

Blood and Blood Product Conservation: Results of Strategies to Improve Clinical Outcomes in Open Heart Surgery Patients at a Tertiary Hospital

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Presented at the 55th AmSECT International Conference, Boston, Massachusetts, April 29 to May 2, 2017.

Abstract: Blood product usage is a quality outcome for patients undergoing cardiac surgery. To address an increase in blood product usage since the discontinuation of aprotinin, blood conservation strategies were initiated at a tertiary hospital in Oakland, CA. Improving transfusion rates for open heart surgery patients requiring Cardiopulmonary bypass (CPB) involved multiple departments in coordination. Specific changes to conserve blood product usage included advanced CPB technology upgrades, and precise individualized heparin dose response titration assay for heparin and protamine management. Retrospective analysis of blood product usage pre-implementation, post-CPB changes and post-Hemostasis Management System (HMS) implementation was done to determine the effectiveness of the blood conservation strategies. Statistically significant decrease in packed red blood

cells, fresh frozen plasma, cryoprecipitate, and platelet usage over the stepped implementation of both technologies was observed. New oxygenator and centrifugal pump technologies reduced active circuitry volume and caused less damage to blood cells. Individualizing heparin and protamine dosing to a patient using the HMS led to transfusion reductions as well. Overall trends toward reductions in hospital length of stay and intensive care unit stay, and as a result, blood product cost and total hospitalization cost are positive over the period of implementation of both CPB circuit changes and HMS implementation. Although they are multifactorial in nature, these trends provide positive enforcement to the changes implemented. **Keywords:** blood conservation, cardiopulmonary bypass, CPB equipment, heparin dose response titration. *J Extra Corpor Technol. 2017;49:273–282*

Patients undergoing open heart surgeries (OHSs) requiring cardiopulmonary bypass (CPB) frequently receive transfusions of various blood products, such as packed red blood cells (PRBCs), platelets, and plasma. Blood usage in this patient population is the highest and the most varied of any type of surgery (1). The complex disease state and compounding comorbidities of the patients are direct contributors to the varying nature of the amount and type of blood products that a patient will receive in the perioperative period. Other factors, such as hemodilution and coagulation factor activation, can also contribute to the need to transfuse in patients both intraoperatively and

postoperatively (1). Transfusion rates in OHS are widely varying and multifactorial.

Although transfusions can be a lifesaving necessity at times, they have been linked with deleterious perioperative outcomes. Many publications (2–6) have documented worse outcomes with regard to mortality and morbidity. These trends have been associated even with low-volume (1–2 units) transfusions. The risk of mortality increases with each unit transfused to the patient (3,5). This translates to increased risk to patients who receive blood product transfusions in the perioperative cardiac surgery timeframe. Transfusions, although necessary at times, add risk to the complex cardiac surgery patient.

Patient dilution and coagulation factor activation while undergoing cardiac surgery with CPB can lead to intraoperative transfusions. The dilution factor can be controlled through addressing the volume given to the patient at all phases of care, including the prime volume of the perfusion circuit. Optimizing the CPB circuit with the perfusion and surgical teams can reduce overall hemodilution

Received for publication May 3, 2017; accepted August 6, 2017.
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The senior author has stated that this project was supported by a grant from Medtronic.

due to prime volume. Looking at items such as line lengths and device optimization can allow for prime volume reductions. Also, the coating that is used on the circuit, especially the oxygenator because of the large surface area of the fiber bundle, is of great impact. Using a bioactive coating has been seen to reduce trauma to blood components such as platelets, white blood cells, and red blood cells while undergoing CPB. This reduction in trauma has been seen to impact blood transfusions, morbidity, mortality, post-operative recovery, and length of stay (7–12). Use of advanced CPB circuits that reduce dilution and trauma to extracorporeal blood have been proven to reduce transfusion rates.

The protocol for dosing and management of heparin varies from facility to facility. Society of Thoracic Surgeons/Society of Cardiovascular Anesthesiologists (STS/SCA) 2011 guidelines require a minimum of activated clotting time (ACT) performed while on CPB with the recommendation for active monitoring of heparin levels especially in cases lasting longer than 2 hours. They also recommend that higher heparin levels are maintained in longer cases to reduce hemostatic system activation. Lastly, with regard to protamine, they recommend a 50% initial reversal dose or protamine titration for more accurate reversal to reduce bleeding and transfusion rates (13). Using individualized heparin management has been studied and shown to use more heparin and less protamine than traditional ACT-only monitoring and results in less transfusions and bleeding complications (14–16). More precise heparin management using the patient-specific heparin dose response (HDR), heparin concentration, and ACT during cardiac surgeries can help (17–21) preventing thrombus formation and preserving clotting factors by reducing the activation of the clotting cascade, resulting in reduction of the need for replenishing platelets and clotting factors. A large cohort study (22) has failed to demonstrate the benefit of using HDR data for reliable heparin dose management when treating to an ACT level of 480 seconds. These studies were referenced in the design of our Hemostasis Management System (HMS) protocol for implementation.

With the goal of improving clinical outcomes, blood conservation strategies were initiated at the Alta Bates Summit Medical Center in Oakland, CA, in 2015. The existing Affinity NT™ Oxygenator was upgraded to one with a more effective hemocompatibility design. The new improved design of the Affinity Fusion™ oxygenation system has been shown to be gentler on blood and blood components in bench-top testing (23). In early 2016, the HMS was implemented to enhance point-of-care anticoagulation monitoring during CPB and align with STS recommendations. The HDR, ACT, and heparin–protamine titration (HPT) levels were monitored and maintained for the duration of all CPB cases.

In this retrospective study, the benefits of using advanced technologies in oxygenation and anticoagulation for open-heart surgery patients were analyzed. The oxygenation and anticoagulation system upgrades were phased in over 2015 and 2016 with both concurrently in place starting in February 2016. Results provided the latest up-to-date evidence for the different CPB technologies and will assist health care providers in making future clinical decisions for CPB practices.

