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Effects of Different Intraoperative Blood Salvage Methods on Blood Protection During Coronary Artery Bypass Grafting

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Abstract: *Objective:* To comparatively analyze the clinical efficacy and blood protection value of three different intraoperative blood salvage methods in patients undergoing coronary artery bypass grafting (CABG) under cardiopulmonary bypass (CPB), so as to screen the optimal intraoperative blood salvage regimen suitable for cardiac surgery and provide evidence-based references for optimizing the perioperative patient blood management system in cardiac surgery. *Methods*: A total of 135 patients with coronary artery disease who underwent elective isolated CABG with CPB in our hospital from January 2022 to December 2025 were enrolled and randomly divided into three groups using the random number table method, with 45 cases in each group. Group A adopted the conventional direct intracardiac suction autologous blood transfusion mode; Group B received non-washed intraoperative blood filtration and salvage transfusion; Group C applied fully automatic washed autologous blood salvage mode. The intraoperative volume of autologous blood transfusion and total perioperative allogeneic blood product transfusion volume were recorded throughout the operation. Hemoglobin (Hb), hematocrit (Hct), platelet count (PLT), serum free hemoglobin (FHb), and coagulation function indicators were detected at three time points: preoperatively, immediately after CPB termination, and 24 hours postoperatively. Postoperative 24-hour mediastinal drainage volume, incidence of transfusion adverse reactions, and rate of reoperation for hemostasis were statistically analyzed. *Results:* There were no significant differences in baseline clinical data among the three groups ($p > 0.05$). Compared with Group A and Group B, Group C exhibited significantly lower perioperative transfusion volumes of allogeneic red blood cells and fresh frozen plasma, as well as a markedly higher effective volume of salvaged autologous blood ($p < 0.05$). At the time points immediately after CPB termination and 24 hours postoperatively, Group C had significantly lower serum FHb levels and higher Hb and Hct levels than Group A and Group B ($p < 0.05$). No significant differences were observed in postoperative mediastinal drainage volume and reoperation hemostasis rate among the three groups ($p > 0.05$). Two cases of mild hemolysis-related adverse reactions occurred in Group B, whereas no adverse events were recorded in Group A and Group C. *Conclusion:* The washed autologous blood salvage mode presents superior blood protection efficacy in CABG surgery with CPB. It can effectively remove fragmented red blood cells, inflammatory mediators, and harmful impurities in salvaged blood, reduce allogeneic blood product transfusion, and lower the risks of intraoperative red blood cell damage and hemolysis. With higher clinical safety and practicability, this mode can be promoted as a routine intraoperative blood protection strategy in cardiac surgery.

Keywords: Coronary artery bypass grafting; Cardiopulmonary bypass; Autologous blood salvage; Blood protection; Free hemoglobin

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1. Introduction

Coronary artery bypass grafting assisted by cardiopulmonary bypass is a core surgical procedure for the clinical treatment of multi-vessel and severe coronary atherosclerotic lesions, which effectively reconstructs myocardial blood perfusion and improves the long-term prognosis of patients. However, this procedure carries a high risk of perioperative blood loss. Multiple superimposed factors, including mechanical shear force generated by CPB pipelines, continuous intraoperative negative pressure suction, systemic heparinization, and intraoperative wound oozing, can cause massive red blood cell damage, hemodilution, and coagulation disorders, further resulting in perioperative anemia that requires allogeneic blood product transfusion for correction in most patients. Allogeneic blood resources are clinically scarce, and allogeneic blood transfusion significantly increases the risks of postoperative immunosuppression, transfusion-related infection, acute lung injury, hemolysis, and other complications, which is detrimental to patients' postoperative rapid recovery. Therefore, standardized and individualized perioperative blood protection has become a core link in the quality control of cardiac surgery [1].

