J Extra Corpor Technol. 2019;51:210–20
The Journal of ExtraCorporeal Technology

Does Standardizing Extracorporeal Circuit Design for Cardiopulmonary Bypass Affect Outcomes? Results from a National Perfusion Registry

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Abstract: Standardization of clinical practice is an effective means of reducing unwanted variation and improving safety. There are numerous extracorporeal circuit (ECC) designs in clinical practice which both complicates the conduct of cardiopulmonary bypass (CPB) and increases costs, especially in situations where clinicians may conduct perfusion at more than one center. The current study was undertaken to determine the effect of standardizing ECCs by incorporating new generation devices as part of a pack enhancement project (PEP). Standardization of ECCs in cardiac centers within a national perfusion provider was undertaken to incorporate new generation oxygenators to reduce variation and improve safety among clinicians. The PEP was carried out in adult centers performing cardiac surgery across America. Data were analyzed for 12 months before the change and compared with those of an equal time thereafter. The outcome measures were ECC prime volume, hematocrit (HCT) drift, and transfusion of intraoperative red blood cells (RBCs). The transition time frame took just less than 12 months and included soliciting input from end-users, pack redesign, and education and implementation. Before the PEP, 91 hospitals used 47 different ECC configurations, which was reduced by 83.0% to eight packs. Regression analysis comparing outcomes between PEP and non-PEP patients showed statistically significant but subtle changes. The net prime volume increased slightly in the PEP group (733–750 mL, $p < .001$), whereas RBC transfusions did not vary, and the PEP group had a small reduction in nadir HCT (28.0 vs. 27.5, $p < .001$) and HCT drift (-9.6 vs. -10.25, $p < .001$). A concurrent analysis of 50,135 patients not in the PEP conducted over the same time period showed no change in RBC transfusions. Although small changes in the net prime volume and transfusion rates were seen with the standardization of ECCs, the primary benefit of this initiative was the increased familiarity and continuity of circuit design across sites. **Keywords:** cardiac surgery, cardiopulmonary bypass, allogenic blood transfusion, standardization. *J Extra Corpor Technol. 2019;51:210–20*

One of the most important tenets of cardiovascular perfusion is the design and utilization of a safe and effective extracorporeal circuit (ECC) for the conduct of cardiopulmonary bypass (CPB). Although the cardiac team is responsible for all facets of the surgical procedure, it is most often the perfusionist who is charged with selecting the ECC design using both previous experience and published best practices as foundations. Professional societies, such as the American Society of Extracorporeal Technology (AmSECT), publish standards and guidelines[1] that serve as a basis for multiple facets of perfusion practice. Although these documents are extremely helpful, they do not contain specific directives of the ECC other than the type of safety devices that should be considered. This has resulted in a wide diversity of circuits seen in clinical use, with pediatric perfusion practices having additional modifications based on the size and condition of the patient.

Cardiopulmonary manufacturers of ECCs attempt to meet the demands of perfusionists by providing a wide

Received for publication April 4, 2019; accepted November 25, 2019.
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The senior author has stated that the authors have reported no material, financial, or other relationship with any healthcare-related business or other entity whose products or services are discussed in this paper.

[1]AmSECT, http://www.amsect.org/p/cm/ld/fid=1617.

array of circuit configurations and designs. Despite the similarity of how CPB is conducted among centers, there is little agreement between perfusionists on the exact type of ECCs that should be used. Some institutions may even have individual practitioners who use different circuitry for the same cardiac procedures being performed. Such lack of standardization is costly, resulting in higher charges for customized circuits and more importantly, may affect patient safety when staff are required to use equipment that they may not be familiar with. This may be even more challenging for perfusionists who travel to several hospitals where the type of ECCs may vary. The following study was undertaken with emphasis on safety to reduce unwanted variation by standardizing the type of perfusion ECCs used in clinical practice for adult cardiac surgery with CPB and is termed the pack enhancement project (PEP). The entire cardiac team contributed to this process, with the perfusionists consulting with physicians, nursing staff, and administration. The study was designed to test the hypothesis that the PEP would result in improved a net prime volume and reduced intraoperative transfusion of red blood cells (RBC), and reduce the decline in hematocrit (HCT) during CPB.

METHODS

A review of the ECC packs at a large out-sourced perfusion provider (SpecialtyCare [SC], Brentwood, TN) was conducted to determine the breadth and distribution of circuit configurations in use. A systematic review of the circuit configurations was carried out by members of the SC medical department and a list of common features seen among the packs determined. These items were categorized according to the importance of each component of the circuit using safety and performance as the two highest indicators for inclusion. There were 31 factors assessed for the analysis, which included the type of the primary arterial pump (centrifugal or roller), the type of the cardioplegia circuit, the diameter and length of tubing, the presence of ancillary "sucker" and "vent" lines, whether ultrafiltration (UF) was used, and a miscellaneous category that included items such as stop cocks, connectors, and pressure monitoring lines.