MATERIALS AND METHODS

This is a retrospective chart review study comprised of OHS patients in a tertiary hospital in Oakland, CA, who underwent CPB, from 2014 to 2016. The local Institutional Review Board approved this retrospective study on January 19, 2017. Data used in the analysis include information collected in the STS database, as well as clinical data extracted from the patients' electronic medical record. Demographics, laboratory results, blood, and blood products [such as platelets, cryoprecipitate, and fresh frozen plasma {FFP}] usage data were analyzed to determine the clinically realized usage reductions and cost savings, and improved clinical outcomes.

All open-heart surgery patients, including aortic valve replacement, mitral valve replacement, dual valves, valve/CABG (coronary artery bypass graft), aneurysm repair, and CABG procedures, who have undergone CPB were included. Both minimally invasive and full open surgical procedure patients were included. However, patients treated with the transcatheter aortic valve replacement, and patients who had emergency type A aortic dissection repair requiring more than 12 units of blood and blood products were excluded from the study. The final Limited Data Set used in the analysis consisted of a total of 718 patients. Analysis was done to identify any comorbidity factors that could influence blood and blood product usage for CPB patients. It was determined that patients with such comorbidity factors did not skew any changes in blood and blood product usage to influence any of our conclusions to be made.

The first strategy to improve blood and blood product conservation was to upgrade the CPB oxygenation system. Although both the old and new designs were coated with the same Carmeda®, now Cortiva®, bioactive surfaces, the new Affinity Fusion Oxygenation System™ has a smaller, integrated arterial filter and bubble trap. The size of the centrifugal pump head is reduced by upgrading to the Affinity CP™. Blood flow path length through the oxygenation system is also reduced from 11 to 3 cm. Together with these technology upgrades and with the inlet tubing size decrease from 1/2" to 3/8", the priming volume was reduced by approximately 360 mL. Moreover, venous

reservoir and oxygenator unit designs were improved to create slower velocity, and smooth and uniform flow distribution resulting in minimum turbulence and reduced static hold up. Slower velocity and minimum turbulence reduces shear stress that can cause red blood cell damage (24). Reduced static hold up prevents coagulation activation and blood clot formation.

The guidelines for blood transfusions during CPB did not change during the study period. Preparations during preoperative period did not change. Patients were required to discontinue antiplatelet and anticoagulant therapies. Antiplatelet function tests (such as P2Y₁₂% inhibition or reaction unit values) were conducted. Patients were reminded not to consume excess fluids. During the procedure, noninvasive cerebral oximetry was used for early detection of cerebral hypoxia-ischemia. Use of intraoperative cerebral oximetry monitoring is associated with relatively improved mortality outcomes (25) and postoperative cognition (26,27). Cerebral oximetry monitoring was done in every cardiac case at the medical center to assess adequacy of tissue oxygen delivery. If hematocrit (HCT) is less than or equal to 20, an evaluation for transfusing PRBC would be initiated. Cerebral oximetry and CPB pump volume status would be key factors in consideration for transfusion. Both hemodynamic and symptomatic transfusion guidelines were maintained during this study in both baseline and treatment arms. No thromboelastography analysis was done.

The second strategy to improve blood product usage was to change the hemostasis management strategy from point-of-care ACT-only monitoring to the use of the HMS. Test results from ACT-only monitoring have previously been shown to correlate poorly with plasma heparin levels during CPB (17). The HMS uses the HDR for bolus heparin dosing, and HPT along with ACT for heparin level management and protamine reversal.

All patients, during the study period, without change, were treated to a target ACT level of 550 seconds to ensure

that the 480 seconds threshold would be met before initiating CPB. This decision was made referencing other studies that showed that the HMS failed to meet the 480 seconds threshold for bypass initiation when 480 seconds was directly targeted (22). For anticoagulation management using point-of-care ACT, a weight-based formula was used to predict the amount of heparin to administer at a level of 400 units/kg. Protamine reversal administration was based on the amount of heparin administered during the case, on the average ratio of 1:1, to an ACT value at or below baseline. Patients, whose heparinization was based on their HDR (target of 550 seconds) to determine their optimal heparin concentration, were treated to that level throughout the case and reversed with the predicted protamine dose provided by the HPT cartridge on the HMS. Protamine reversal was verified after dosing using a final HPT to ensure no circulating heparin remained. If any bleeding was noticed at the surgical field, another titration was run to determine the additional protamine dose needed for reversal. No transfusion triggers were changed over the period studied.

RESULTS

During the study period, there was no change in the cardiothoracic surgeons in the medical center, and no other significant changes in the support staff. Table 1 shows the demographics of the 718 CPB patients from 2014 through 2016. As can be seen, patients treated in this tertiary hospital are diversified, and no ethnic group is more than 50% of the total population. Table 2 shows the racial distribution of the CPB patients during baseline, oxygenator upgrade only, and both oxygenator and HMS upgrade periods. Age, race, sex, body mass index (BMI), HCT, and hemoglobin (Hb) were similar across all groups. In the same table, it is shown that there is an increase in dialysis patients in the oxygenator-only upgrade period, but it is

Table 1. Demographics of OHS patients who had undergone CPB from 2014 through 2016. Patient count over the 36-month study period shows a diverse patient population. African Americans and Pacific Islanders showed higher percentage of patients on dialysis, and elevated creatinine. Pacific Islanders showed higher average BMI.

Race	Count	Ave Age	% Female	BMI (kg/m ²)	% on Dialysis	Ave Preop Hb (g/dL)	Ave Preop HCT (%)	% Preop INR > 1.2	Ave Preop Creatinine (mg/dL)	Ave Total RBC Used (units)
White	298	66	29.5	28.2	3.0	13.0	38.0	11.7	1.20	2.03
Black	127	63	44.0	28.9	10.2	11.9	36.2	17.3	1.84	2.46
Asian	144	66	27.1	24.8	3.5	12.9	38.3	8.3	1.36	2.40
Hawaiian/Pacific Islanders	13	57	23.1	35.3	15.4	13.1	41.1	7.7	1.93	1.77
Other	120	62	30.0	29.1	7.5	12.7	37.6	11.7	1.36	2.22
Unknown	11	63	36.4	28.4	0	16.2	35.0	9.1	.82	2.55
Prefer not to answer	5	67	60.0	32.9	0	13.2	39.6	20.0	1.24	1.40
Total/Ave	718	65	31.9	28.0	5.3	12.8	37.7	12.2	1.38	2.21

INR, International Normalized Ratio.

