thoracic Surgeons definitions) and acute kidney injury (using modified Kidney Disease Improving Global Outcomes criteria). One secondary outcome variable, total initial ventilation hours, used Society of Thoracic Surgeons definitions. Differences in length of stay in the intensive care unit and total ventilation time were analyzed using Kruskal–Wallis and stepwise multiple linear regression. Acute kidney injury stage used chi-square and stepwise cumulative logistic regression.

Results: A total of 1404 cases (795 preprogram; 609 program) were identified. Overall reductions of 6.8 and 4.4 hours in intensive care unit length of stay ($P = .08$) and ventilation time ($P = .03$) were found, respectively. No significant association between proportion of patients identified with acute kidney injury by stage and period was found.

Conclusions: Adding artificial intelligence–guided hemodynamic management to cardiac enhanced recovery pathways resulted in associated reduced time in the intensive care unit for patients undergoing nonemergency cardiac surgery across institutions in a real-world setting. (JTCVS Open 2023;16:480-9)



ICU hours pre–HPI-guided protocol and after introduction of HPI-guided protocol.

CENTRAL MESSAGE

By using AI-enabled hemodynamic monitoring in an ERAS pathway, favorable outcomes could be shown for ICU LoS and AKI.

PERSPECTIVE

This study reveals meaningful information for perioperative care of cardiac surgical patients in a real-world ICU setting. By using automated hemodynamic feedback that is readily available and combining it with enhanced recovery pathways, patients may experience decreased stay in the intensive care unit and AKI after nonemergency cardiac surgery.

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Abbreviations and Acronyms

AI	=	artificial intelligence
AKI	=	acute kidney injury
CPB	=	cardiopulmonary bypass
ERAS	=	enhanced recovery after surgery
HPI	=	Hypotension Prediction Index
ICU	=	intensive care unit
IOH	=	intraoperative hypotension
LoS	=	length of stay
MAP	=	mean arterial pressure
STS	=	Society of Thoracic Surgeons

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Hemodynamic instability and related hypotension are common after cardiotomy procedures. Sustained mean arterial pressure (MAP) values less than 65 mm Hg may have implications for overall outcomes in these challenging patients. Hemodynamic instability and related hypotension also affect the burden on intensive care resources, because it has implications for nursing time and intensity as well as for intensive care physicians. Intraoperative hypotension (IOH) has been associated with adverse postoperative outcomes including acute kidney injury (AKI), myocardial injury, stroke, and mortality after noncardiac surgeries.[1-4] IOH in cardiac surgery also has been correlated with increased risk of AKI, prolonged hospital stays, mortality, and stroke.[5,6] Moreover, cardiac surgery–associated AKI has been associated with prolonged intensive care unit (ICU) and hospital stays, increased morbidity and mortality, and elevated healthcare costs.[7] However, studies comparing methods of avoiding the negative consequences of postoperative hypotension are lacking. In recent years, enhanced recovery after surgery (ERAS) has become increasingly adopted in cardiac surgery centers around the world.[8,9] The goal of ERAS is to decrease variability in care while implementing techniques for best practice.[10] ERAS has been shown in other surgical populations to decrease lengths of stay while simultaneously reducing patient morbidity and improving patient satisfaction.[11] The desire to improve outcomes and shorten lengths of stay has become more important, because ICU and overall hospital resources such as staffing are scarcer after the COVID-19 postpandemic era.

Beginning with the introduction of ERAS into gastrointestinal surgery pathways 25 years ago, fluid and hemodynamic management protocols have more broadly become a core component of ERAS and are used in most surgical pathways today.[12,13] More recently, there has been evidence in the literature of improved patient outcomes by avoiding not just deep and prolonged episodes of hypotension, but cumulative short periods of hypotension, defined as MAP less than 65 mm Hg.[1-4]

Cardiac surgery is thought to be fundamentally different from other areas of surgery because of the need for cardiopulmonary bypass (CPB) in the majority of cases. Intraoperative blood pressure is controlled by a combination of CPB techniques and use of vasoactive drugs, with the disadvantage of nonpulsatile flow, but the advantage of minute-to-minute observation and interventions maintaining steady-state hemodynamics. Essentially all postoperative care begins after cessation of CPB and associated influence on fluid balance, myocardial performance, and vascular tone and reactivity. However, we hypothesized that the addition to our ERAS protocols of hemodynamic management with reduction in the burden of hemodynamic instability would translate into better patient outcomes, with shorter ventilator times and decreased total and ICU lengths of stay.