A taskforce made up of perfusion associates who were end-users of the circuits was established and met on a weekly basis to design and review appropriate circuitry using the requirements stated earlier. Circuit schematics were designed and sent to several cardiopulmonary device manufacturers, who then created circuit prototypes based on the requirements and sent them to SC for examination. These were reviewed by the taskforce and placed on heart–lung machines located in a simulation laboratory that was identical to a standard cardiac surgical operating room. Modifications to the circuit design were made and the changes sent back to the manufacturers for redesign. This entire process was repeated several times until suitable circuit configurations were agreed on. After this, each manufacturer constructed a lot of sterile circuits (50) that were then sent to test hospitals for evaluation. Surveys were sent to the perfusion associates at the test hospitals concerning the ECC, and the results were tabulated and reviewed by the taskforce. Once consensus was reached on further modifications to the circuitry, a final configuration was determined which was then sent to hospitals that participated in the process. Once the pack design was completed and the new ECC made available, members from the medical department traveled to each hospital to educate the perfusion team on the new ECC.

Study Design

The sequential study was conducted over a 24-month period at participating hospitals performing adult cardiac surgery, where the cardiac team agreed to evaluate a standardized ECC. All surgical patients older than 18 years who underwent a cardiac procedure requiring CPB were included. No effort was made to standardize blood management protocols across facilities. The anesthesia and perfusion teams were responsible for administering crystalloid and/or colloid solutions to maintain hemodynamic stability during the surgical procedure. Specific transfusion algorithms were not standardized across centers. Instead, individual clinical teams made decisions regarding transfusion of blood products. Patients were excluded from the analysis if they did not have all required quality indicators recorded, or if they had missing data.

Study Groups

Each hospital served as its own baseline for data collection. The study groups were determined on the ECC use with time delineation as the pre-pack change (Pre-CH) and post-pack change (Pst-CH). The study time period was from January 1, 2017 through December 31, 2018. The Pre-CH period was approximately January 1, 2017 through June 30, 2017, with individual sites adopting a standardized ECC at unique dates within this window. Each hospital was provided with the new packs, and a 30-day transition time was implemented where data were not included in the study. This buffer period was used to provide the end-users with an opportunity to become familiar with the new circuitry. The Pst-CH period was from approximately from July 1, 2017 through December 30, 2018, again with slightly different post-buffer dates, marking the beginning of the Pst-CH period at each site. Hospitals were included in the final analysis if there were more than 50 procedures performed at each hospital with the new packs after the change had been made. A second evaluation was completed based on hospitals that initially made the change yet decided to revert to the Pre-CH circuitry and are identified as the

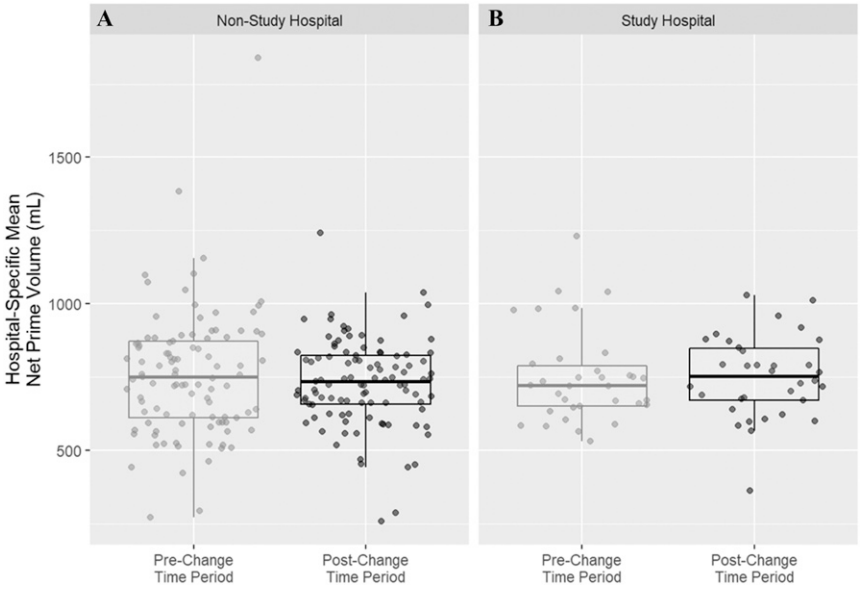

Figure 1. Mean change in the net prime volume. (A) Non-study hospital: concurrent time period for 101 hospitals not involved in the PEP. (B) Study hospital: 34 hospitals where pack standardization was performed. The thick middle line represents the median, and lower and upper edges of each box represent 25th and 75th percentiles, respectively. The "whiskers" extending from the top and bottom have a length that is 1.5 times the inter-quartile range; that is, they are 1.5 times the distance between the 25th and 75th percentiles for a given group of data points.

reversion (REV) group. Hospitals in the REV group were included in the final analysis if there were more than 50 procedures performed during the initial pack change and thereafter.

Once the distribution of pack configurations was made, a review of perfusion records contained within the SC Operative Procedure rEgistry (SCOPE™) was conducted. SCOPE was established as a national quality control database for systematically collecting intraoperative data from cardiac surgical procedures and serves a multifunctional purpose focused on performance improvement. Institutional ethics review board approval[2] was obtained for this study.

Endpoints

The primary endpoint was the net volume used to prime the CPB circuit, with secondary endpoints including the intraoperative transfusion of allogeneic RBC, and the change in HCT was defined as the first in room HCT minus CPB nadir HCT and is also termed HCT drift. For the purposes of regression analysis, HCT drift was re-operationalized as nadir HCT on CPB while controlling for the first HCT in room, to ensure statistically valid results.

Statistical Analysis

Descriptive statistics, determined within site-level transfusion performance subgroups, were calculated as the count and percentage for categorical variables, and mean and SD for continuous variables. Data are described as mean and SD unless otherwise specified. Unadjusted group differences were assessed using chi-squared tests and Welch's ANOVA.

