Can J Anesth/J Can Anesth (2025) 72:417–425
https://doi.org/10.1007/s12630-024-02893-0

REPORTS OF ORIGINAL INVESTIGATIONS

Quality comparison of autotransfusion devices in cardiac surgery: a prospective observational cohort study

Comparaison de la qualité des dispositifs d'autotransfusion en chirurgie cardiaque : une étude de cohorte observationnelle

Mark Alm, BSc, CPC, CCP · Margarita Otalora-Esteban, MD · Natasha Bush, MSc, CPC, CCP · Amanda Dranfield, BSc, CPC, CCP · Keyvan Karkouti, MD · Brian Beairsto, BSc, CPC, CCP

Received: 13 March 2024 / Revised: 19 August 2024 / Accepted: 21 August 2024 / Published online: 4 February 2025
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Abstract

Purpose *We sought to conduct a quality improvement initiative to compare the wash quality and speed of autologous red blood cell (RBC) processing of four autotransfusion devices during cardiac surgery.*

Methods *Using a prospective observational cohort study approach, we prospectively evaluated four commercially available autologous cell savage devices (autoLog IQ™, Medtronic plc, Minneapolis, MN, USA [135 mL]; Xtra™, LivaNova, plc, Houston, TX, USA [125 mL, 225 mL]; Cell Saver® Elite®+, Haemonetics Corp., Boston, MA, USA [125 mL, 225 mL]; and CATSmart®, Fresenius Kabi AG, Bad Homburg vor der Höhe, Germany) in adult patients undergoing cardiac surgery. Device settings were determined by manufacturer recommendations for optimal wash quality. We collected pre- and postprocessing samples, volumes, and processing times from each device to calculate removal ratios of heparin, potassium, plasma free hemoglobin (PfHb), white blood cells (WBCs), platelets, reinfusion concentrations of heparin and potassium, and red blood cell (RBC) recovery rates.*

Results *A total of 130 consecutive patients underwent autologous cell salvage, but 15 cases were excluded because of incomplete data. All devices removed > 99% heparin, > 95% potassium, > 94% platelets, and > 85% PfHb from collected shed blood. Comparison of processing sets showed significant differences in median [interquartile range] WBC removal ratios, ranging from 26 [19–33]% to 59 [42–68]%, and median heparin reinfusion concentrations, which ranged from 0.09 [0.08–0.11] to 0.63 [0.55–0.70] U·mL^{-1} processed red cells. Median RBC recovery rates also showed significant differences between processing sets, ranging from 8 [8–10] mL RBC·min^{-1} to 24 [22–25] mL RBC·min^{-1}.*

Conclusion *Wash quality and processing speed differed between autotransfusion devices and processing sets. These findings may have clinical implications when large volumes of shed blood are processed and reinfused.*

Résumé

Objectif *Nous avons cherché à mener une initiative d'amélioration de la qualité visant à comparer la qualité de lavage et la vitesse de traitement des globules rouges*

Mark Alm and Margarita Otalora-Esteban have contributed equally to the work.

M. Alm, BSc, CPC, CCP (✉)
Department of Perfusion Services, Peter Munk Cardiac Centre, University Health Network, Toronto, ON, Canada

University Health Network, 585 University Ave, Toronto, ON M5G 2C4, Canada

e-mail: mark.alm@uhn.ca

M. Otalora-Esteban, MD
Department of Anesthesiology & Pain Medicine, Temerty Faculty of Medicine, University of Toronto, Toronto, ON, Canada

N. Bush, MSc, CPC, CCP · A. Dranfield, BSc, CPC, CCP · B. Beairsto, BSc, CPC, CCP
Department of Perfusion Services, Peter Munk Cardiac Centre, University Health Network, Toronto, ON, Canada

K. Karkouti, MD
Department of Anesthesiology & Pain Medicine, Temerty Faculty of Medicine, University of Toronto, Toronto, ON, Canada

Department of Anesthesia and Pain Management, University Health Network, Sinai Health System, and Women's College Hospital, Toronto, ON, Canada

Peter Munk Cardiac Centre, University Health Network, Toronto, ON, Canada

(GR) autologues de quatre dispositifs d'autotransfusion pendant une chirurgie cardiaque.