Acumen Hypotension Prediction Index (HPI) software (Edwards Lifesciences) provides the clinician insight into a patient's hemodynamic stability and trend toward the likelihood of occurrence of a hypotensive event (defined as MAP < 65 mm Hg for at least 1 minute). A computational algorithm using arterial waveform analysis predicts the likelihood of hypotension, presented as a numerical value ranging from 1 to 100. In addition to MAP, other parameters including stroke volume, cardiac output, stroke volume variation, systemic vascular resistance, dP/dt (a proxy for cardiac contractility), and Eadyn (a measure of dynamic elastance) provide input to inform the use of volume, inotropes, or vasopressors to improve hemodynamic stability and prevent the predicted hypotension. Acumen HPI software is used as a bedside clinical decision support tool to supplement the clinician's assessment of the patient's physiological condition.

MATERIALS AND METHODS

The study protocol and data request were reviewed by Institutional Review Board boards at the participating hospitals and determined to be exempt. A Health Insurance Portability and Accountability Act–compliant Data Sharing Agreement was executed between all parties.

This study represents a multicenter, historical control, observational cohort analysis of the implementation of HPI-Guided Hemodynamic Management within existing ERAS pathways. Data for cardiac surgical cases were obtained from 3 hospital intensive care units located in Seattle, Washington, Nashville, Tennessee, and Indianapolis, Indiana.

The hemodynamic management software was introduced at each of the 3 sites beginning March 1, 2021. Therefore, 2 data extraction periods were identified: August 1 to December 31, 2019 (preprogram), and April 1 to August 31, 2021 (program). The periods were specifically chosen to assess postsurgical practice before the impact of the coronavirus pandemic on ICU census (preprogram) and to allow a 1-month implementation period for the Hemodynamic Management system (program). Given the relative stability of the ERAS pathway during the study periods, this study design allowed for an assessment of the adoption of the technology. The same hemodynamic management protocol was used across all institutions. The Acumen technology was used in the ICU only and not in the operating room.

All first-time cardiac surgery cases that occurred during the 2 study time periods were identified. Cases were excluded if identified as emergency or emergency salvage or required mechanical assist devices. Data elements were extracted from electronic medical records using Society of Thoracic Surgeons (STS) definitions, supplemented with chart reviews to clarify data elements at participating sites; de-identified data were provided for statistical analysis using a secure, 1-way (upload only) FTP site. The study data were collected through a combined retrospective and prospective method with the preprogram and program period being conducted retrospectively and prospectively, respectively.

Two primary outcome variables were identified for the study: intensive care unit (ICU) length of stay (LoS) and AKI. A secondary outcome variable was identified as total initial ventilation hours. Both ICU LoS and total initial ventilation hours used STS measure definitions. These outcome variables were analyzed first as the difference in unadjusted mean values between the 2 observation periods using the Kruskal–Wallis test, with a follow-up Welch's *t* test (unequal variances test). Welch's *t* test is generally applied when there is a known or assumed difference between the variations of 2 populations and when their sample sizes are unequal.[14] A stepwise, multiple linear regression model included hospital site and observation period (preprogram and program) with 39 additional confounding variables and 1 interaction term (observation period by hospital site) in modeling.

AKI was measured using the modified Kidney Disease Improving Global Outcomes (KDIGO) criteria (Table 1).[15] The association between observation period and AKI stages (no AKI, stages 1, 2, and 3) was first analyzed using chi-square. This was followed by a stepwise, cumulative logistic regression model of AKI stages (0-3) that included hospital site and observation period (preprogram and program) and the same 39 variables and interaction terms applied for the other analyses.

Data management and statistical analyses were completed using SAS v9.4 (SAS Institute, Inc).

TABLE 1. Acute kidney injury is staged for severity according to the following criteria (not graded)

Stage	Serum creatinine	Urine output
1	1.5-1.9 times baseline OR ≥0.3 mg/dL (≥26.5 μmol/L) increase	<0.5 mL/kg/h for 6-12 h
2	2.0-2.9 times baseline	<0.5 mL/kg/h for ≥12 h
3	3.0 times baseline OR Increase in serum creatinine to ≥4.0 mg/dL (≥353.6 μmol/L) OR Initiation of renal replacement therapy OR, in patients <18 y, decrease in eGFR to <35 mL/min per 1.73 m^2	<0.3 mL/kg/h for ≥24 h OR Anuria for ≥12 h

eGFR, Estimated glomerular filtration rate.