Regression analyses were conducted using a mixed-effects linear regression. To rigorously assess the relative importance of site- and patient-level factors related to the likelihood of transfusion, our statistical model controlled for the following confounding variables identified elsewhere in the cardiac surgery literature: individual-level patient physiology (age, gender, and estimated circulating blood volume [via the Nadler formula], first HCT on arrival to the OR, and first HCT during CPB), procedure-based characteristics (non-elective acuity and duration of the bypass run), and assorted factors associated with intraoperative management of patient physiology (net priming volume of the ECC, asanguineous volume added by anesthesia and perfusion, urine output on CPB, and UF volume removed). A generic statistical control was also added to account for hospital-specific tendencies in outcomes of interest. Variables with missing data were excluded from all analyses. All analyses were completed using the R statistical computing environment (1) in conjunction with "tableone," "lme4," and "sjPlot" packages (2–4).

RESULTS

Before the start of the PEP, 91 hospitals used 47 different ECC configurations. The total time for the PEP and transition to the new packs occurred over 6 months. A total of 74 hospitals agreed to participate in the PEP and transitioned to the new ECC. There was a reduction in the total number of pack configurations by 61.8% to 18 packs.

[2]Protocol #12017, ADVARRA, Center for IRB Intelligence, 6940 Columbia Gateway Drive, Suite 110, Columbia, MD 21046.

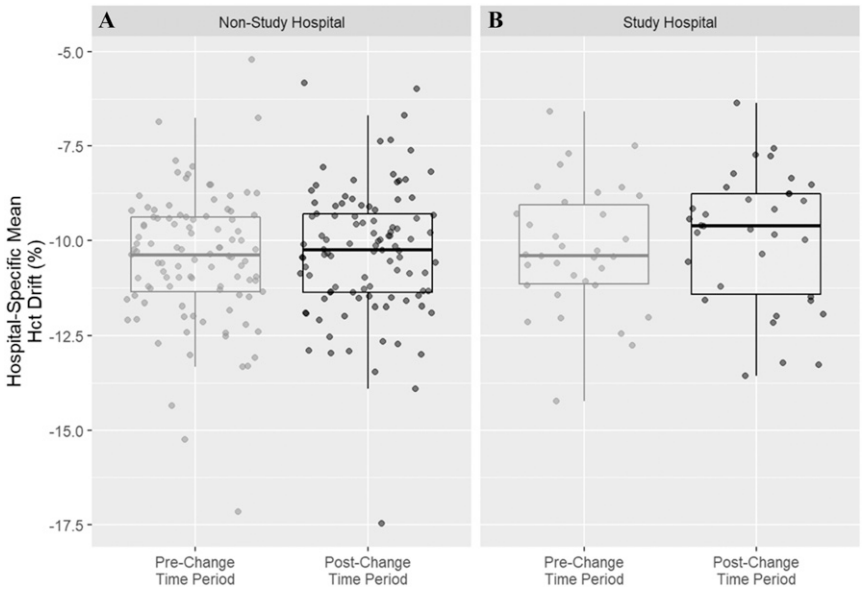

Figure 2. Mean change in HCT drift. (A) Non-study hospital: concurrent time period for 101 hospitals not involved in the PEP. (B) Study hospital: 34 hospitals where pack standardization was performed. HCT drift: the change from the first HCT in the operating room to the lowest CPB HCT. The thick middle line represents the median, and lower and upper edges of each box represent the 25th and 75th percentiles, respectively. The "whiskers" extending from the top and bottom have a length that is 1.5 times the inter-quartile range; that is, they are 1.5 times the distance between the 25th and 75th percentiles for a given group of data points.

However, the pack configurations were almost identical in 11 of the remaining packs, with only minor specification changes (inclusion of second ancillary packs such as an UF or vacuum-assisted venous drainage kit and use of a 3/8-inch or ½-inch venous line), which resulted in a total of eight new configurations for an overall reduction by 83.0% (Figures 1–3).

A total of 34 hospitals performed more than 50 procedures once the pack change had been made. There were 5,746 historical cases in the Pre-CH cohort compared with 5,702 Pst-CH cases. There were very minor differences between groups in demographics and operative characteristics, with the Pst-CH group having very slight increases in estimated blood volume, larger body surface area (BSA), and a higher number of male patients (Table 1). The net prime volume increased slightly in the Pst-CH group from 733.0 (272.0) mL to 749.6 (251.8) mL, $p < .001$ (Table 2). There was a statistically significant but clinically small decrease in intraoperative RBC transfusions in the Pst-CH group (.37 vs. .42 units, $p = .05$), along with a smaller HCT drift (-9.96 vs. -10.25, $p < .001$). There was a higher usage of UF (38% vs. 29%, $p < .001$), and more UF volume was removed (490 vs. 393 mL, $p < .001$) in the Pst-CH group as well.