Table 2. Demographic comparison of the reference and two implementation periods. Similar averages with regard to the key demographics across each period. The only value of note is during the oxygenator-only upgrade period, there was elevated creatinine as to be expected with higher percentage of patients on dialysis.

	White (%)	Black (%)	Asian (%)	Hawaiian/ Pac Islanders (%)	Ave Age (yrs)	% Female	BMI (kg/m ²)	% on Dialysis	Ave Preop Hb (g/dL)	Ave Preop HCT (%)	% Preop INR > 1.2	Ave Preop Creatinine (mg/dL)
Baseline (January 1, 2014 to July 31, 2015)	41.98	18.27	18.77	2.22	64	32.4	28.2	4.2	12.9	37.9	10.4	1.27
Oxygenator Upgrade (August 1, 2015 to January 31, 2016)	44.33	18.56	19.59	1.03	65	29.9	28.2	11.4*	12.5	37.2	15.5	1.72**
Oxy and HMS Upgrade (February 1, 2016 to December 31, 2016)	39.35	16.20	22.69	1.39	65	31.9	27.5	4.6	12.8	37.5	13.4	1.42
Overall (January 1, 2014 to December 31, 2016)	41.50	17.69	20.06	1.81	65	31.9	28.0	5.3	12.8	37.7	12.0	1.38

*Significant % increase from baseline.

** $p = .0096$.

similar before and after that time. This higher incidence of dialysis patients presents an expected elevated serum creatinine during that time interval. When both post-implementation periods are averaged, this trend diminishes. No significant changes in demographics are observed among the three different periods, with exception of the peak dialysis and creatinine in the oxygenator implementation period which does not impact the blood utilization trend analysis.

Comorbidities that Could Affect Blood Product Usage

Comorbidity analysis indicated that both end-stage renal disease on dialysis and small BMI can affect blood and blood product usage for CPB patients. See Tables 3 and 4. However, the number of patients on dialysis and fluctuations in BMI were evenly distributed throughout the study period, such that blood and blood product usage analysis will not be skewed by any of these patients. See Figures 1 and 2.

During the study period, there were no significant changes in the bypass time, cross-clamp time (Figure 3), suggesting that

complexities of the OHS cases may not have changed. Any small decrease in cross-clamp and bypass time shown could not contribute to significant changes in blood and blood product transfusions. Also, cell salvage usage protocol was not changed, and overall average cell saver volume remained consistent throughout the different study periods. See Figure 4.

Effects of Oxygenator System Upgrade

Perfusion system upgrade began in June and July 2015, with complete conversion to the new advanced

Table 4. Effects of BMI are shown for patients over the 36-month period. Although the smaller BMI (normal weight) patients seem to have slightly worse average preoperative lab values and slightly higher blood product usage, none of the values are statistically significant ($p > .05$), except for total PRBC usage, where overweight patients showed statistically significant lower usage when compared with the normal weight patients.

Table 3. Effects of renal failure comorbidity on blood product use are shown. Patients in dialysis have significantly worse pre-operative lab results and more blood product usage, and have longer hospital and ICU stays creating higher hospital costs.

	Patient Not on Dialysis	Patient on Dialysis	<i>p</i> -Value
Ave preop Hb (g/dL)	12.9 ± 2.2	10.7 ± 1.8	<.0001
Ave preop HCT (%)	38.3 ± 5.4	32.6 ± 5.1	<.0001
Ave preop Creatinine (mg/dL)	1.0 ± .6	7.1 ± 3.2	<.0001
% INR > 1.2 preop	10.58%	21.05%	
Ave IntraOp PRBC Units	.37 ± 1.25	.89 ± .99	.001
Ave Total PRBC Units	1.91 ± 2.55	3.82 ± 2.62	<.0001
Ave IntraOp Platelets (units)	.74 ± 1.15	1.63 ± 1.51	<.0001
Ave OHS Time (hrs)	3.5 ± 1.5	4.0 ± 1.8	.029
Ave ICU Stay (hrs)	60.7 ± 50.6	89.6 ± 71.6	.001
Ave Hospital Cost (normalized)	1.0 ± .3	1.46 ± .7	<.0001

	Normal BMI	Overweight	Obese
BMI	<25	25 ≤ BMI < 30	≥30
Patient count	258	228	232
Ave BMI	22.3 ± 1.9	27.2 ± 1.5	35.0 ± 4.7
Ave preop Hb	12.5 ± 2.0	12.8 ± 1.9	13.0 ± 2.6
Ave preop HCT	37.1 ± 5.5	37.7 ± 5.6	38.3 ± 6.0
% preop INR > 1.2	11.6%	9.2%	15.1%
Ave preop creatinine	1.32 ± 1.6	1.53 ± 2.0	1.29 ± 1.6
% Intraop RBC	29.8%	21.1%	23.3%
Ave intraop RBC	.64 ± 1.1	.48 ± 1.1	.50 ± 1.1
Ave total RBC	2.48 ± 2.8	2.00 ± 2.3*	2.13 ± 2.8
Ave intraop platelets	.56 ± .8	.52 ± .8	.48 ± .8
Ave total platelets	.96 ± 1.3	.86 ± 1.1	.84 ± 1.3
Ave intraop cryoprecipitate	.48 ± 1.0	.50 ± 1.0	.47 ± .9
Ave total cryoprecipitate	1.20 ± 1.8	1.19 ± 1.8	1.20 ± 1.9
Ave intraop FFP	.42 ± 1.0	.38 ± .9	.40 ± 1.1
Ave total FFP	.74 ± 1.4	.61 ± 1.2	.71 ± 1.7
Ave Surgery time	3.4 ± 1.4	3.6 ± 1.7	3.7 ± 1.5
Ave ICU hours	70.0 ± 85.2	60.6 ± 48.4	64.4 ± 46.3
Ave normalized hospital cost	1.06 ± .49	1.0 ± .38	1.04 ± .40

* $p < .05$, compared with normal weight value.