RESULTS

A total of 1404 surgical cases were included in statistical analysis: 795 in the preprogram period and 609 in the program period. There were no differences in the underlying demographic characteristics of the surgical cases between the preprogram and program cohorts (Table 2). The STS predicted morbidity and mortality scores were also not statistically significantly different (Table 2). Among the 11 clinical history characteristics, 2 (heart failure and liver disease) were significantly different between the observation periods, with less heart failure and slightly more liver disease in the program cohort.

Unadjusted Mean Differences in Intensive Care Unit Length of Stay

There was an overall reduction of 6.8 hours in the mean time of ICU LoS for the surgical cases during the program period (64.2 ± 75.74 hours preprogram hours vs 57.4 ± 68.6 hours program). The difference in means was not statistically significant ($P = .078$). Two clinical sites had reductions in ICU LoS; for 1 (Hospital B), the difference was a statistically significant reduction of 17.3 hours ($P = .019$) (Table 3).

Unadjusted Mean Differences in Total Initial Ventilation Hours

Overall, there was a reduction of total initial ventilation hours of 4.4 hours (13.0 hours ± 41.14 hours preprogram vs 8.6 hours ± 33.79 hours program; $P = .030$). All 3 sites experienced a reduction in total initial ventilation hours (Table 3).

Chi-Square Analysis of Acute Kidney Disease Stages

No statistically significant association was found between the proportion of patients identified with AKI by stage and observation period for the 1404 surgical cases in total or at any of the 3 clinical sites (Table 3). There was a 40% relative reduction (absolute reduction 3.0% to 1.8%; $P = .255$) in stage 3 AKI, and all 3 institutions had relative reductions ranging from 0.7% to 1.7% (Table 3).

The change in mean differences for total initial ventilation hours and ICU LoS were largely driven by reductions in the number of surgical cases with 24 hours or more initial time on ventilator and 72 hours or more ICU stay, respectively (Figures 1 and 2). The proportion of cases at or exceeding 24 initial total initial ventilation hours was reduced from 5.4% to 2.8% ($P = .016$). The proportion of surgical cases at or exceeding 72 hours of ICU LoS was reduced from 26.7% of cases to 21.7% of cases ($P = .036$).

Multivariate Analysis of Intensive Care Unit Length of Stay

Stepwise multiple linear regression identified a significant interaction between the program period and hospital site (Table 4). Compared with Hospital C (the referent

TABLE 2. Preprogram and program descriptive variables

Descriptor			HL A	HL B	HL C	All	*P* value of difference
Demographics	Gender Female	Preprogram	33.3%	32.7%	31.0%	32.1%	.678
		Program	33.0%	28.3%	32.1%	31.0%	
	Race non-White	Preprogram	3.0%	26.1%	11.5%	14.9%	.730
		Program	3.5%	26.9%	14.5%	15.6%	
	Non-Hispanic	Preprogram	99.4%	98.6%	99.1%	99.0%	.084
		Program	99.4%	94.3%	100%	97.9%	
	Mean age	Preprogram	65.0	64.5	63.0	64.0	.310
		Program	64.1	64.6	65.0	64.6	
Predicted morbidity and mortality scores	Mean score	Preprogram	0.016	0.018	0.019	0.018	.178
		Program	0.016	0.016	0.018	0.017	
Discharge status	Live	Preprogram	97.6%	98.3%	96.4%	97.4%	.141
		Program	98.8%	98.6%	100%	98.7%	
Clinical history	History: Renal No	Preprogram	98.2%	97.3%	95.5%	96.7%	.055
		Program	99.4%	98.1%	97.8%	98.4%	
	History: HTN No	Preprogram	17.3%	27.2%	14.9%	19.9%	.057
		Program	10.4%	21.7%	14.7%	15.9%	
	History: Db No	Preprogram	61.3%	66.7%	58.6%	62.1%	.144
		Program	56.7%	64.2%	54.0%	58.3%	
	History: PAD No	Preprogram	90.5%	89.4%	89.0%	89.4%	.079
		Program	80.9%	91.0%	86.2%	86.4%	
	History: CVD No	Preprogram	80.7%	77.0%	67.9%	73.9%	.292
		Program	80.9%	78.3%	71.0%	76.4%	
	History: CVA No	Preprogram	92.3%	90.0%	90.8%	90.8%	.755
		Program	91.9%	89.2%	92.9%	91.3%	
	History: MI No	Preprogram	78.0%	70.5%	63.1%	68.9%	.082
		Program	65.9%	68.4%	59.8%	64.5%	
	History: Lung disease No	Preprogram	91.1%	97.3%	79.8%	88.6%	.978
		Program	90.2%	98.6%	77.8%	88.5%	
	History: HF No	Preprogram	70.8%	61.9%	49.4%	58.5%	.005*
		Program	59.0%	64.9%	71.9%	65.8%	
	History: Liver disease No	Preprogram	94.1%	98.6%	87.8%	93.1%	<.005*,†
		Program	96.5%	98.6%	96.4%	97.2%	
	History: AFib >30 d No	Preprogram	97.0%	98.6%	97.9%	98.0%	.257
		Program	93.1%	99.1%	98.2%	97.0%	
	History: AFib ≤30 d No	Preprogram	86.3%	80.8%	87.5%	84.8%	.845
		Program	87.9%	78.3%	87.5%	84.4%	