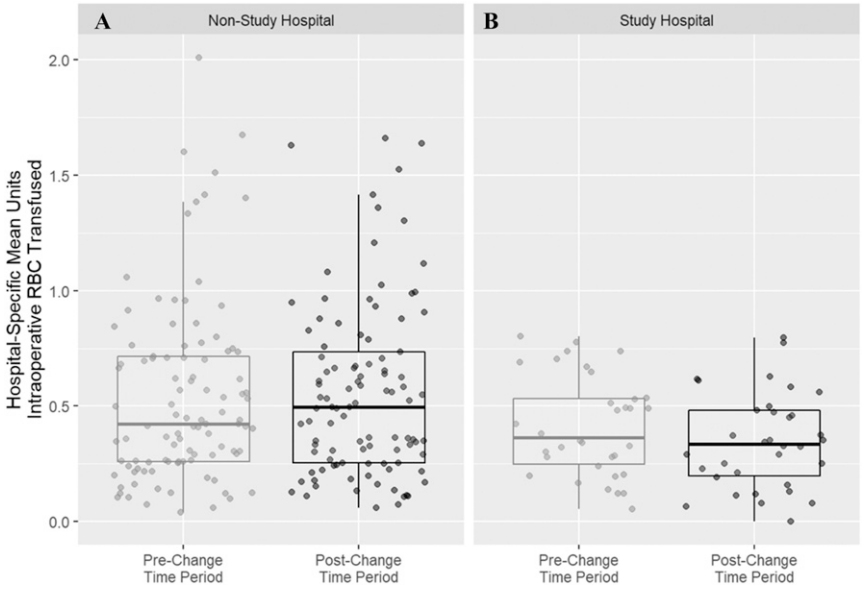

Figure 3. Mean change in RBC transfusion. (A) Non-study hospital: concurrent time period for 101 hospitals not involved in the PEP. (B) Study hospital: 34 hospitals where pack standardization was performed. The thick middle line represents the median, and lower and upper edges of each box represent the 25th and 75th percentiles, respectively. The "whiskers" extending from the top and bottom have a length that is 1.5 times the inter-quartile range; that is, they are 1.5 times the distance between the 25th and 75th percentiles for a given group of data points.

Table 1. Descriptive statistics for patients in each hospital group.

n	Pre-CH (n = 5,746)	Pst-CH (n = 5,702)	*p* Value
Male (%)	4,034 (70.2)	4,132 (72.5)	.008
Age (years), mean (SD)	65.1 (11.4)	64.8 (11.8)	.155
Height (cm), mean (SD)	172.0 (10.3)	172.3 (11.1)	.100
Weight (kg), mean (SD)	89.6 (20.1)	90.3 (21.0)	.065
BSA, mean (SD)	2.02 (.24)	2.03 (.25)	.049
Nadler total blood volume, mean (SD)	5.26 (.95)	5.30 (.98)	.013
Procedure type (%), count (%)	–	–	.007
Aortic surgery	122 (2.1)	146 (2.6)	–
AV surgery + CABG	373 (6.5)	420 (7.4)	–
CABG reoperation	59 (1.0)	58 (1.0)	–
Combined AV/MV surgery	74 (1.3)	57 (1.0)	–
Isolated AV surgery	541 (9.4)	523 (9.2)	–
Isolated CABG	3,677 (64.1)	3,730 (65.5)	–
Isolated MV surgery	301 (5.2)	227 (4.0)	–
MV surgery + CABG	129 (2.2)	112 (2.0)	–
Other	463 (8.1)	425 (7.5)	–

AV, aortic valve; CABG, coronary artery bypass graft; MV, mitral valve; Pre-CH: pre-change; Pst-CH: post change.

A concurrent analysis of 50,135 patients at 101 hospitals not involved in the PEP was conducted over the same time period, with 24,045 cases performed concurrently with the Pre-CH group and 26,090 in the Pst-CH period (Appendices 1 and 2). This provided a benchmark for comparison related to changes that may have occurred overtime. Although there was a slight but significant decline in the net prime volume (8 mL from the pre-change to post-change time periods, there were no differences in RBC transfusions. The HCT drift was significantly lower and decreased by approximately .25% over both time periods.

Regression Results

After controlling for known correlates of our stated outcomes, the Pst-CH group had a statistically significant but very small reduction in HCT drift (.23%, $p < .001$), whereas there was no difference between groups from pre to post in the average number of units of allogeneic RBC transfused intraoperatively (Appendix 3). The Pst-CH group also had a small and statistically significant increase in the net CPB circuit priming volume (32.6 mL, $p < .001$).

Descriptive Analysis of REV Group

After several months, 12 hospitals (16.2%) switched back to the Pre-CH packs, with six hospitals performing over 50 procedures during the pack consolidation period; these six comprise the REV group for analysis. The decision to revert was made by members of the cardiac team who reported that the initial change in the ECC was not conducive to their operative process, which was most often a decision made by the surgeon. There was, however, no report that there were any safety-related issues or that the new ECC was ineffective. A total of 1,951 packs were used at the six centers that used the packs for an average of 5 months (range, 3–11 months), before changing back to the Pre-CH circuits. For the REV group, a total of 1,422 packs were used after the REV. Outcomes on these cases were compared with 2,100 historical control cases conducted before the initial pack consolidation trial period. The results of the REV groups are shown in Table 3, with the average values for each of the six programs summarized in Figures 4–6. The net prime volume reduced by approximately 70 mL but continued to decline by an additional 20 mL after REV (Figure 4), with a similar observation seen

Table 2. Comparison between Pre-CH and Pst-CH variables.