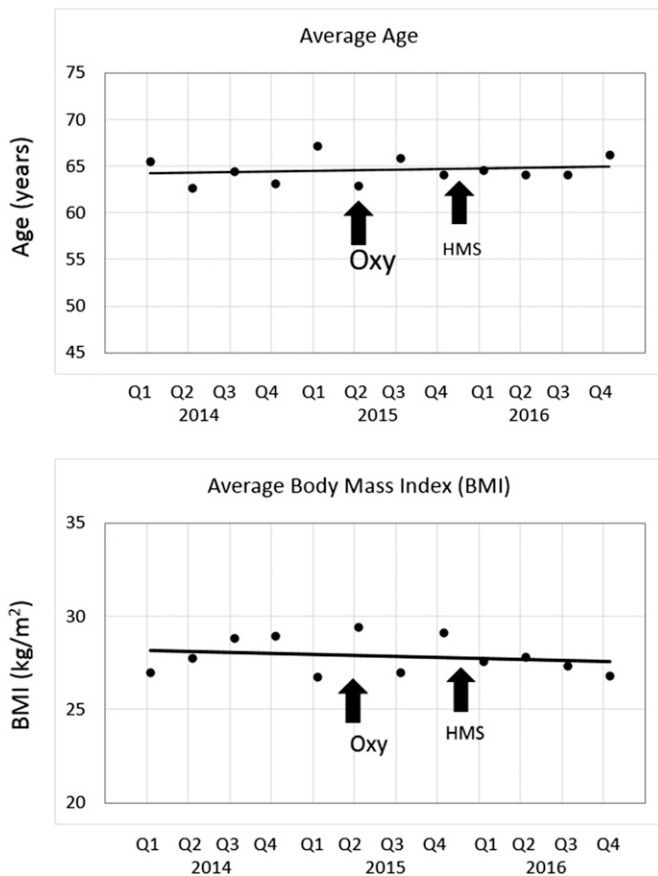


Figure 1. Age and BMI (averaged over each calendar quarter) for the on-pump OHS patients are shown. No significant fluctuations in BMI were observed that would skew the blood and blood product usage analysis. Black arrows indicated when oxygenator system upgrade (Oxy), and both oxygenator and HMS anticoagulation monitoring system upgrades (HMS) were completed.

CPB system in August 2015. With reduction in blood flow path length and size, as well as smaller active circuitry, quarterly average prime fluid usage, plotted in Figure 5, showed a decrease that was coincident with the system upgrade. No new techniques such as acute normovolemic hemodilution nor retrograde autologous priming were used during the study period. Figure 6 shows the intraoperative PRBC rate of transfusion trend from 2014 to 2016. As can be seen, statistically significant reduction in the average rate of transfusion is observed from 26.7% down to 22.7% after the perfusion upgrade ($p = .0211$). Another significant decrease in blood usage was observed after the anticoagulation methodology was changed in February 2016 and was decreased to an average of 8.8% ($p = .0017$).

Effects of HDR Anticoagulation Approach

Heparin management using point-of-care ACT-only monitoring was upgraded to the HMS in February 2016.

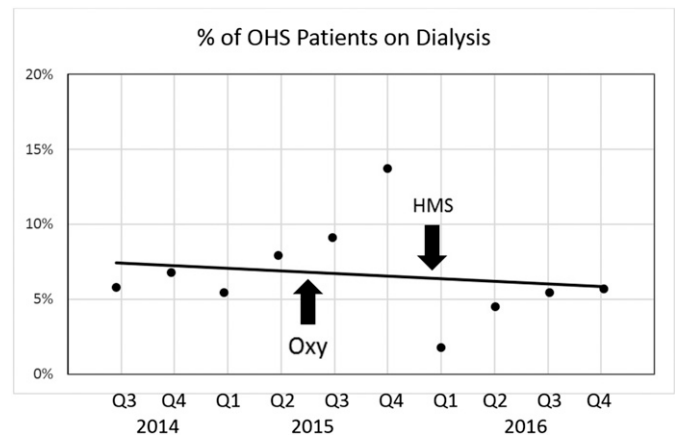


Figure 2. Percentage of patients who are on dialysis because of end-stage renal disease diagnosed before the OHS. Overall average of dialysis patients was similar, except for a significant increase in late 2015, in the post-oxygenator implementation, which can be explained by lower patient numbers.

Figure 7 shows the quarterly average heparin usage where a significant drop was observed when HDR is used to predict a patient's specific heparin management. Average heparin usage decreased from $56,903 \pm 16,543$ units to $43,796 \pm 13,629$ units, with the upgrade in anticoagulation management ($p < .0001$).

Quarterly average protamine usage trend is shown in Figure 8. Average protamine dose per patient for reversing the heparin anticoagulation was reduced from 340 ± 119 mg down to 183 ± 70 mg ($p < .0001$) after the HMS was implemented.

When ACT is used for anticoagulation monitoring, percentage of cases where platelets were transfused averaged at 50.5%. See Figure 9a. After the HMS upgrade was complete, the percentage of cases where platelets were transfused decreased down to an overall average of 22.2% ($p < .0001$).