HL A, Hospital A; *HL B*, Hospital B; *HL C*, Hospital C; *HTN*, hypertension; *Db*, diabetes; *PAD*, peripheral artery disease; *CVD*, cerebral vascular disease; *CVA*, cerebral vascular accident; *MI*, myocardial infarction; *HF*, heart failure; *AFib*, atrial fibrillation. *$P < .05$. †N = 1118 due to missing values.

group), surgical cases at Hospital A had an estimated ICU LoS of 12.5 hours longer on average ($P < .007$), whereas surgical cases at HL B had an estimated 11-hour shorter ICU LoS on average ($P = .01$). One prior medical history variable, having no atrial fibrillation diagnosis, was associated with a shorter ICU LoS of 13.5 hours on average ($P < .001$). Two preoperative variables, left ventricular ejection fraction and hematocrit, were associated with shorter ICU LoS hours, each unit increase in left ventricular ejection fraction was associated with a shorter ICU LoS of 0.85 hours on average ($P < .001$), and each unit increase in hematocrit value was associated with in a shorter ICU LoS of 1.5 hours on average ($P < .001$). As would be anticipated, the experience of postsurgical events, although happening infrequently, were associated with significant increases in ICU LoS (Table 4).

Multivariate Analysis (Acute Kidney Injury Stages)

Stepwise logistic regression identified a significant interaction between the program period and the hospital site (Table 5). Compared with Hospital A and Hospital C, cases at Hospital B had a 1.6 times higher probability of higher AKI stages ($P = .014$). Three prior medical history variables (calculated body mass index, hypertension, and recent atrial fibrillation), 1 procedure type (valve), and 4 postsurgical variables (intubation, pneumonia, gastrointestinal

TABLE 3. Unadjusted primary and secondary outcomes

Primary outcome: ICU LoS (mean hours)					
	Preprogram	52.69	65.67	68.74	64.23
	Program	66.35	48.34	59.01	57.38
	P value	.019*	.019*	.122	.078
Primary outcome: AKI stage (%)					
No AKI	Preprogram	82.7%	83.0%	85.4%	83.9%
	Program	85.0%	77.8%	86.6%	83.1%
Stage 1	Preprogram	11.31%	12.2%	10.2%	11.1%
	Program	10.40%	14.6%	11.2%	12.2%
Stage 2	Preprogram	3.0%	1.7%	1.5%	1.9%
	Program	2.3%	5.7%	0.9%	3.0%
Stage 3	Preprogram	3.0%	3.1%	3.0%	3.0%
	Program	2.3%	1.9%	1.3%	1.8%
	P value	.940	.065	.551	.255
Secondary outcome: total initial ventilation hours (mean hours)					
		HL A	HL B	HL C	All
	Preprogram	8.01	17.52	11.56	12.99
	Program	7.08	9.14	9.36	8.64
	P value	.787	.075	.149	.030*

ICU, Intensive care unit; *LoS*, length of stay (in hours); *AKI*, acute kidney injury; *HL A*, Hospital A; *HL B*, Hospital B; *HL C*, Hospital C. **P* < .05.

event and reoperation) were associated with an increased probability of higher AKI stage. One preoperative variable (higher preoperative hematocrit) was associated with a lower probability of higher AKI stage.

Multivariate Analysis of Total Initial Ventilation Hours

Observation period (preprogram and program) was not a significant factor in total initial ventilation hours (Table 4). Having an atrial fibrillation event within 30 days before surgery was associated with increased total initial ventilation hours by an estimated 6.1 hours ($P = .019$), whereas having no atrial fibrillation event was associated with lower total initial ventilation hours by an estimated 5.5 hours ($P = .003$). Four postoperative events were associated with increased total initial ventilation hours as would be anticipated, with the highest increased hours occurring with postoperative sepsis (145.6 hours; $P < .001$) followed by postoperative encephalopathy with an estimated increase of 83.1 hours ($P < .001$).