Méthode *À l'aide d'une approche d'étude de cohorte observationnelle prospective, nous avons évalué prospectivement quatre dispositifs d'épargne cellulaire autologue disponibles dans le commerce (autoLog IQ™, Medtronic plc, Minneapolis, MN, États-Unis [135 mL]; Xtra™, LivaNova, plc, Houston, TX, États-Unis [125 mL, 225 mL]; Cell Saver® Elite® + , Haemonetics Corp., Boston, MA, États-Unis [125 mL, 225 mL]; et CATSmart®, Fresenius Kabi AG, Bad Homburg vor der Höhe, Allemagne) chez des patient·es adultes bénéficiant d'une chirurgie cardiaque. Les paramètres de l'appareil étaient déterminés selon les recommandations du fabricant pour une qualité de lavage optimale. Nous avons collecté des échantillons de pré- et post-traitement, les volumes et temps de traitement de chaque appareil pour calculer les taux d'élimination de l'héparine, du potassium, de l'hémoglobine plasmatique libre (PfHb), des globules blancs (GB), des plaquettes, les concentrations de réperfusion d'héparine et de potassium et les taux de récupération des globules rouges (GR).*

Résultats *Au total, 130 cas consécutifs ont bénéficié d'une épargne cellulaire autologue, mais 15 cas ont été exclus en raison de données incomplètes. Tous les appareils ont éliminé > 99 % de l'héparine, > 95 % de potassium, > 94 % de plaquettes, et > 85 % de PfHb provenant du sang traité. La comparaison des ensembles de traitement a révélé des différences significatives dans les taux médians [écart interquartile] d'élimination des globules blancs, allant de 26 [19-33] % à 59 [42-68] %, et les concentrations médianes d'héparine reperfusée, qui variaient de 0,09 [0,08-0,11] à 0,63 [0,55-0,70] U·mL^{-1} des globules rouges traités. Les taux médians de récupération des globules rouges ont également montré des différences significatives entre les ensembles de traitement, allant de 8 [8 à 10] mL de globules rouges par minute^{-1} à 24 [22–25] mL de globules rouges·min^{-1}.*

Conclusion *La qualité du lavage et la vitesse de traitement différaient entre les dispositifs d'autotransfusion et les kits de traitement. Ces résultats peuvent avoir des implications cliniques lorsque de grands volumes de sang versé sont traités et reperfusés.*

Keywords autologous cell salvage · autotransfusion · wash quality

Autologous cell salvage is recommended for surgical procedures where high-volume blood loss (> 500 mL) is expected, and for any procedure where it is likely to reduce allogeneic (donor) red blood cell (RBC) transfusion.[1] In cardiac surgery, it is recommended that autologous cell salvage be used for all cases, at least in "collect only" mode to allow for subsequent processing and reinfusion if significant blood loss occurs.[1] Several products are commercially available for RBC salvage and processing. Although these devices function using similar principles, they employ different strategies for blood processing that may impact the quality of the end-product (i.e., salvaged RBCs).

Surgical bleeding is aspirated via a specialized suction line that allows continuous mixing of shed blood with an anticoagulant, such as heparinized saline or citrate. This blood-anticoagulant mixture passes through a gross particulate filter before being collected in a reservoir. When a sufficient volume of shed blood has been collected, the autotransfusion device uses centrifugation to separate blood components by density. The high density of RBCs compared with other blood components displaces plasma, white blood cells (WBCs), and platelets to an external waste bag as RBCs continue to enter the processing chamber. When the processing chamber reaches an adequate volume of packed RBCs, a wash cycle using 0.9% sodium chloride removes any remaining contaminants before the processed blood is transferred to a collection bag for retransfusion.[2] For discontinuous bowl-style devices, users select from a range of processing set sizes based on the volume of shed blood to allow complete filling of the processing set with packed RBCs, ensuring effective plasma displacement and wash efficacy.[2] For continuous devices, blood passes through a closed, spiral washing chamber, propelled by incoming RBCs without any requirement for filling and emptying cycles, thereby allowing low-volume processing.[2] Filtration of processed blood through an additional filter ($\leq$ 40 μm) is recommended to remove any residual debris before reinfusion.[2]

Comparative analysis of a previous generation of autotransfusion devices showed differences in removal of unfractionated heparin (UFH), potassium (K^+), plasma free hemoglobin (PfHb), WBCs, and platelets in cardiac surgery.[2] To our knowledge, there has been no published comparison of the wash quality and speed for the complete range of autotransfusion devices that are currently commercially available.

We sought to conduct a quality improvement initiative to compare the wash quality and rate of recovery for autologous RBCs processed during cardiac surgery by four commercially available autotransfusion devices: autoLog IQ™ (Medtronic, plc, Minneapolis, MN, USA), Xtra™ (LivaNova, plc, Houston, TX, USA), Cell Saver® Elite® + (Haemonetics®, Boston, MA, USA), and CATSmart® (Fresenius Kabi, Bad Homburg vor de Höhe, Germany).