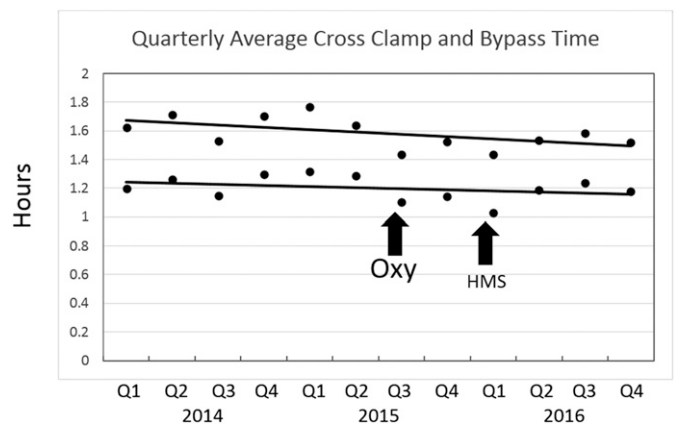


Figure 3. Average cross-clamp and bypass time in hours are shown. Although there were slight downward trends in the quarterly averages, cross-clamp and bypass time did not change significantly across the study period, to suggest case complexities changes.

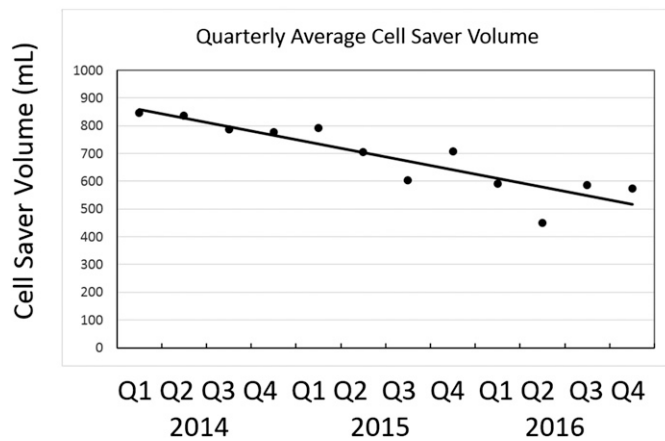


Figure 4. Quarterly average cell saver volume is shown. There were no changes in cell salvage usage during the study. As can be seen, overall average cell saver volume remained consistent throughout the time interval, with a nonsignificant decreasing trend that would not contribute to overall changes in transfusion rates.

Quarterly average of number of units of platelets per patient is shown in Figure 9b. As can be seen, quarterly average number of platelet units given intraoperatively decreased from .63 down to .12 units ($p < .0001$). Overall usage (intra- and postop) per patient showed a constant downward trend since the beginning of 2014. Similar downward trends were also observed for both cryoprecipitate and FFP usage. (Fit to linear model: intraop $R^2 = .7916$, $R^2 = .8931$; total $R^2 = .8603$, $R^2 = .8699$, respectively.) See Figures 10A and 10B.

Intensive care unit (ICU) hours of stay and hospital length of stay in days are shown in Figures 11A and 11B. Gradual decrease in ICU time and length of stay were observed along the study period, but the system upgrades did not seem to trigger any statistically significant changes in these two parameters. Minimal change was observed for

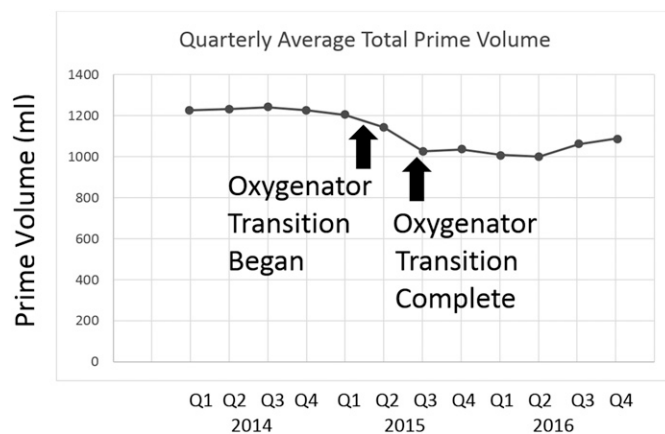


Figure 5. Total prime fluid volume used on average per quarter. Prime volume reductions are illustrated by the changes that occurred in the timeframe from June to August 2015, when the new oxygenation system was phased in.

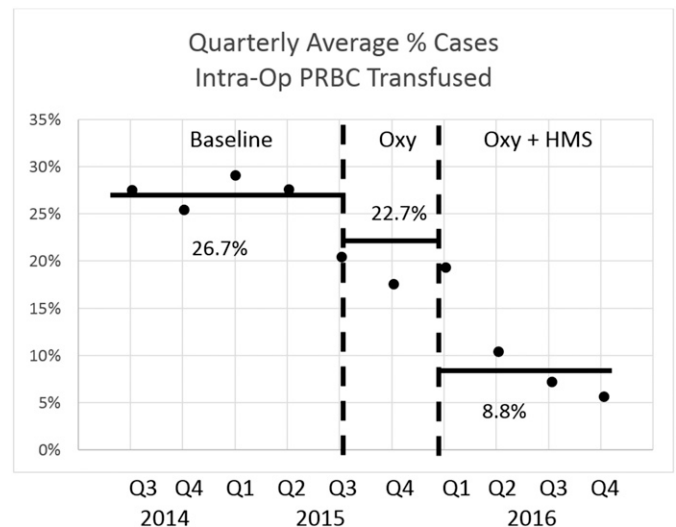


Figure 6. Intraoperative PRBC transfusion average per quarter are shown. Statistically significant reduction in intraoperative transfusion rates can be seen with both stepwise implementations of technology upgrades. Change from baseline to oxygenator upgrade took place in June 2015. Average percentage of cases requiring intraoperative PRBC transfusion dropped from 26.7 to 22.7% ($p = .021$). Change of anticoagulation monitoring from ACT to the use of the HMS took place in February 2016. Average percentage dropped from 22.7 to 8.8% ($p = .0017$).