Intraoperative autologous blood salvage is currently the preferred minimally invasive blood protection technology in clinical practice, which effectively reduces reliance on allogeneic blood transfusion [2]. At present, three mainstream clinical modalities are available, including conventional direct intracardiac suction transfusion, non-washed filtration salvage transfusion, and fully automatic centrifugal washed salvage transfusion [3]. Significant differences exist in the blood processing procedures of different salvage modalities, which vary greatly in the removal capacity of damaged red blood cells, inflammatory mediators, residual heparin, and other harmful substances, thereby directly affecting perioperative blood protection efficacy and surgical safety [4]. Current domestic and international guidelines have not formulated unified criteria for the optimal selection of intraoperative autologous blood salvage methods in cardiac surgery. In addition, prospective parallel controlled clinical studies comparing the three salvage modalities are insufficient, leading to diverse clinical selection strategies among medical institutions and a lack of a clear clinical application basis. Based on the above background, this prospective randomized controlled study systematically compared the clinical effects of three intraoperative blood salvage methods in CABG surgery with CPB. The blood protection efficacy was evaluated from multiple dimensions, including blood loss, allogeneic transfusion demand, hemolytic indicators, and clinical prognosis, aiming to screen the optimal intraoperative blood salvage scheme for cardiac surgery and provide reliable evidence-based references for improving the perioperative blood management system and reducing surgical complication risks in cardiac surgery [5].

2. Subjects and methods

2.1. Study subjects

A total of 135 patients who underwent elective isolated CABG with CPB in the Department of Cardiac

Surgery of our hospital from January 2022 to December 2025 were enrolled.

2.1.1. Inclusion criteria

(1) Aged 45–72 years;
(2) Normal preoperative routine blood and coagulation function with preoperative Hb ≥ 110 g/L and no congenital hematological diseases;
(3) First-time cardiac surgery, with only routine dual antiplatelet drugs administered preoperatively without additional anticoagulant or thrombolytic drugs;
(4) Estimated intraoperative blood loss ≥ 400 mL with indications for autologous blood salvage;
(5) Patients and their families fully informed of the study contents, with signed informed consent;
(6) The study was approved by the Ethics Committee of our hospital.

2.1.2. Exclusion criteria

(1) Combined with severe hepatorenal dysfunction, active infection, malignant tumor, or autoimmune diseases;
(2) With a history of cardiac surgery, intraoperative conversion to off-pump CABG, or concurrent cardiac valve surgery;
(3) Intraoperative massive hemorrhage requiring emergency high-volume allogeneic blood transfusion;
(4) Incomplete clinical data or inability to cooperate with the whole study and follow-up.

All enrolled patients were randomly divided into Group A, Group B, and Group C using the random number table method, with 45 cases in each group. Baseline clinical data were comparable among the three groups ($p > 0.05$) (**Table 1**).

Table 1. Comparison of baseline clinical data among the three groups ($\overline{x} \pm s$)

Index	Group A (n = 45)	Group C (n = 45)	F/χ^2	p
Age (years)	62.3 ± 6.8	63.1 ± 6.5	0.542	> 0.05
Gender (male/female)	28/17	27/18	0.416	> 0.05
Preoperative Hb (g/L)	123.6 ± 10.2	124.2 ± 9.3	0.671	> 0.05
Preoperative PLT (×10⁹/L)	213.5 ± 41.6	216.1 ± 43.2	0.328	> 0.05
Number of grafts	3.1 ± 0.7	3.2 ± 0.6	0.703	> 0.05
CPB time (min)	92.6 ± 18.3	93.8 ± 19.1	0.467	> 0.05

Note: No significant differences in baseline data were observed among the three groups, indicating good comparability.

2.2. Anesthesia and CPB protocol

All patients received standardized general anesthesia performed by a professional cardiac anesthesia team. Systemic intraoperative heparinization was implemented to maintain the activated clotting time (ACT) above 480s. Imported membrane oxygenators and CPB devices were uniformly applied for moderate hypothermic CPB. Hemodynamic parameters were continuously monitored during CPB to maintain the mean arterial pressure at 60–80 mmHg and ensure adequate blood perfusion of the myocardium and vital organs. After CPB termination, residual heparin was neutralized with protamine sulfate at a 1:1 ratio to reduce postoperative bleeding risk. A unified restrictive transfusion criterion was adopted throughout the perioperative period: allogeneic suspended red blood cells were transfused when Hb was lower than 70 g/

L, and fresh frozen plasma was supplemented when active bleeding was accompanied by fibrinogen levels below 1.5 g/L. Basic intraoperative and postoperative treatment regimens were consistent across all groups to eliminate the interference of therapeutic differences on study results [6].