Table 1 Autotransfusion device settings

Device (bowl size)	Fill rate (mL·min^{-1})	Wash volume (mL)	Wash rate (mL·min^{-1})	Empty rate (mL·min^{-1})
autoLog IQ™ (135 mL)	600	250	*Not disclosed by manufacturer*	
Xtra™ (125 mL)	300	700	250	300
Xtra™ (225 mL)	400	800	300	400
Cell Saver® Elite® + (125 mL)	225	750	200	300
Cell Saver® Elite® + (225 mL)	500	1000	450	500
CATSmart®	*Variable based on Flex Wash Factor 3 settings*			

Methods

With approval from the institutional Quality Improvement Review Committee (University Health Network, Toronto, ON, Canada; April 2023; QI ID 23-0572), we used a prospective observational cohort study approach for this initiative. As a quality improvement project, no individual clinical data were collected, so informed patient consent was not required. The study included 130 adult patients undergoing cardiac surgery with autologous cell salvage at Toronto General Hospital between 9 May 2023 and 29 September 2023. Each autotransfusion device was used in 33 consecutive cardiac surgery cases, irrespective of any patient- or surgery-related factors. Cases that did not collect an adequate volume of blood for processing were not included in the study. The sample size was determined based on findings from a multidevice comparison of an earlier generation of autotransfusion devices.[2] The results of our prospective observational cohort are presented in accordance with Standards for Quality Improvement Reporting Excellence 2.0 reporting guidelines.[3]

All devices were set to manufacturer-recommended settings for optimal wash quality and allowed to complete the entire automated processing program (Table 1). All collection reservoirs had a vacuum (surgical site suction) set at − 150 mm Hg, apart from Cell Saver Elite + , which used Smart Suction® (Haemonetics®, Boston, MA, USA), a setting that autoregulated the vacuum between − 20 and − 150 mm Hg. Anticoagulation for suction tubing consisted of 30,000 IU heparin in 1 L 0.9% saline (30 U·mL^{-1}), and perfusionists chose processing set sizes of 125 mL or 225 mL when applicable.

Sample collection

We used a standardized sampling protocol. Collection of preprocessing samples from the homogeneously mixed collection reservoir began once the perfusionist determined there was a sufficient volume of salvaged blood for processing. After completion of the first wash cycle, we collected postprocessing samples directly from the blood storage bag.

Processing cycle time was recorded (start of filling to end of emptying). After sampling, we passed the washed blood through a 40-μm filter before returning it to the patient. We recorded the device's measurements for volume processed and volume produced. For bowl-style autotransfusion devices, we only sampled and measured the first bowl. For the CATSmart continuous autotransfusion device, we processed the entire reservoir volume at once.

Laboratory procedures

The hospital laboratory performed complete blood count and biochemistry tests according to institutional standards. Samples for PfHb underwent centrifugation as soon as possible after collection to separate plasma for spectrophotometric analysis at an external laboratory (In-Common Laboratories, North York, ON, Canada).

The processing of shed surgical blood by autotransfusion devices removes most coagulation proteins.[4] Anti-factor Xa measurement by chromogenic assay may underestimate UFH levels in samples with low levels of coagulation factors and therefore requires addition of a known volume of standard plasma to produce accurate results.[4] Adaptations were required to precisely measure UFH levels by anti-factor Xa activity in the high concentrations expected in our preprocessing samples and in the low concentration of coagulation factors expected in our postwash samples. Following centrifugation, the prewash samples were diluted 1:20 with standard plasma and the postwash samples were diluted 1:2.

Calculations and statistical analysis

Red blood cell mass recovery rate

We calculated the rate of RBC recovery for each device using the method described by Serrick *et al*. for processing speed comparison.[2]

$$\text{RBC Mass Recovery Rate} = \frac{\textit{volume PRC produced} \times \textit{hct PRC}}{\textit{time to process}}$$

where the processed red cell (PRC) volume is multiplied by the hematocrit of the PRC (hct PRC) to yield the volume of RBC (at a hematocrit of 100%) in the washed product. This is then divided by the time it took to run the processing cycle to yield mL RBC·min^{-1}, a standardized unit of processing speed that adjusts for variances in hematocrit.

Washout quality

Washout quality for plasma soluble contaminants (UFH, PfHb, K^+) was calculated using the methods described by Gruber *et al*.[5]

$$\text{Elimination rate}\ (\%) = \left(1 - \frac{\textit{CPpost}([1 - \textit{hct postwash}] \times \textit{volume produced})}{\textit{CPpre}([1 - \textit{hct prewash}] \times \textit{volume processed})}\right) \times 100\%$$

CP*pre* and CP*post* are the concentrations of the substances measured in the plasma, and (1 − hct) × volume yields the plasma component for the pre- and postprocessing volumes.

Washout quality for components measured in whole blood samples (WBCs, platelets) was calculated using the methods described by Serrick *et al*.[2]

$$\text{Elimination rate}\ (\%) = \left(1 - \frac{\textit{CBpost} \times \textit{volume produced}}{\textit{CBpre} \times \textit{volume washed}}\right) \times 100\%$$

CB*pre* and CB*post* are the concentrations of the components measured in whole blood.