n	Pre-CH (n = 5,746)	Pst-CH (n = 5,702)	*p* Value
Net prime volume (mL), mean (SD)	733.0 (272.0)	749.6 (251.8)	.001
Intraoperative RBC units, mean (SD)	.42 (1.23)	.37 (1.19)	.050
HCT drift, mean (SD)	−10.25 (4.01)	–9.96 (3.92)	<.001
First HCT in OR %, mean (SD)	36.1 (5.6)	36.4 (5.6)	.018
First HCT on CPB %, mean (SD)	27.5 (4.9)	28.0 (5.0)	<.001
UF use, count (%)	1,664 (29.0)	2,158 (37.8)	<.001
UF volume (mL), mean (SD)	393.2 (765.3)	489.8 (788.4)	<.001
Asang. fluid added during CPB (mL), mean (SD)	566.5 (698.5)	537.5 (639.8)	<.001
Asang. fluid added by anesthesia (mL), mean (SD)	1,609.8 (761.1)	1,661.4 (791.7)	.021
Crystalloid cardioplegia (mL), mean (SD)	462.0 (451.7)	529.7 (509.2)	.001

Asang, asanguineous; HCT drift, change from the first HCT in the operating room to the lowest CPB HCT.

Table 3. Comparison of the REV group between pre-change, post-change, and REV time periods.

n	n = 2,100	n = 1,951	n = 1,422	*p* Value
Net prime volume (mL), mean (SD)	809.8 (241.5)	735.5 (203.4)	716.0 (198.7)	<.001
Intraoperative RBC units, mean (SD)	.41 (1.03)	.35 (.98)	.33 (1.07)	.037
HCT drift, mean (SD)	10.3 (3.9)	−10.1 (3.8)	−10.1 (3.8)	.299

HCT drift, change from the first HCT in the operating room to the lowest CPB HCT.

in RBC transfusion, which reduced by .06 U per procedure and continued to decline by .03 U following the change back to the original ECC (Figure 5). The HCT drift did decline during the initial change and remained at a lower level once the REV occurred (Figure 6).

DISCUSSION

The present study reports the effects of standardizing the use of perfusion packs for CPB across a large number of American hospitals where adult cardiac surgery was performed. Although only modest benefits could be seen with regard to intraoperative RBC use and change in HCT, other aspects of this research are noteworthy. This is the first study to attempt to reduce inter-hospital variability in the use of ECCs incorporating the latest technologies in circuit features and oxygenator design. Increased variation in clinical practice may lead to an increased chance for error, which could not only potentially harm patients, but also lead to excessive medical costs. The Institute of Medicine has identified variability in the delivery of health care as one of the greatest opportunities to improve quality and reduce costs through process improvement and standardization (5). The importance of reducing unwanted variation is evident throughout all aspects of the healthcare system, and the Centers for Medicare and Medicaid Services has identified standardizing process measures that are focused on specific features such as safety, timeliness, effectiveness, efficiency, equity, and patient centeredness (6). Few would argue that standardizing perfusion circuitry would not improve safety and increase operating room efficiencies. Perfusionists have traditionally designed and implemented ECC componentry that were customized to facilitate both personal preference and patient need. Whereas there is a paucity of information regarding the results for standardizing perfusion circuitry, we have previously reported that efforts to control variability in perfusion practice will result in improved outcomes (7).

The conduct of CPB could be considered as a "sterile cockpit" made up of the heart–lung machine and ECCs (8). Effective communication in this environment among members of the cardiac team is essential, especially when the focus is on the exchange between the surgeon and perfusionist (8). Such communication would be enhanced if the perfusionist is comfortable with the ECC and associated complex technological tasks surrounding the application of CPB. This may be especially important in situations where perfusionists travel between several discordant hospitals and are required to operate heart–lung machines with which they have limited familiarity. In the present-day environment where the shortage of staff perfusionists has resulted in a proliferation of companies providing temporary relief, having a standardized ECC would mitigate some of the challenges associated with movement from hospital to hospital.

One important aspect of the PEP was to shift the use of oxygenators from those which required an external arterial line filter to those that contain an integrated arterial filter. We have previously shown that these newer generation oxygenators are superior to older systems with regard to gas transfer and to improving patient outcomes (9). Although it was surprising that the net prime volume was slightly, but significantly, increased in the Pst-CH group, it was not completely unexpected. One of the integrated arterial filter oxygenators[3] had a static prime volume that was slightly higher than many older oxygenators, although the prime volume of the arterial line filter required in the latter devices results in higher total circuit volumes. Also, the entire ECC was reconfigured so the higher net prime volume reflected the totality of the circuit as opposed to a single component. The concurrent analysis of cases performed at centers not in the PEP revealed a small but significant drop in net prime volume (9 mL) over the study period, which was only 5 mL higher than in the Pst-CH group. A similar finding was observed in the HCT drift from the first HCT in the operating room to nadir CPB. Although there was a significant improvement in HCT drift, this was also observed in the concurrent analysis of 50,135 patients at 101 hospitals, implying that the trend for reduced hemodilution was occurring elsewhere outside the study centers. Interestingly, this was not the case with the distribution of RBC transfusions, where the study hospitals had significant declines that were not seen in the non-PEP analysis.

Although the emphasis of this PEP was based on improving the safe conduct of CPB by standardization of

[3]Inspire 8F, LivaNova, Arvada, CO.