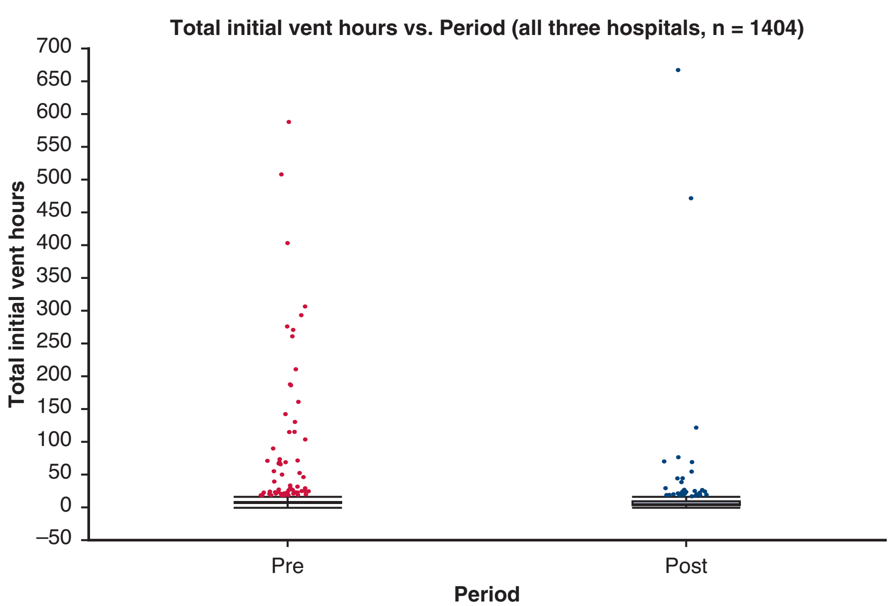

FIGURE 1. Box plot of ICU LoS hours overall. The *lower and upper borders*: 25th and 75th percentiles; *horizontal line*: median of the values; *lower and upper whiskers*: minimum and maximum values of nonoutliers, respectively; *dots*: outlier observations.

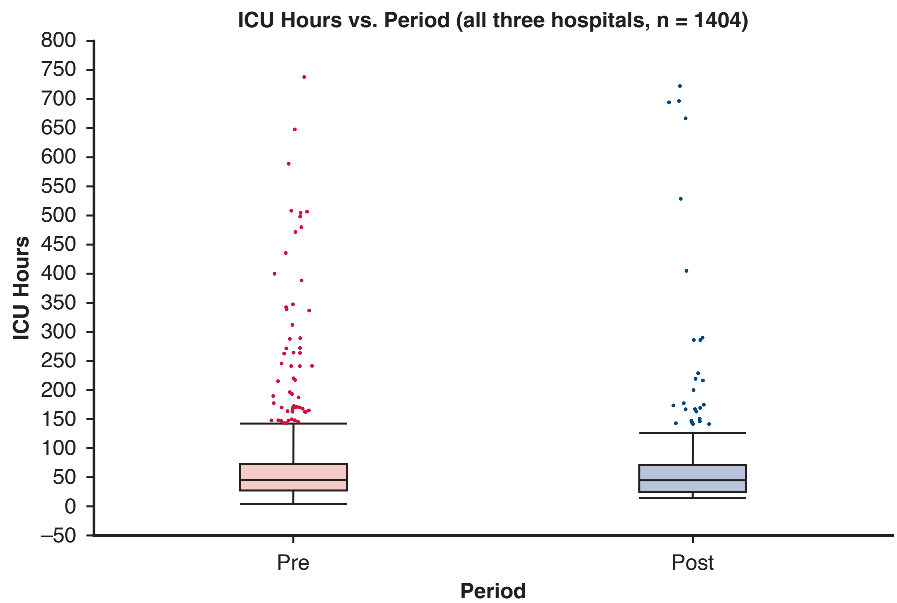

FIGURE 2. Box plot of total ventilation hours overall. The *lower and upper borders*: 25th and 75th percentiles; *horizontal line*: median of the values; *lower and upper whiskers*: minimum and maximum values of nonoutliers, respectively; *dots*: outlier observations. *ICU*, Intensive care unit.