Reinfusion concentration

To effectively compare the quality of the returned product between devices for UFH and K^+ concentrations, we converted the concentration per mL of plasma measured by the lab to concentration per mL of washed PRC for reinfusion using the following equations:

$$\text{Reinfusion concentration heparin (IU/mL)} = \frac{\textit{UFH IU/mL plasma} \times ([1 - \textit{hct postwash}] \times \textit{volume produced (mL)})}{\textit{volume produced(mL)}}$$

$$\text{Reinfusion concentration potassium (mmol/L)} = \frac{K^+\textit{mmol/Lplasma} \times ([1 - \textit{hct postwash}] \times \textit{volume produced(L)})}{\textit{volume produced (L)}}$$

where the plasma concentration of each substance is multiplied by the calculated volume of plasma in the washed PRC before being divided by the total PRC volume. Calculating reinfusion concentration in this way offers a metric for comparing amounts of residual plasma-soluble substances that are independent of hematocrit.

Standard descriptive statistics are reported for all measures. Continuous variables are presented as mean with standard deviation (SD) or median with interquartile range [IQR] when applicable, and categorical data are presented as proportions. Results were tested for normal distribution using graphical evaluation and the Shapiro–Wilks test. Statistical analysis was performed on normally distributed data using one-way analysis of variance, and on nonnormally distributed data using a Kruskal–Wallis one-way analysis of variance on ranks. We considered a P value of < 0.05 significant. Data were analyzed using R Statistical Software version 4.2.3 (R Foundation for Statistical Computing, Vienna, Austria).[6]

Results

Patient characteristics

A total of 130 consecutive patients underwent autologous cell salvage with the devices under evaluation. We excluded 15 patients because of incomplete data, leaving 30 patients for autoLog IQ, 30 for Xtra, 29 for Cell Saver Elite + , and 26 for CATSmart. Patient baseline characteristics are presented in Table 2. Complete blood count and plasma concentrations by device are presented in Table 3.

Outcome measures

A summary of outcomes and their analyses are shown in Table 4. Devices showed differences in the median hematocrit of the PRC concentrate produced, with CATSmart showing the highest median [IQR] hematocrit at 71 [66–74]% (H = 0.42; 95% confidence interval [CI], 0.26 to 0.49; $P < 0.01$). Comparisons between bowl sizes within devices showed no difference in hematocrit for Xtra (H = 0.09; 95% CI, − 0.03 to 0.39; $P = 0.06$), while Cell Saver Elite + (225 mL bowl) yielded a significantly lower hematocrit (H = 0.34; 95% CI, 0.07 to 0.62; $P < 0.01$) (Fig. 1).

Hematocrit values of the PRC concentrate measured by CATSmart and laboratory showed significant correlation

Table 2 Baseline characteristics of the population

	autoLog IQ™	Xtra™	Cell Saver® Elite® +	CATSmart®	SMD
n/total *N* (%)	30/115 (26%)	30/115 (26%)	29/115 (25%)	26/115 (23%)	
Age (yr)	62 (17)	61 (16)	58 (17)	64 (12)	0.19
Female	5/30 (17%)	7/30 (23%)	6/29 (21%)	8/26 (31%)	0.18
BMI ($kg \cdot m^{-2}$)	27.3 (6.2)	28.4 (4.0)	28.5 (5.8)	28.8 (4.4)	0.14
Baseline Hb ($g \cdot L^{-1}$)	127 (23)	135 (12)	139 (17)	139 (15)	0.37
Baseline K^+ ($mmol \cdot L^{-1}$)	3.8 (0.5)	4.1 (0.5)	4.0 (0.3)	3.8 (0.4)	0.34
CPB time (min)	107 (65)	98 (74)	98 (58)	101 (69)	0.07
Cross-clamp time (min)	85 (59)	78 (62)	71 (49)	76 (46)	0.13
Net blood loss (mL)	1,134 (745)	948 (547)	943 (463)	1,091 (603)	0.20
Volume processed (mL)†	818 (358)	917 (288)	753 (326)	1576 (439)	1.14
Volume produced (mL)†	132 (3)	181 (57)	169 (61)	252 (142)	0.81
Procedure					0.84
Isolated CABG	10/30 (33%)	6/30 (20%)	5/29 (17%)	3/26 (12%)	
Single non-CABG	2/30 (7%)	2/30 (7%)	2/29 (7%)	2/26 (8%)	
2 procedures	3/30 (10%)	6/30 (20%)	9/29 (31%)	10/26 (39%)	
$\geq$ 3 procedures	2/30 (7%)	6/30 (20%)	3/29 (10%)	3/26 (12%)	
MICS	2/30 (7%)	0/30 (0%)	0/29 (0%)	3/26 (12%)	
Thoracic aorta	1/30 (3%)	1/30 (3%)	2/29 (7%)	1/26 (4%)	
Redo	3/30 (10%)	3/30 (10%)	4/29 (14%)	0/26 (0%)	
Off-pump	4/30 (13%)	6/30 (20%)	4/29 (14%)	4/26 (15%)	
Assist devices	1/30 (3%)	0/30 (0%)	0/29 (0%)	0/26 (0%)	
Heart transplant	2/30 (7%)	0/30 (0%)	0/29 (0%)	0/26 (0%)	

All continuous variables are presented as mean (standard deviation) and categorical data as *n*/total *N* (%)

†Volume for first wash cycle

BMI = body mass index; CABG = coronary artery bypass graft; CPB = cardiopulmonary bypass; Hb = hemoglobin; MICS = minimally invasive cardiac surgery; SMD = standardized mean difference

(r = 0.72; 95% CI, 0.46 to 0.87), while those for Xtra showed very low correlation (r = 0.15; 95% CI, − 0.23 to 0.48).