2.3. Intraoperative blood salvage interventions

Group A (conventional direct intracardiac suction transfusion group): Intraoperative surgical field blood was directly drained into the CPB reservoir through conventional intracardiac suction pipelines without additional filtration, washing, or purification procedures. Uniform negative pressure suction parameters were adopted, and the salvaged blood was directly re-infused into systemic circulation as the traditional clinical routine mode.

Group B (non-washed blood salvage group): Intraoperative blood from the surgical field was collected using a dedicated blood collection bag with a 40 μm precision filter to remove coarse impurities such as fat particles and tissue debris. No centrifugation or washing treatment was performed. The collected autologous blood was re-infused into patients via central venous access within 6 hours without connection to the CPB pipeline.

Group C (washed autologous blood salvage group): A fully automatic autologous blood recovery system was used to collect intraoperative surgical field blood and residual blood in CPB pipelines throughout the operation. High-speed centrifugation was performed for blood component stratification. The supernatant containing free hemoglobin, inflammatory mediators, residual heparin, and fragmented cells was discarded. Intact red blood cells were repeatedly washed and concentrated with sterile normal saline to prepare pure red blood cell suspension, which was re-infused according to patients' intraoperative hemodynamic status and Hb levels.

2.4. Observation indicators

(1) Intraoperative blood recovery and transfusion indicators

The total volume of effective intraoperative autologous blood transfusion and perioperative (intraoperative to 24 h postoperatively) transfusion volumes of allogeneic red blood cells and fresh frozen plasma were recorded.

(2) Laboratory indicators

Venous blood samples were collected at three time points: preoperatively (T0), immediately after CPB termination (T1), and 24 hours postoperatively (T2). Levels of Hb, Hct, PLT, and serum FHb were measured to evaluate the degree of anemia and red blood cell injury.

(3) Clinical prognostic indicators

Postoperative 24-hour mediastinal drainage volume was recorded, and the incidence of transfusion adverse reactions and reoperation for hemostasis were statistically analyzed.

2.5. Statistical analysis

SPSS 28.0 statistical software was used for data analysis. All normally distributed measurement data were expressed as mean ± standard deviation ($\overline{x} \pm s$). One-way analysis of variance (ANOVA) was used for overall comparison among multiple groups, and the LSD-*t* test was used for pairwise comparison within groups. Count data were expressed as cases (percentage) and compared via the χ^2 test. The test level α was

set at 0.05, and $p < 0.05$ was considered statistically significant.

3. Results

3.1. Comparison of perioperative blood product transfusion

Group C had a significantly higher effective volume of autologous blood transfusion and remarkably lower perioperative transfusion volumes of allogeneic red blood cells and fresh frozen plasma than Group A and Group B (all $p < 0.05$). No significant differences in autologous blood recovery volume and allogeneic transfusion volume were found between Group A and Group B ($p > 0.05$) (**Table 2**).

Table 2. Comparison of perioperative blood product transfusion among the three groups ($\overline{x} \pm s$)

Observation index	Group A (n = 45)	Group B (n = 45)	Group C (n = 45)	*F*	*p*
Autologous blood transfusion volume (mL)	346.2 ± 87.4	391.5 ± 92.6	573.8 ± 112.3	68.342	< 0.05
Allogeneic RBC transfusion volume (U)	2.42 ± 0.86	2.27 ± 0.79	1.16 ± 0.53	42.615	< 0.05
Fresh frozen plasma volume (mL)	215.6 ± 94.3	201.4 ± 86.7	92.5 ± 61.2	36.728	< 0.05

Note: Pairwise comparison between Group C and Group A/B, all $p < 0.05$; pairwise comparison between Group A and Group B, $p > 0.05$.