ICU hours, but the quarterly average length of stay decreased from 9–10 days to less than 7 days. Table 5 illustrates the average percent reduction in blood product and total hospitalization cost per patient per study period. The percent reductions are based on data pulled from Epic medical record accounting pages, representative of the medical center. There is a significant decrease in cost from the reference period to the oxygenator implementation

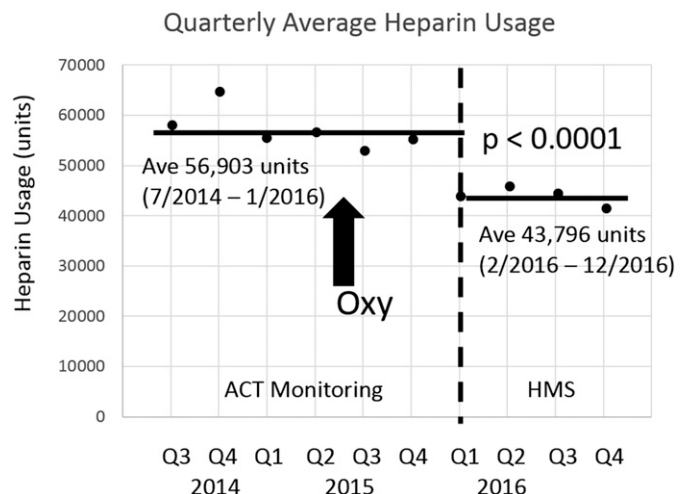


Figure 7. Quarterly average heparin usage is shown. Reduction in the use of heparin is evident on the implementation of the HMS and sustained throughout the use of the new anticoagulation protocol starting in February 2016. Average heparin usage before HMS upgrade was $56,903 \pm 16,543$ units, vs. $43,796 \pm 13,629$ units after the upgrade ($p < .0001$).

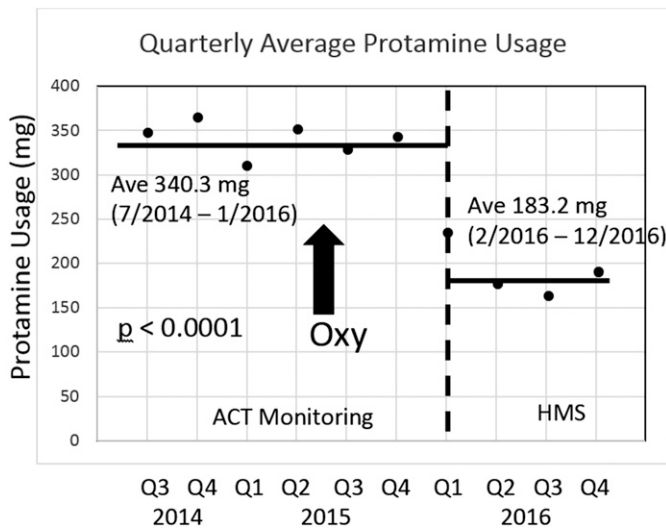


Figure 8. Quarterly average protamine usage can be seen to fall on the implementation of the HMS and sustained by its continued use from February 2016 onwards. Average usage before upgrade was 340.3 ± 119 mg vs. 183.2 ± 70 mg after the upgrade ($p < .0001$).

period of 21% in blood products and 7% in total hospitalization. The decreases continue further with the implementation of the HMS to 61 and 8%, respectively. The net effect of both technology upgrades when extrapolated over procedure type and blood product averages are approaching \$5,500 in blood product cost and \$12,000–\$15,216 in total hospitalization costs per patient (28,29).

DISCUSSIONS

Blood and blood product usage in OHS patients who underwent CPB was being reviewed and scrutinized because of increased morbidities and mortalities and cost-containment considerations. The analysis provided covering the patient population for the length of 30 months shows similar rates of all demographics and case complexity. The similarities across the time periods allow for a comparison across the cardiac surgery patients at the time of preimplementation, post-CPB oxygenator changes, and post-HMS implementation. The dialysis graph fluctuation in the late 2015 and early 2016 time frame can be explained with relatively low case volumes for those periods and higher or lower than normal dialysis patient numbers. If this had a direct impact on the usage of blood products, ICU time, or length of stay, the phenomenon would be present in the usage or time graphs, which is not seen to be significant.

Reductions in the intraoperative transfusion rates can be seen starting in the June 2015 time frame with the implementation of the CPB changes. The bioactive surface Cortiva® remained the same from the old system to the new