RBC mass recovery rates differed between devices and bowl sizes (Fig. 2). Within-device comparisons showed a significantly lower rate with the 125 mL bowl in both Xtra (H = 0.66; 95% CI, 0.50 to 0.73; $P < 0.01$) and Cell Saver Elite + (H = 0.63; 95% CI, 0.46 to 0.71; $P < 0.01$).

The median washed product reinfusion concentration of UFH differed significantly (H = 0.33; 95% CI, 0.21 to 0.49; $P < 0.01$). We also found significant differences between 125 mL and 225 mL bowls for both Xtra (H = 0.45; 95% CI, 0.13 to 0.72; $P < 0.01$) and Cell Saver Elite + devices (H = 0.52; 95% CI, 0.17 to 0.74; $P < 0.01$) (Fig. 3).

Discussion

In this quality improvement initiative, we evaluated all autotransfusion devices available on the Canadian market for cardiovascular surgery. Our investigation focused on comparing key parameters including RBC recovery rate, hematocrit of PRC concentrate, washout removal ratios of UFH, K^+, PfHb, WBCs, and platelets, and reinfusion concentrations of K^+ and UFH. While all devices exhibited satisfactory performance overall, our analysis revealed significant differences among them.

Significant differences emerged in the median hematocrit of the PRC concentrate. The CATSmart produced the highest PRC concentration, with a median [IQR] hematocrit of 71 [66–74]%. Conversely, the Cell Saver Elite + (225 mL) exhibited the lowest hematocrit, with a median [IQR] value of 56 [54–59]%. These results align with the hematocrit target of 50–70% commonly reported for autotransfusion devices.[7]

The hematocrit measurement of the PRC concentrate by the CATSmart correlated strongly with laboratory measurements (r = 0.72), in contrast to a very low correlation observed for Xtra (r = 0.15). Prior studies have reported the underestimation of hematocrit values by Xtra.[8]

Table 3 Concentrations by autotransfusion device

A. Complete blood count

	Bowl size	*n*/total *N* (%)	Pre-HCT %	Post-HCT %	Pre-PLT ($\times 10^9$ L^{-1})	Post-PLT ($\times 10^9$ L^{-1})	Pre-WBC ($\times 10^9$ L^{-1})	Post-WBC ($\times 10^9$ L^{-1})
autoLog IQ™	135 mL	30/115 (26%)	14 [10–17]	63 [62–65]	50.5 [34.3 -68.8]	8.5 [5.3–15.8]	3.1 [2.0–3.6]	10.4 [7.2–12.3]
Xtra™	125 mL	15/115 (13%)	11 [10–14]	63 [62–64]	36.0 [28.5–54.5]	7.0 [3.0–15.5]	2.2 [1.7–3.3]	6.6 [5.0–10.7]
Xtra™	225 mL	15/115 (13%)	16 [15–19]	62 [61–63]	60.0 [41.0–71.0]	17.0 [6.5–33.5]	4.4 [3.0–5.1]	12.0 [9.2–13.0]
Cell Saver® Elite® +	125 mL	15/115 (13%)	13 [10–20]	62 [60–65]	55.0 [44.0–75.0]	15.0 [7.5–48.0]	3.4 [2.2–5.0]	13.6 [7.8–21.8]
Cell Saver® Elite® +	225 mL	14/115 (12%)	19 [17–19]	56 [54–59]	66.0 [53.8–78.0]	12.5 [10.0–24.0]	4.4 [3.2–6.5]	12.4 [8.2–16.5]
CATSmart®	N/A	26/115 (23%)	16 [12–18]	71 [66–74]	49.5 [40.8–80.3]	6.0 [3.0–14.3]	3.5 [2.4–5.6]	10.1 [6.8–15.5]