3.2. Comparison of routine blood and hemolytic indicators at different time points

At T0 (pre-operation), no significant differences in Hb, Hct, and FHb levels were detected among the three groups ($p > 0.05$). At T1 (immediately after CPB termination) and T2 (24 h postoperation), Hb and Hct levels decreased while FHb levels increased in all groups compared with baseline. However, Group C maintained significantly higher Hb and Hct levels and lower FHb levels than Group A and Group B (all $p < 0.05$), indicating that washed autologous blood salvage effectively alleviated intraoperative red blood cell mechanical damage and reduced hemolysis risk (**Table 3**).

Table 3. Comparison of Hb, Hct and FHb levels at different time points among the three groups ($\overline{x} \pm s$)

Index	Time point	Group A	Group B	Group C	*F*	*p*
Hb (g/L)	T0	123.6 ± 10.2	121.9 ± 9.7	124.2 ± 9.3	0.671	> 0.05
	T1	94.3 ± 8.7	95.1 ± 8.2	98.6 ± 7.9	3.864	< 0.05
	T2	91.5 ± 9.1	92.4 ± 8.6	97.3 ± 8.3	4.127	< 0.05
FHb (mg/L)	T0	32.6 ± 11.4	31.8 ± 10.9	33.1 ± 12.1	0.219	> 0.05
	T1	168.3 ± 34.2	159.7 ± 31.5	87.4 ± 22.6	92.531	< 0.05
	T2	116.4 ± 27.5	108.2 ± 25.3	52.7 ± 18.4	76.884	< 0.05

3.3. Comparison of postoperative clinical outcomes

The 24-hour postoperative mediastinal drainage volume was (426 ± 113) mL in Group A, (418 ± 107) mL in Group B, and (405 ± 98) mL in Group C, with no significant intergroup difference ($F = 0.481$, $p > 0.05$). The reoperation hemostasis rate was 4.4% (2/45) in Group A, 4.4% (2/45) in Group B, and 2.2% (1/45) in Group C, showing no statistical difference ($\chi^2 = 0.694$, $p > 0.05$). In terms of transfusion adverse reactions, 2 cases of transient hemoglobinuria and mild hemolysis occurred in Group B and were relieved after symptomatic intervention without severe complications. No transfusion-related adverse events were observed in Group A and Group C, indicating superior clinical safety, which was consistent with previous studies [7].

4. Discussion

4.1. Differences in blood protection mechanisms and efficacy among various blood salvage methods

Blood injury during CABG with CPB mainly originates from two aspects: mechanical shear force of high-speed blood flow in CPB pipelines and red blood cell damage caused by intraoperative negative pressure suction and wound friction, which constitute the core causes of perioperative hemolysis and anemia. The conventional direct intracardiac suction transfusion mode is simple and equipment-free, which is commonly adopted in primary hospital cardiac surgery. However, without any blood purification procedure, damaged red blood cells, free hemoglobin, and inflammatory impurities in surgical field blood directly re-enter the systemic circulation. Accumulated FHb increases renal metabolic burden and elevates the risk of postoperative renal dysfunction, resulting in poor blood protection efficacy. Non-washed salvage only removes coarse tissue debris and fat particles but fails to eliminate plasma-free hemoglobin, activated inflammatory mediators, and residual intraoperative heparin. Although it moderately increases autologous blood transfusion volume, it cannot avoid hemolysis and inflammatory risks. The mild hemolysis adverse reactions in Group B of this study further confirm the limitations of this modality, which is consistent with domestic research conclusions.

Washed autologous blood salvage technology removes more than 90% of free hemoglobin, inflammatory factors, residual heparin, and fragmented cell impurities via centrifugal stratification and precise normal saline washing and concentration, retaining only structurally intact and functional red blood cells to fundamentally reduce hemolysis and organic damage. This study verified that Group C had significantly reduced perioperative allogeneic blood transfusion volume, more stable perioperative Hb levels, and superior hemolytic indicators, fully demonstrating that washed salvage achieves efficient and safe blood protection with dual values of blood resource conservation and surgical safety guarantee.