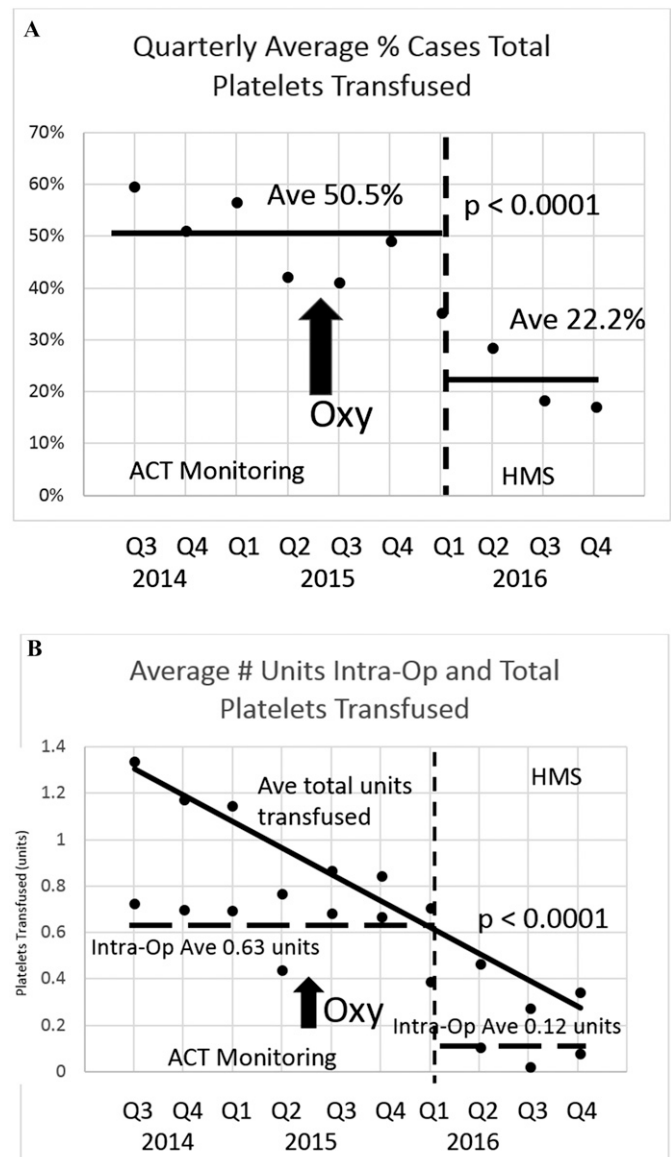


Figure 9. Quarterly average platelets transfused data are shown. Platelet transfusion reductions are evident in the HMS implementation period from February 2016 and beyond. (A) Percentage of cases required platelet transfusions fell to an average of 22.2% from 50.5%, a greater than 50% overall reduction. (B) Intraoperative average number of units transfused can be seen to fall as well in the same time frame to .12 units/patient from .63 units/patient ($p < .0001$). Total (intraoperative and postoperative) average units of platelets transfused showed a strong linear decrease, indicating a strong reduction of need for postoperative platelet transfusion.

system. The decision to maintain a bioactive surface came from the studies that link this coating to reduction in morbidity and mortality when using this coating on a CPB circuit (10). The largest change made was the CPB circuit upgrade to the Affinity Fusion™ oxygenation system. Two hundred and twenty milliliters of prime volume was removed with the integration of the arterial filter. Another 100 mL reduction was realized with the reduction of the

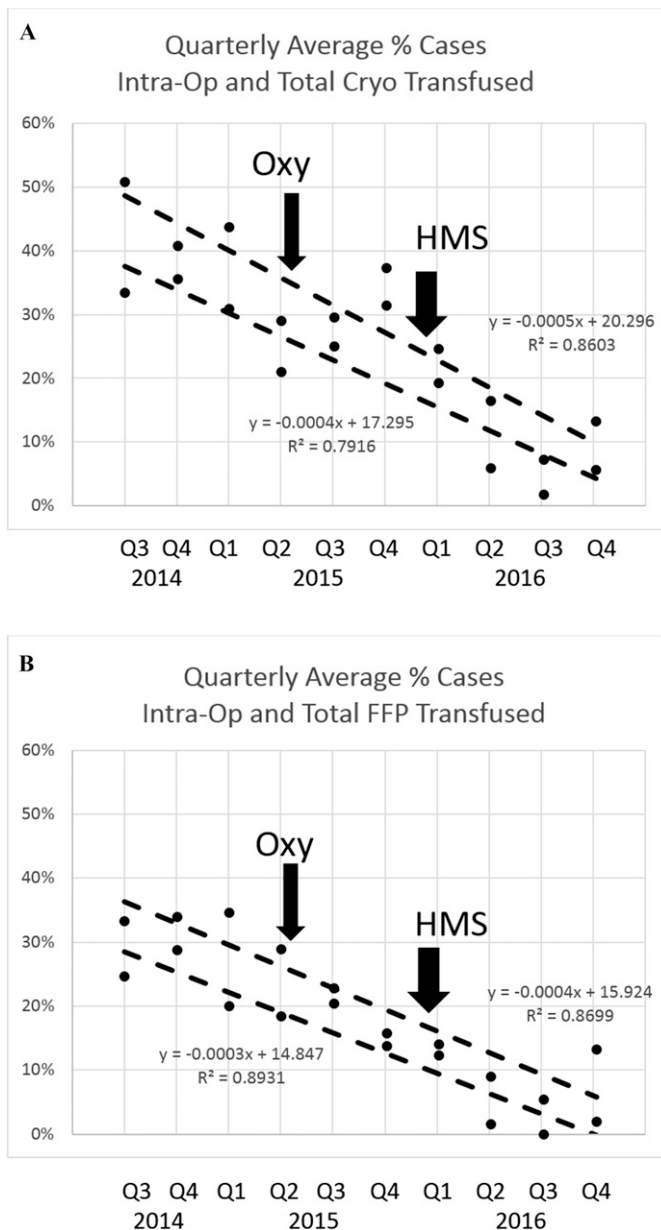


Figure 10. Quarterly average percentage of cases where (A) cryoprecipitate and (B) FFP were postfused. The intraoperative curves and the total (intraoperative plus postoperative) curves are shown. Both cryoprecipitate and FFP usage are seen to fall below 10% in intraoperative usage by the conclusion of the study. Downward trends seem to fit a linear model as shown in the best-fit equations listed.

venous line from 1/2" to 3/8" size tubing. Lastly, changing from the Biomedicus™ to the smaller and more efficient Affinity CP™ centrifugal pump head saved an additional 40 mL of prime. The total savings of prime in the circuit were 360 mL. Less PRBC transfusion after implementation of the CPB can be attributed partly to prime reduction and reduced hemodilution.

In addition to being lower volume, the new oxygenator and centrifugal pump head have enhanced blood handling capabilities as seen in bench-top studies (30). The integrated