B. Plasma concentrations

	Bowl size	*n*/total *N* (%)	Pre-UFH (U·mL^{-1})	Post-UFH (U·mL^{-1})	Pre-K^+ (mmol·L^{-1})	Post-K^+ (mmol·L^{-1})	Pre-PfHb (mg·L^{-1})	Post-PfHb (mg·L^{-1})
autoLog IQ™	135 mL	30/115 (26%)	17.0 [13.8–19.7]	0.57 [0.34–0.66]	4.7 [3.9–5.9]	2.1 [1.6–2.6]	1,905 [1,277–3,546]	2,373 [1,867–3,330]
Xtra™	125 mL	15/115 (13%)	16.2 [15.0–17.3]	1.70 [1.46–1.88]	4.2 [3.2–5.2]	1.7 [1.5–2.2]	1,530 [1,298–2,912]	2,884 [2,395–3,602]
Xtra™	225 mL	15/115 (13%)	15.0 [12.8–15.7]	0.92 [0.59–1.01]	5.4 [4.7–7.3]	1.9 [1.6–2.7]	2,668 [2,054–3,134]	2,800 [2,207–3,424]
Cell Saver® Elite® +	125 mL	15/115 (13%)	17.6 [16.0–19.3]	0.24 [0.20–0.28]	4.8 [3.9–5.7]	2.4 [2.1–3.1]	2,060 [1,415–2,280]	3,395 [3,063–5,175]
Cell Saver® Elite® +	225 mL	14/115 (12%)	15.4 [13.5–17.7]	0.55 [0.45–0.70]	5.5 [4.4–5.7]	1.9 [1.6–2.4]	3,180 [2,153–4,585]	2,500 [2,020–2,923]
CATSmart®	N/A	26/115 (23%)	15.2 [14.4–16.8]	1.06 [0.66–2.32]	4.8 [4.0–5.9]	2.7 [2.2–3.2]	2,391 [1,618–4,191]	2,991 [2,191–5,363]

Values presented as median [interquartile range] or as *n*/total *N* (%)

HCT = hematocrit; N/A = not applicable; PfHb = plasma free hemoglobin; PLT = platelets; UFH = unfractionated heparin; WBC = white blood cells

Table 4 Red blood cell recovery rate and washout quality by autotransfusion device

	autoLog IQ™ 135 mL	Xtra™ 125 mL	Xtra™ 225 mL	Cell Saver® Elite® + 125 mL	Cell Saver® Elite® + 225 mL	CATSmart® N/A	*P* value	Kruskal–Wallis effect size (95% CI)
RBC_{RecR}	19 [17–20]	12 [11–13]	19 [17–21]	8 [8–10]	24 [22–25]	14 [12–16]	0.021	0.07 (0.02 to 0.21)
WBC_{RR}	42 [34–58]	50 [44–62]	35 [29–48]	27 [21–35]	26 [19–33]	59 [42–68]	< 0.001	0.27 (0.13 to 0.43)
PLT_{RR}	97 [94–98]	97 [95–98]	95 [86–96]	95 [86–97]	94 [89–96]	98 [97–99]	< 0.001	0.15 (0.05 to 0.34)
$PfHb_{RR}$	92 [87–95]	89 [83–91]	89 [85–91]	85 [72–88]	88 [87–91]	93 [88–94]	< 0.001	0.15 (0.06 to 0.32)
K^+_{RR}	96 [95–98]	97 [95–98]	96 [94–97]	94 [94–98]	95 [93–95]	97 [96–98]	0.004	0.09 (0.01 to 0.25)
UFH_{RR}	100 [100–100]	99 [99–99]	99 [99–99]	100 [100–100]	99 [99–100]	100 [99–100]	< 0.001	0.22 (0.12 to 0.35)
K^+_{RC}	0.75 [0.60–0.97]	0.63 [0.57–0.78]	0.68 [0.61–1.72]	0.87 [0.75–1.13]	0.84 [0.74–1.10]	0.78 [0.68–0.87]	0.13	0.02 (−0.02 to 0.16)
UFH_{RC}	0.21 [0.13–0.24]	0.63 [0.55–0.70]	0.34 [0.24–0.39]	0.09 [0.08–0.11]	0.23 [0.19–0.30]	0.30 [0.21–0.67]	< 0.001	0.33 (0.21 to 0.49)

Values are presented as median [interquartile range] unless otherwise indicated

CI = confidence interval; K^+_{RC} = K^+ reinfusion concentration (mmol·L^{-1}); K^+_{RR} = K^+ removal ratio (%); PLT_{RR} = platelets removal ratio (%); $PfHb_{RR}$ = plasma free hemoglobin removal ratio (%); RBC_{RecR} = red blood cell recovery rate (mL RBC·min^{-1}); UFH_{RC} = unfractionated heparin reinfusion concentration (units·mL^{-1}); UFH_{RR} = unfractionated heparin removal ratio (%); WBC_{RR} = white blood cell removal ratio (%)

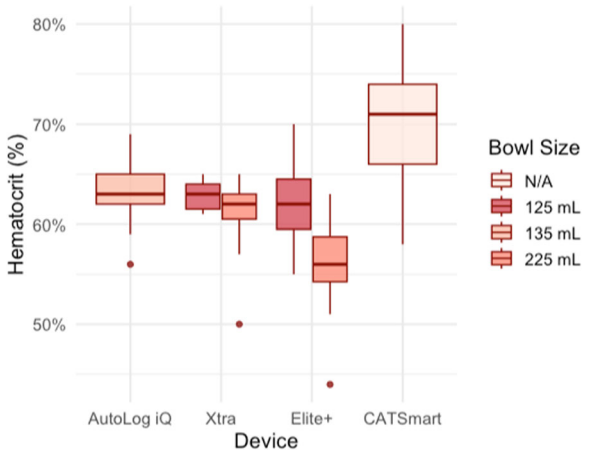

Fig. 1 Hematocrit by autotransfusion device and bowl size. Hematocrit in the processed red blood cells reported as measured by laboratory analyzer.