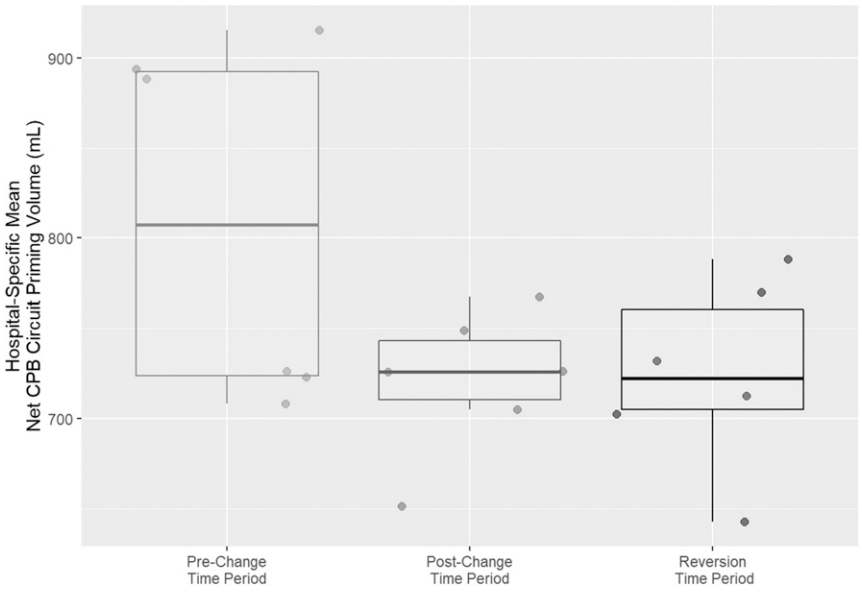

Figure 4. Net prime volume in six hospitals for pre-change, post-change, and REV in extracorporeal circuitry to the original pack. The thick middle line represents the median, and lower and upper edges of each box represent the 25th and 75th percentiles, respectively. The "whiskers" extending from the top and bottom have a length that is 1.5 times the inter-quartile range; that is, they are 1.5 times the distance between the 25th and 75th percentiles for a given group of data points.

ECCs across a wide range of hospitals, a secondary benefit may have been improving economic value, although this was not demonstrated in our study. Manufacturers of cardiopulmonary perfusion products are challenged to construct numerous circuit configurations, which creates logistical complexities and results in increased costs that are passed on to the end-user. Hospital supply expenses form the second largest expense category after payroll and may be an easier target for improving cost efficiency compared with payroll (10). In surgery-intensive hospitals, supply expenses can be as high as 30–40% of total hospital expenses (10). Standardizing circuits allows for a more efficient production process that creates consistencies in the manufacture and assembly of cardiopulmonary products. Supply chain management is further improved both from a distribution and hospital management perspective. Inventory control is improved on multiple levels, which include contract negotiation, ordering, billing, and inventory management. Perfusion packs require significant space for storage both in distribution warehouses and in operating rooms where they are placed in close proximity to the cardiac surgical theater. Reducing the type and number of

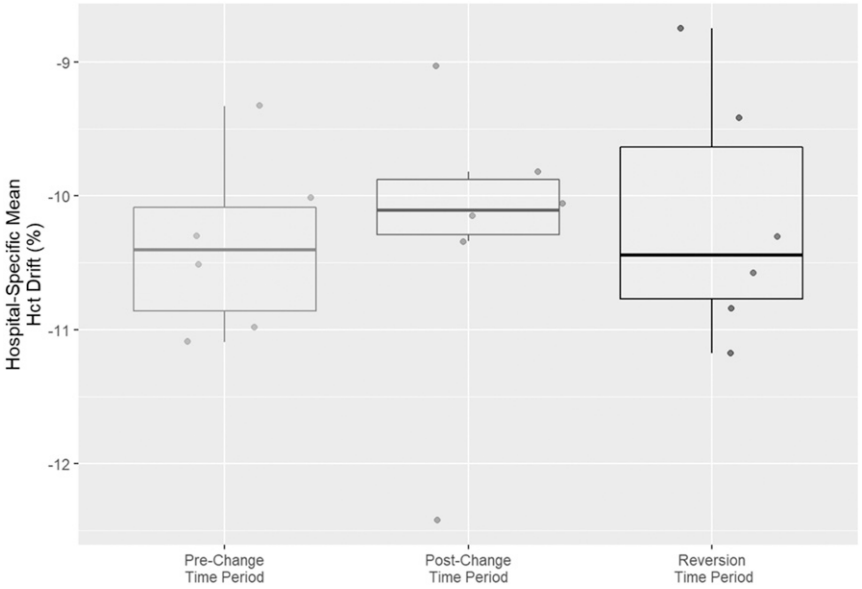

Figure 5. HCT drift (first in room HCT minus nadir CPB HCT) in six hospitals for pre-change, post-change, and REV in extracorporeal circuitry to the original pack. HCT drift: change from the first HCT in the operating room to the lowest CPB HCT. The thick middle line represents the median, and lower and upper edges of each box represent the 25th and 75th percentiles, respectively. The "whiskers" extending from the top and bottom have a length that is 1.5 times the inter-quartile range; that is, they are 1.5 times the distance between the 25th and 75th percentiles for a given group of data points.