DISCUSSION

Optimal perioperative hemodynamic monitoring and management result in enhanced perfusion of the vital organs and subsequent improvement of the postoperative course by reducing ICU and hospital LoS, and postoperative complications such as AKI, ileus, and pulmonary complications.[16-22] Recent advancements in technology have led to hemodynamic monitoring tools moving away from

TABLE 4. Multiple linear regression analysis of intensive care unit length of stay and total initial ventilation hours

Variable	Estimated difference per 1 unit change	Standard error	*t* value	Pr > |t|
ICU length of stay				
Intercept	159.13	13.14	12.11	<0.001
Program by HL A	12.53	4.63	2.71	0.007
Program by HL B	−10.96	4.26	−2.57	0.010
No AFib noted	−13.50	3.15	−4.28	<0.001
Preoperative left ventricular ejection fraction	−0.85	0.13	−6.50	<0.001
Preoperative hematocrit	−1.53	0.27	−5.60	<0.001
Postoperative ventilation hours indicator	72.23	8.17	8.84	<0.001
Postoperative pneumonia	66.71	9.48	7.04	<0.001
Postoperative delirium	66.53	20.62	3.23	0.001
Postoperative encephalopathy	170.15	11.38	14.95	<0.001
Postoperative sepsis	166.53	18.73	8.89	<0.001
Postoperative AFib	7.53	3.14	2.39	0.017
Postoperative GI event	33.74	7.04	4.80	<0.001
Postoperative reoperation indicator	34.51	6.12	5.64	<0.001
Total initial ventilation hours				
Intercept	63.37	8.33	7.61	<0.001
Age	−0.32	0.08	−4.24	<0.001
No AFib noted	−5.51	1.87	−2.95	0.003
AFib recent (w/in 30 d)	6.13	2.60	2.36	0.019
Preoperative hematocrit	−0.86	0.16	−5.35	<0.01
Postoperative encephalopathy	83.08	6.48	12.82	<0.01
Postoperative sepsis	145.64	10.92	13.34	<0.01
Postoperative GI event	12.448	4.05	3.07	0.002
Postoperative reoperation I	24.73	3.49	7.09	<0.001
ICU readmission	−27.17	4.64	−5.86	<0.001

ICU, Intensive care unit; *HL A*, Hospital A; *HL B*, Hospital B; *AFib*, atrial fibrillation; *GI*, gastrointestinal.

TABLE 5. Logistic regression acute kidney injury stages

Effect	Odds ratio per 1 unit change	95% confidence limits	
Prog_HL B	1.63	1.11	2.39
Calculated BMI	1.04	1.01	1.06
Hypertension	1.70	1.08	2.69
AFib recent (within 30 d)	2.29	1.58	3.30
Preoperative hematocrit	0.92	0.90	0.95
Surgical valve	1.54	1.12	2.13
Postoperative intubation	4.92	2.76	8.77
Postoperative pneumonia	5.60	2.86	10.97
Postoperative GI event	3.83	2.24	6.55
Postoperative reoperation indicator	2.07	1.27	3.38

HL B, Hospital B; *BMI*, body mass index; *AFib*, atrial fibrillation; *GI*, gastrointestinal.

pulmonary artery catheters for lower-risk patients and more widespread adoption of less-invasive techniques such as pulse contour technologies.[23] HPI, a novel technology predicting hemodynamic instability, has been validated in cardiac surgery using an algorithm based on arterial pressure waveforms. This technology can be used to improve hemodynamic management by generating more accurate and actionable artificial intelligence (AI)-produced indices that can be coupled with pathways of care.[6] HPI can be used to predict hypotension after cardiac surgery with a high degree of sensitivity and specificity.[6] Multiple studies have shown that adoption of goal-directed therapy protocols in cardiac surgery improves postoperative outcomes, such as reductions in mechanical ventilation time, hospital and ICU LoS, pulmonary complications, and AKI.[18-22,24-29] On the basis of the existing evidence, ERAS Cardiac Society Guidelines recommend the adoption of Goal Directed Fluid Therapy in the immediate postoperative period to reduce postoperative complications.[10,30,31] The post-CPB period is the most critical phase for the kidneys as hypotension during the postoperative phase of cardiac surgery has been associated with increased risk of renal replacement therapy.[7] Additionally, IOH during CPB has shown to contribute to a higher risk of AKI, mortality, and stroke.[4] In this multicenter study looking at adding AI-enhanced hemodynamic management decision support to standard cardiac surgery ERAS protocols, we showed a decrease in mechanical ventilation times and associated decrease in ICU LoS. Additionally, we noted no difference in overall AKI but relative reduction in more severe (KDIGO Stage 3) kidney injury.

An important adjunct observation imbedded in the data revealed that there were reductions in variability of care. This was demonstrated by the improved clustering of data points and smaller standard deviations around the mean for several important end points. For example, the data plots show that patients with HPI-Guided Hemodynamic Management had a reduction in variability of extubation times (Figures 1 and 2). Variability in care has repeatedly been shown to have adverse effects on overall patient outcomes regardless of the measured end point. If AI-enhanced decision support tools such as HPI can be more widely and uniformly implemented, one can hypothesize that subsequent reductions in variability-associated morbidity will be observed. In addition, this variability reduction was shown across all centers, regardless of size or existing resources.