4.2. Clinical limitations of different salvage modalities

Despite the significant advantages of washed autologous blood salvage, it has certain limitations. Compared with conventional direct transfusion and non-washed salvage, it requires dedicated equipment and disposable consumables, which slightly increases medical costs. In addition, the washing process discards plasma, platelets, and coagulation factors, which may lead to coagulation factor loss in elderly patients with low baseline platelet counts and low intraoperative blood loss, requiring individualized adjustment combined with bedside coagulation monitoring rather than sole reliance on autologous blood salvage. No significant differences in postoperative mediastinal drainage volume and reoperation rate were found among the three groups in this study, indicating that intraoperative blood salvage modalities only optimize red blood cell reserve and reduce hemolysis damage, and cannot replace basic hemostasis measures such as precise surgical hemostasis and antifibrinolytic medication. A comprehensive blood protection system requires combining multiple interventions. Although non-washed and conventional direct transfusion modes are low-cost and easy to operate, they have insufficient blood purification capacity and high hemolysis risks with limited blood protection efficacy, and can only be used as temporary alternative schemes in emergency situations without dedicated washing equipment.

4.3. Clinical implications for perioperative blood management in cardiac surgery

With the comprehensive popularization of restrictive transfusion concepts in cardiac surgery, a single blood

protection method can no longer meet the clinical needs of refined diagnosis and treatment. The construction of an individualized and multi-dimensional perioperative blood management system has become the mainstream clinical trend. Based on the study results, washed autologous blood salvage should be prioritized for CABG patients with CPB when equipment conditions permit, to maximize the reduction of allogeneic blood transfusion and lower the risks of hemolysis and transfusion complications. Routine application of non-washed salvage should be strictly restricted to avoid potential safety hazards, and conventional direct transfusion should only be used as an emergency alternative. Meanwhile, a full-process blood management strategy should be improved, including preoperative screening and correction of baseline anemia, optimization of antiplatelet and anticoagulant regimens, standardization of intraoperative negative pressure suction parameters, strengthening of precise surgical hemostasis, and dynamic postoperative monitoring of blood routine and coagulation function to guide accurate transfusion therapy, so as to comprehensively improve perioperative blood protection efficacy.

4.4. Study limitations

This is a single-center prospective study with a limited sample size, and only patients undergoing isolated on-pump CABG were enrolled, excluding complex cardiac surgeries such as off-pump CABG and concurrent valve surgery, which limits the generalizability of the results. In addition, the follow-up period was limited to 24 hours postoperatively, and the long-term effects of different salvage modalities on postoperative renal function, cardiac function, and graft patency were not observed. Further multi-center, large-sample clinical studies with extended follow-up periods are required to refine the applicable population and clinical indications of different intraoperative blood salvage methods, providing more comprehensive evidence for the standardized promotion of blood protection strategies in cardiac surgery.

5. Conclusion

Significant differences exist in the blood protection efficacy and clinical safety of the three intraoperative blood salvage methods in on-pump CABG surgery. The washed autologous blood salvage mode can effectively remove harmful substances in salvaged blood, reduce intraoperative red blood cell damage and hemolysis, and markedly decrease perioperative allogeneic blood product transfusion demand, presenting the optimal blood protection effect and the highest clinical safety. The non-washed salvage mode has limited blood purification capacity and potential hemolysis risks with low clinical application value. The conventional direct intracardiac suction transfusion mode causes obvious red blood cell damage and poor blood protection efficacy. When clinical conditions allow, washed autologous blood salvage is recommended as the preferred intraoperative blood protection strategy for on-pump CABG. Combined with individualized perioperative blood management, this strategy can effectively improve the quality of cardiac surgery diagnosis and treatment and save clinical blood resources, which is worthy of clinical promotion and application.

Disclosure statement

The author declares no conflict of interest.

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