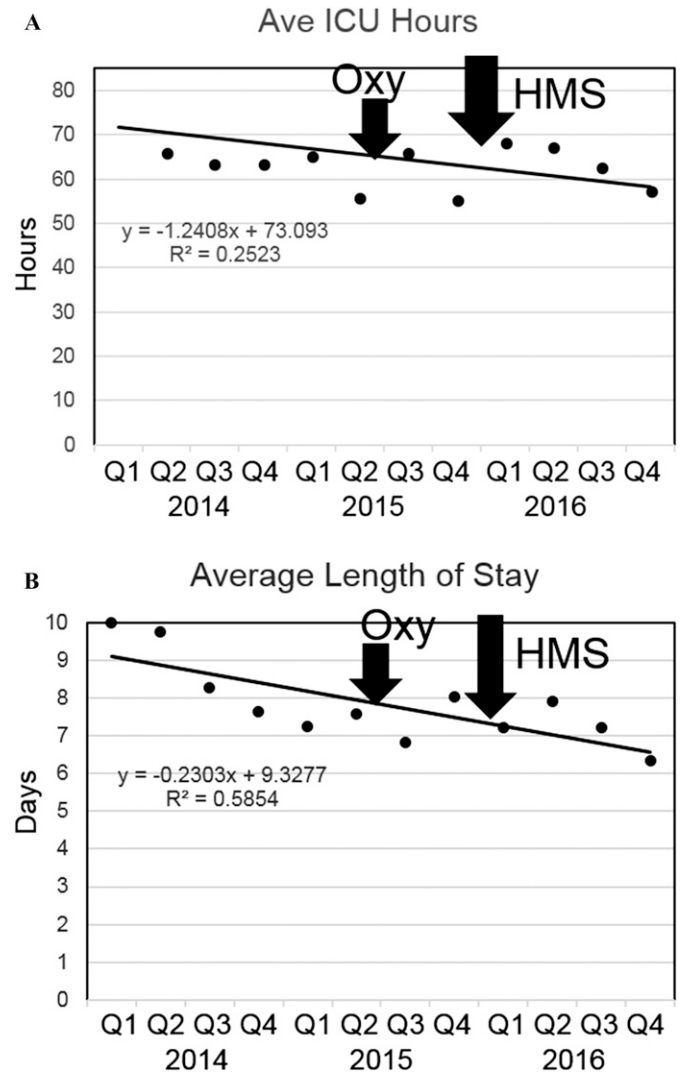


Figure 11. ICU hours of stay (A) and hospital length of stay in days (B) are shown. Gradual decrease in ICU hours of stay and hospital length of stay was observed. The realized reductions are not statistically significant, but aligning trends.

oxygenator that was selected during circuit optimization had a built-in bubble trap for upfront air handling and a 3 cm flow path through the heat exchanger and oxygenator. This, combined with the Cortiva® coating creates a less traumatic blood path and effective air handling. In addition to the oxygenator, the design of the reservoir slows blood as it enters creates a siphon effect allowing the reduction in tubing diameter on the venous line without compromising drainage (31). The new centrifugal pump head generates less heat than the old head and places less shear stress on the blood (30). Overall, less blood trauma was demonstrated with the reduction of PRBC and platelet transfusions after CPB circuit implementation.

With the implementation of the HMS in February 2016, the additive reduction in intraoperative PRBC and platelet transfusions is evident. The individualization of heparin

Table 5. Average comparative cost savings for the implementation period vs. reference period for blood products and total hospitalization are shown. The average cost for blood product and total hospitalization decreased over the two implementation periods. Although there are many factors to a total hospitalization, the 7%–8% decrease in total cost and close to 60% decrease in blood product cost is notable in the averages.

	% Savings Blood Product Cost	% Savings Total Hospitalization	Average Blood Product Savings	Average Total Hospitalization Cost Savings
			Based on internal hospital blood acquisition costs (28)	Average total hospitalization cost based on AHA 2016 \$149,480 bypass surgery, \$190,194 (29)
Oxygenator upgrade	21%	7%	\$2,000	\$10,464–\$13,314
Oxygenator plus HMS	61%	8%	\$5,500	\$11,958–\$15,216

dosing based on the HDR performed at the beginning of the case, allows a patient to be administered the proper bolus and maintained at the proper heparin level for the whole case. Consequently, patients responded positively with reductions in PRBC, FFP, cryoprecipitate, and platelet transfusions. Studies (17–20) have shown that personalizing heparin administration and maintaining patient-specific heparin levels leads to less transfusions. Also, the reduction in the dosage of protamine also directly correlates with the reductions in transfusion rates (6,17–20). There are varying schools of thought as to why individualizing heparin and protamine dosing to a patient leads to transfusion reductions. Heparin in excess can do damage whereas not enough heparin does not properly maintain anticoagulation and can lead to subclinical thrombin generation (6,17). This leads to the consumption of clotting factors and can drive the inability to clot once heparin is reversed. The levels of heparin decreased with the implementation of the HMS which point to the abundant use of heparin before its implementation. This is not traditionally observed in HMS studies as many see an increase of heparin when implementing the HMS (19–21).

Protamine also has effects outside of its initial intent as a reversal agent. Protamine in excess has been seen to impact factor IX and factor VII as an inhibitor that can have effects up to 24 hours after administration. As little as 25 mg in excess can cause an anticoagulant effect in a normal patient (32–35). The cardiac team can overlook the effect of protamine as an anticoagulant and even clinically interpret oozing as still having heparin actively creating anticoagulation. With the heparin–protamine titration cartridge, the exact reversal dose of protamine is given with each heparin level test. This allows for accurate 1.0–.8 ratio reversal of heparin to protamine circulating in the patient's system. Also, the reversal verification of heparin–protamine titration gives validation or added information at the end of the case about the presence or absence of heparin. The processing of the titration cartridges is typically complete within 40–60 seconds, far before an ACT would give an indication as to the level of anticoagulation. Patients who are

reversed using the HMS are given significantly lower doses of protamine, clinically seemed drier and required less blood products than before its use.

Overall trends toward reductions in hospital length of stay and ICU stay are positive over the period of implementations of both CPB circuit changes and HMS. Although both reductions are multifactorial in nature, the trend provides positive enforcement to the changes implemented. The resultant reduction in ICU time and LOS over these implementation periods is reflected in the blood product and total hospitalization average percent cost savings. With what has been clinically observed and verified in this study, the patients at Alta Bates Summit Medical Center are benefiting from the changes made intraoperatively. Clinically, the reduction of CPB surface contact area, coagulation factor activation, prime volume, flow path, and over reversal of protamine have demonstrated implications in the intraoperative blood product savings in our tertiary institution over this 30-month period.

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