It has been well documented that appropriate and meticulous fluid management can result in improved ventilation times due to avoidance of overtreating hypotension with large volume of saline or colloidal infusions, which could result in hypoxemia or additional ventilator associated events in the acute postoperative period.[32] Given the higher probability of optimal hemodynamic management benefits to be demonstrated in sicker cases and patients with prolonged ICU stay, another important finding of the study is the significant reduction in the proportion of cases with 24 hours or more initial total initial ventilation hours and the number of surgical cases with 72 hours or more of ICU LoS.

Study Strengths and Limitations

The study has several strengths and limitations. The addition of the HPI-Guided Hemodynamic Management to existing cardiac ERAS pathways was conducted at multiple hospitals located in 3 different geographic regions. This has the benefit of representing more real-world data sets because these hospitals were not uniform in size or resources. Conversely, it has the potential for more confounding of findings given this variation. Additionally, because of the availability of transesophageal echocardiography and other tools in the operating room, the Acumen protocol was used only in the ICU and not the operating room, which might have been a potential confounder.

The pseudo-experimental combined retrospective and prospective design is a limitation. Although the preprogram and program groups at each hospital site were reasonably well matched on demographic variables and the predictive morbidity and mortality scores, possible confounders remain, among them, organizational structure and culture differences that impact implementation of quality improvement projects. Nursing, financial, and administrative resources also may be significantly different between hospitals.

This study took place during the COVID-19 era, with the accompanying reduced staffing and bed resources affecting the study cohort. With restrictions on patient movement out of the ICU, we used the actual time of ICU transfer as the time stamp for the end of ICU stay. This, along with challenges for bed availability throughout most hospital systems, may have adversely affected the true effect on this end point.

Although careful selection of the preprogram and program periods was made in an effort to minimize the impact that the coronavirus pandemic could have, this could not be completely avoided and may have played a major role. The pandemic experience differed at each hospital site in terms of severity and effect, with the first emergence of the coronavirus occurring in later months of the preprogram period and continuing into the program period. Although our ICU intensivists and nurses were educated and adopted the hemodynamic protocols, cultural changes with a high level of compliance take time. Despite continuous efforts to ensure uniform implementation and compliance with the protocols, we may have seen a more powerful effect in all end points if we had waited for a steady-state period postpandemic.

AKI, one of the most common complications in the perioperative phase, has been a major focus in cardiac surgery for the past several years, and many protocols have emerged to reduce its occurrence in the postoperative period.[33,34] Although adoption of the KDIGO bundle of care in high-risk cardiac surgery patients, a recommendation from the Society of Cardiovascular Anesthesiologists, did not