N/A = not applicable

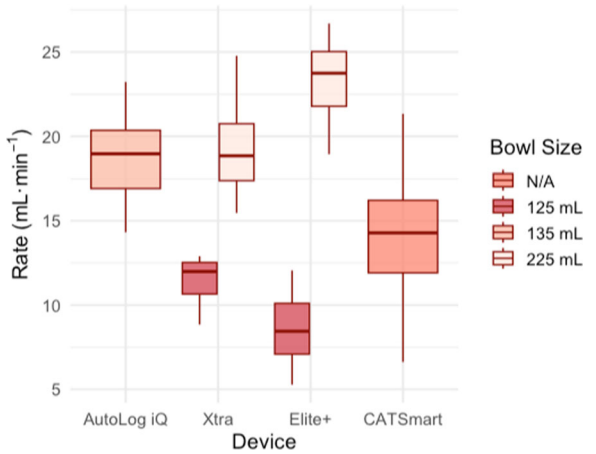

Fig. 2 Red blood cell mass recovery rate by autotransfusion device and bowl size. Red blood cell recovery rate was calculated for each device for processing speed comparison.

N/A = not applicable

Red blood cell recovery rate was highest for the 225 mL processing sets, with Cell Saver Elite + processing the most RBCs per minute (median [IQR], 24 [22–25] mL RBC·min^{-1}). For lower volume recovery, the autoLog IQ processed RBCs quickly (median [IQR] 19 [17–20] mL RBC·min^{-1}), matching the rate of Xtra 225 mL (median [IQR], 19 [17–21] mL RBC·min^{-1}). In contrast, the 125 mL processing sets had a substantially slower RBC recovery rate than all other devices and processing sets. Rate of RBC recovery was lower than those previously reported for the Xtra processing sets, likely because of lower preprocessing hematocrits in our study.[9] The observed distinctions in RBC mass recovery rates

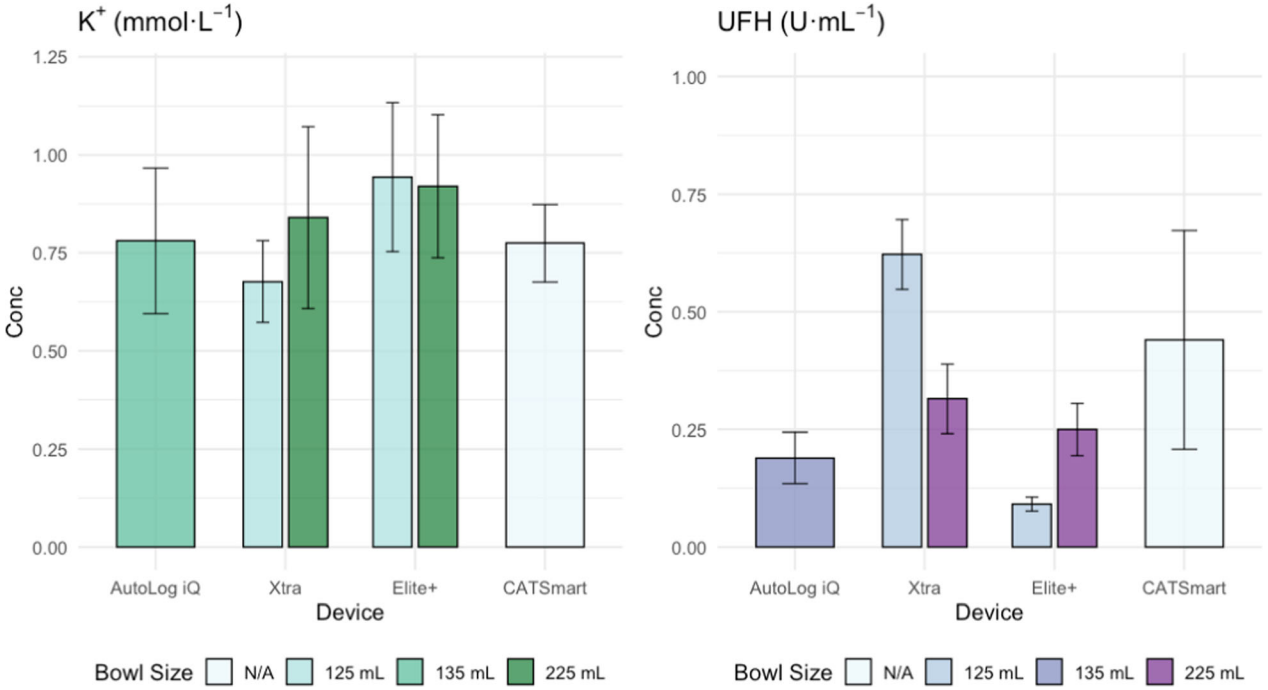

Fig. 3 Reinfusion concentrations. Reinfusion concentrations of potassium and unfractionated heparin grouped by autotransfusion device. Values represent concentration per volume of washed red blood cells.