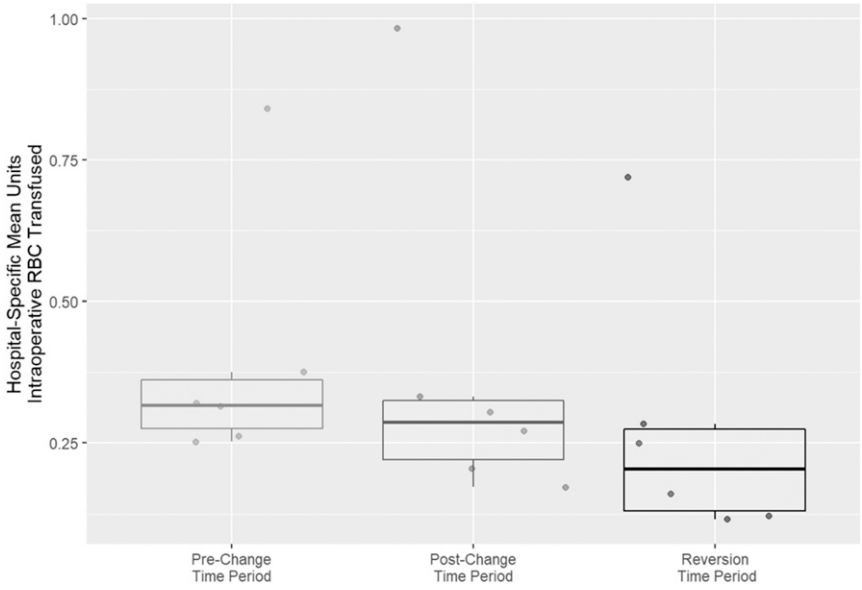

Figure 6. Intraoperative RBC transfusion in six hospitals for pre-change, post-change, and REV in extracorporeal circuitry to the original pack. The thick middle line represents the median, and lower and upper edges of each box represent the 25th and 75th percentiles, respectively. The "whiskers" extending from the top and bottom have a length that is 1.5 times the inter-quartile range; that is, they are 1.5 times the distance between the 25th and 75th percentiles for a given group of data points.

perfusion packs in hospitals is desirable, especially because just-in-time inventory management plans are implemented to improve efficiencies and reduce costs. We did not choose to analyze any cost savings associated with pack standardization because of the diverse nature of contract negotiations that occur at the numerous hospitals involved in this analysis.

Several important observations are apparent in our analyses. First, this study represents the effects of moving beyond a local hospital-centric approach to a more global scale of standardization. Completing a study of this magnitude at a single or small group of hospitals would be difficult. Outsourced perfusion providers have the distinct benefit of economies of scale where broad changes, focused on improving quality and enhancing outcomes, can be implemented. Furthermore, the use of a national registry on perfusion interventions (SCOPE) allows for a rapid analysis of outcomes across multiple facilities when process changes are implemented. Manufacturers of cardiopulmonary perfusion products will also benefit from standardization because they no longer have to spend resources at a local level, but can centralize their efforts nationally, dealing with fewer individuals, which results in quicker, more efficient decision-making. And finally, although there were only minor benefits in reducing net prime volume and lowering intraoperative RBC transfusions, in the six hospitals where there was a REV to the previous circuit, continued positive direction for improvement was observed. Perhaps in these centers, the focus on standardization and change elicited a functional catalyst for quality improvement. Proof of the safety and economic benefits of the reduced variability resulting from our PEP remains to be demonstrated in future studies.

Limitations

The present study has limitations. This study was conducted using a national registry of data collected in a prospective, but non-randomized manner. Registry data do not permit the investigation of certain factors that may be pertinent in determining effects not found with limited variable analysis. We chose not to limit the study to a specific procedure group but include all operations. Because of this, we cannot rule out some of these differences that may have been procedure specific, related to bleeding or other surgical conditions. Transfusion guidelines were not standardized across and within individual hospitals, so the administration of RBC may have been biased by clinical decisions. The retrospective study design is subject to limitations of inherent selection bias, and the reported results are limited to describe observed associations between the implementation of the described protocol and the improved patient outcomes and do not demonstrate a direct cause-and-effect relationship. All results are limited to short-term intraoperative outcomes, and intermediate or long-term follow-up data were not available. This was not a longitudinal study, so the effect of postoperative blood management cannot be accounted for in these analyses. And finally, there exists a potential for the miscoding of data, which despite steps for validation must be considered in any secondary analysis of registry data.

CONCLUSIONS

The standardization of extracorporeal circuitry used for CPB was facilitated by the concerted efforts of a focused taskforce charged with creating a universally accepted pack with broad application in adult cardiac surgery. Although

minor benefits were seen in reducing intraoperative transfusion rates of RBCs, the reduction in variation created a process that improved familiarity with a critical aspect of CPB.

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitude to the perfusion associates of SpecialtyCare who participate daily in the quality improvement process that improves patient outcomes for working on this project to standardize care.

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Appendix 1. Descriptive statistics for patients in a concurrent time period for study from hospitals where no pack change had occurred.

n	Pre-Change Time Period (n = 24,045)	Post-Change Time Period (n = 26,090)	*p* Value
Male (%)	17,004 (70.7)	18,246 (69.9)	.053
Age (years), mean (SD)	64.9 (12.3)	65.0 (11.9)	.255
Height (cm), mean (SD)	171.3 (10.8)	171.4 (10.6)	.199
Weight (kg), mean (SD)	87.4 (20.8)	87.8 (21.0)	.086
BSA, mean (SD)	1.99 (.46)	1.99 (.25)	.764
Nadler total blood volume, mean (SD)	5.17 (.97)	5.18 (.98)	.227
Procedure type (%), count (%)	–	–	.001
Aortic surgery	792 (3.3)	900 (3.5)	–
AV surgery + CABG	1,683 (7.0)	1,710 (6.6)	–
CABG reoperation	259 (1.1)	256 (1.0)	–
Combined AV/MV surgery	376 (1.6)	442 (1.7)	–
Isolated AV surgery	2,605 (10.8)	2,581 (9.9)	–
Isolated CABG	13,819 (57.5)	15,440 (59.2)	–
Isolated MV surgery	1,444 (6.0)	1,521 (5.8)	–
MV surgery + CABG	630 (2.6)	621 (2.4)	–
Other	2,412 (10.0)	2,591 (9.9)	–

AV, aortic valve; CABG, coronary artery bypass graft; MV, mitral valve; Pre-CH: pre-change; Pst-CH: post change.