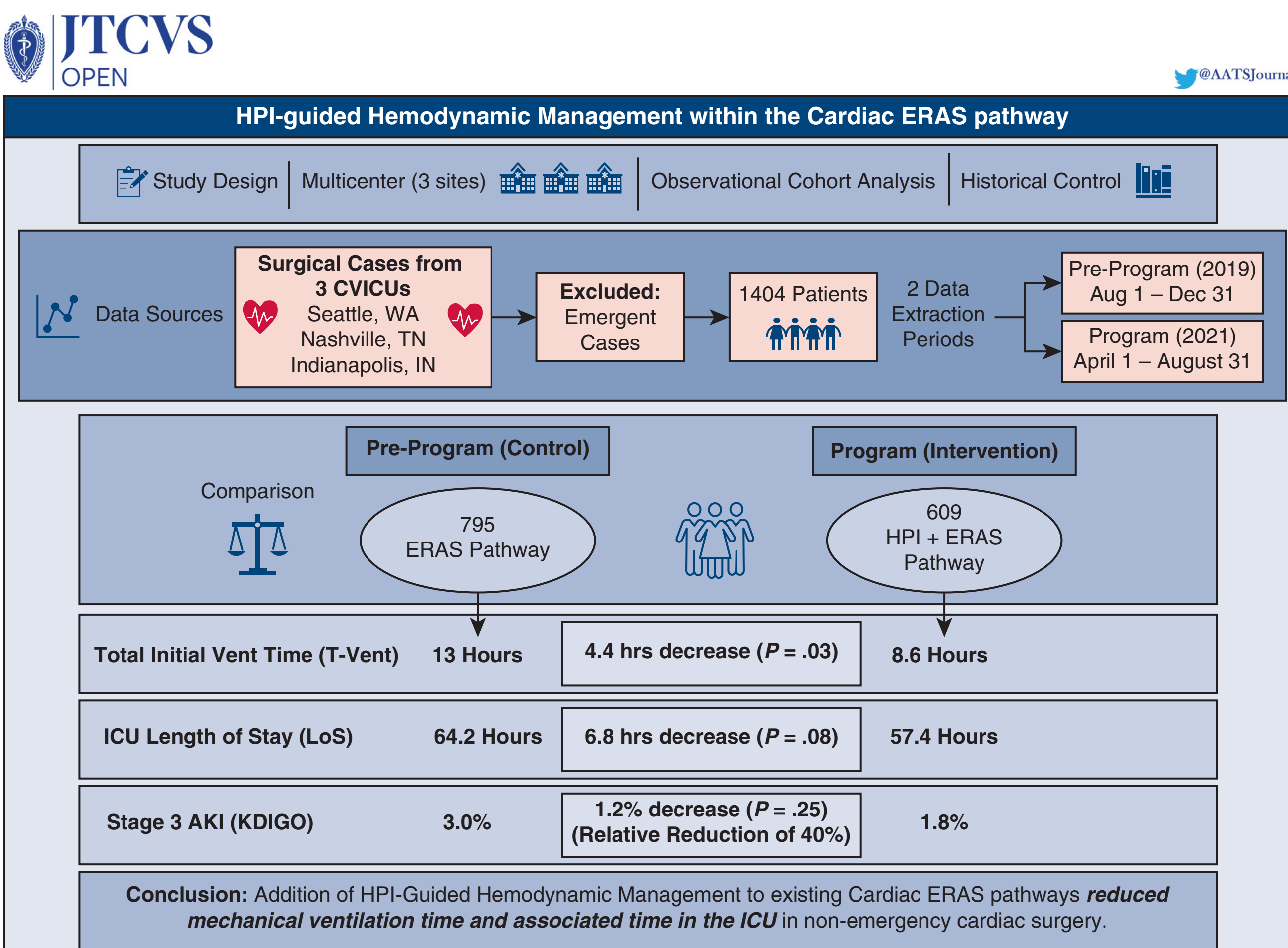

FIGURE 3. HPI guided management. *HPI*, Hypotension Prediction Index; *ERAS*, enhanced recovery after surgery; *CVICUs*, cardiovascular intensive care unit; *ICU*, intensive care unit; *AKI*, acute kidney injury; *KDIGO*, Kidney Disease Improving Global Outcomes.

decrease the overall incidence of cardiac surgery–associated AKI, it resulted in a reduction in moderate to severe (stages 2 and 3) AKI.[35] Postcardiac surgery AKI is usually multifactorial, but sustained hypotension is frequently listed as a primary driver. Hypotension in surgery, defined as absolute and relative values of MAP for sustained periods of time as short as 1 minute, has been associated with increasing the risk of AKI and myocardial damage. Despite the relatively large sample size of this study, the study was not sufficiently powered to determine the statistical significance of the relatively rare complication of stage 3 AKI. More than 5000 patients would be required to determine the significance, or not, of a relative reduction of 40% from a baseline of just 3%. However, AKI is a devastating, costly, and potentially avoidable postoperative harm, and so this is worthy of further investigation. Of note, some of the centers in the study had already adopted the KDIGO bundle pathway of care, which may account for the lack of impact on this variable. Other centers may see a more major effect on AKI if they do not have kidney protection–oriented pathways of care.

CONCLUSIONS

AI-enhanced decision support algorithms for implementation of hemodynamic and fluid management strategies have demonstrated clinical benefits related to mechanical ventilation times, ICU LoS, and AKI in patients undergoing cardiac surgery (Figure 3). A hemodynamic monitoring tool that alerts clinicians to impending hemodynamic instability and provides insights to guide more specific fluid and medication administration may result in decreased variation across providers and centers. In this observational multicenter study, adding an AI-Guided Hemodynamic Management tool to existing cardiac ERAS pathways resulted in reduction in associated time in the ICU for patients undergoing nonemergency cardiac surgery.

Webcast

You can watch a Webcast of this AATS meeting presentation by going to: https://www.aats.org/resources/2967.

Conflict of Interest Statement

V.S.R. is a paid consultant for Edwards Lifesciences. D.S. is a paid consultant for Edwards Lifesciences. C.J. is a paid consultant for Edwards Lifesciences. M.G. is a paid consultant for Edwards Lifesciences. All other authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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