N/A = not applicable; UFH = unfractionated heparin

between bowl sizes for the Xtra and Cell Saver Elite + devices could have implications for the efficiency and performance of these systems when a high rate of blood loss is anticipated.

As a continuous device, the CATSmart could process a range of volumes in a single cycle. Nevertheless, when very low volumes of RBC were recovered, the initial time cost associated with filling could negatively influence RBC recovery rate. As larger RBC volumes were processed, the absence of subsequent filling-emptying cycles improved RBC recovery rates for this device.

Differences in washout quality defined by the removal ratio were notable between devices for all measures (WBC, PLT, PfHb, K^+, and UFH). Nevertheless, despite finding statistically significant differences in washout quality, these are unlikely to be clinically relevant when small volumes of washed PRCs are reinfused, but may warrant consideration when large volumes of shed blood are processed. It is noteworthy that WBC removal rates ranged from 27% to 59%, reaffirming the need for additional postprocessing blood filtration methods.[2]

Unfractionated heparin plasma concentrations in the washed PRCs were higher for the Xtra and Cell Saver Elite + than previously reported.[4,10] This may be a consequence of higher UFH concentrations in our collection reservoir prior to processing compared with those previously reported.[10] Reinfusion concentrations of UFH varied significantly between devices and processing sets, ranging between a median [IQR] of 0.09 [0.08–0.11] $U{\cdot}mL^{-1}$ PRC for the Cell Saver Elite + (125 mL) to 0.62 [0.36–0.87 $U{\cdot}mL^{-1}$ PRC for the Xtra (125 mL). Concentrations of UFH may be clinically relevant when larger volumes of shed blood are processed and returned to the patient.

We did not identify any difference in prewash PfHb concentrations between devices. Therefore, we were unable to show any reduction in suction blood hemolysis when using the autoregulating Smart Suction feature from the Cell Saver Elite + compared with constant − 150 mm Hg suction.

The present study possesses several strengths that enhance the reliability and relevance of our findings. We conducted a detailed comparison of *in vivo* wash quality among all commercially available autotransfusion devices and within devices offering multiple bowl sizes. Additionally, our study distinguishes calculations performed on plasma from those on whole blood, providing precision not consistently detailed in similar studies.[2,8,11] By reporting the quantity of UFH and K^+ per mL of washed blood for each device and bowl size, we offer clinical users a metric for comparing reintroduced drug amounts into the patient's system that is independent of hematocrit.

Nevertheless, it is crucial to recognize some inherent limitations of our quality improvement initiative. Our sample size for each processing set was small. We relied on device-reported volume measurements for computation of filling and washed product volumes instead of direct measurements.[7,9] Because we only tested one processing mode per device, our results may not be generalizable to other processing modes. Our sampling protocol assessed only the first processing cycle for each device and did not evaluate if wash quality remained consistent during subsequent cycles. It would be an interesting topic for future study to investigate potential deterioration of autotransfusion device performance during subsequent wash cycles. If certain devices deteriorate more than others, this could have an impact on clinical decision-making. Given the objective of the present study did not include subsequent wash cycles, we cannot confidently extrapolate the quality of subsequent wash cycles to volumes encountered in real clinical settings.

Despite these limitations, our findings provide insights into the comparative performance of the latest generation of autotransfusion devices, offering clinicians valuable information regarding autologous blood transfusion.

Author contributions *Mark Alm* contributed to project design and methodology, sample and data collection, calculations, and writing the manuscript. *Margarita Otalora-Esteban* contributed to data cleaning, data analysis, and writing. *Natasha Bush*, *Amanda Dranfield*, and *Keyvan Karkouti* contributed to project design and methodology, sample and data collection, and editing the manuscript. Brian Beairsto contributed to project management and logistics, project design and methodology, sample and data collection, and editing the manuscript.

Acknowledgments The authors would like to thank Dr. Davor Brinc, Cyril Serrick, and the University Health Network Department of Perfusion Services (Toronto, ON, Canada) for their contributions to this project.

Disclosures Keyvan Karkouti is supported in part by a merit award from the Department of Anesthesiology & Pain Medicine, University of Toronto (Toronto, ON, Canada) and has received research funding and honoraria from Octapharma and Instrumentation Laboratory.

Funding statement This quality improvement initiative received no external funding.

Prior conference presentations Presented at the 2024 Canadian Anesthesiologists' Society Annual Meeting (7–10 June, Victoria, BC, Canada).

Editorial responsibility This submission was handled by Dr. Philip M. Jones, Deputy Editor-in-Chief, *Canadian Journal of Anesthesia/ Journal canadien d'anesthésie*.

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