Appendix 2. Comparison between patients in a concurrent time period for study from hospitals where no pack change had occurred.

n	Pre-Change Time Period (n = 24,045)	Post-Change Time Period (n = 26,090)	*p* Value
Net prime volume (mL), mean (SD)	763.3 (297.5)	755.36 (250.3)	.001
Intraop RBC units, mean (SD)	.51 (1.40)	.52 (1.52)	.593
HCT drift, mean (SD)	−10.30 (4.38)	−10.05 (4.44)	<.001
First HCT in OR %, mean (SD)	36.0 (5.7)	36.8 (5.9)	.001
First HCT on CPB %, mean (SD)	27.1 (4.9)	27.2 (5.0)	<.001
UF use, count (%)	11,845 (49.3)	12,988 (49.8)	<.001
UF volume (mL), mean (SD)	683.3 (918.7)	6,678 (899.1)	<.068
Asang. fluid added during CPB (mL), mean (SD)	521.3 (654.4)	524.4 (675.3)	.600
Asang. fluid added by anesthesia (mL), mean (SD)	1,521.9 (708.1)	1,524.4 (742.6)	.705
Crystalloid cardioplegia (mL), mean (SD)	482.9 (514.0)	462.9 (526.3)	<.001

Asang, asanguineous; HCT drift: change from the first HCT in the operating room to the lowest CPB HCT.

Appendix 3. Random effects linear regression results.

	Lowest HCT on CPB			Intraop RBC Units Transfused			Net ECC Prime Volume		
	Estimates	95% CI	*p* Value	Estimates	95% CI	*p* Value	Estimates	95% CI	*P* Value
Fixed effects									
Intercept	3.7	3.35 to 4.05	<.001	3.88	3.75 to 4.02	<.001	929.23	894.37 to 964.08	<.001
Study hospital	.07	−.39 to .53	.754	.01	−.15 to .17	.867	−4.99	−65.61 to 55.62	.872
Within study post window	.12	.07 to .18	<.001	0	−.02 to .02	.906	−19.11	−23.20 to −15.02	<.001
Estimated blood volume (Nadler)	1.15	1.12 to 1.18	<.001	−.07	−.08 to −.06	<.001	−1.32	−3.68 to 1.04	.273
First HCT in operating room	.48	.48 to .49	<.001	−.05	−.05 to −.04	<.001	−2.29	−2.64 to −1.95	<.001
Lowest HCT on CPB	–	–	–	−.05	−.05 to −.04	<.001	–	–	–
Female	−.85	−.91 to −.78	<.001	−.03	−.05 to .00	.065	.66	−4.36 to 5.69	.796
AV surgery with CABG	−.26	−.42 to −.10	.002	−.73	−.80 to −.67	<.001	−67.62	−79.74 to −55.51	<.001
CABG reoperation	−.37	−.64 to −.11	.006	−.58	−.68 to −.47	<.001	−32.99	−53.34 to −12.65	.001
Combined AV/MV surgery	.51	.26 to .75	<.001	−.67	−.77 to −.57	<.001	−74.47	−91.95 to −56.98	<.001
Isolated AV surgery	.7	.55 to .86	<.001	−.88	−.94 to −.81	<.001	−77.93	−89.37 to −66.49	<.001
Isolated CABG	.09	−.05 to .23	.204	−.81	−.87 to −.75	<.001	−66.33	−76.69 to −55.97	<.001
Isolated MV surgery	.8	.63 to .97	<.001	−.86	−.93 to −.79	<.001	−77.77	−90.22 to −65.32	<.001
MV surgery with CABG	−.19	−.39 to .02	.076	−.61	−.69 to −.52	<.001	−59.81	−74.97 to −44.65	<.001
Other	.58	.42 to .74	<.001	−.48	−.55 to −42	<.001	−39.94	−51.60 to −28.28	<.001
UF volume	0	.00 to .00	<.001	0	.00 to .00	<.001	–	–	–
UF used	–	–	–	–	–	–	17.33	12.35 to 22.32	<.001
Asanguineous volume added on CPB	0	−.00 to −.00	<.001	0	.00 to .00	<.001	–	–	–
Anesthesia asanguineous volume	0	−.00 to −.00	<.001	0	.00 to .00	<.001	–	–	–
Crystalloid cardioplegia	0	−.00 to −.00	<.001	0	−.00 to −.00	.02	–	–	–
Total urine (mL)	0	.00 to .00	.028	0	−.00 to .00	.093	–	–	–
Study hospital * within study post window	.23	.11 to .35	<.001	.01	−.04 to .05	.816	32.61	23.42 to 41.81	<.001
Random effects									
Hospital intra-class correlation coefficient		.19			.15			.39	

Effect for each procedure type is defined relative to non-reoperative CABG.
Hosptial intra-class correlation coefficient represents the proportion of total variance in the outcome attributable to differences between hospitals.
*Indicates and interaction effect.