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REVIEW

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REVIEW

The impact of a chest drainage system on retained blood-associated complications after cardiac surgery

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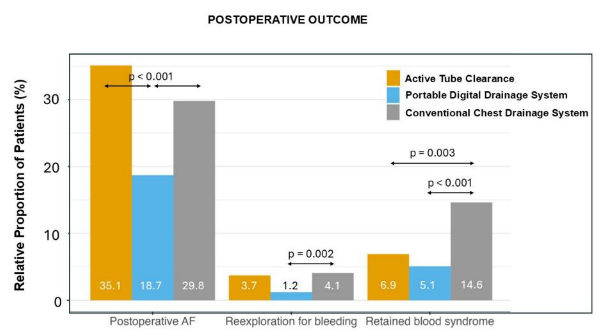
The impact of chest drainage system on retained blood associated complications after cardiac surgery

Summary

- Retrospective study of 1,049 patients after myocardial revascularization (+/- valve)
- Comparison of conventional drainage (369), active tube clearance (188), and portable digital drainage system (492)
- Propensity weighting adjusted analysis of the complications (PoAF, re-exploration for bleeding, RBS)
- Effective chest drainage is vital to minimize retained blood complications.



Legend: PoAF – postoperative atrial fibrillation; AF – atrial fibrillation; RBS – retained blood syndrome

Abstract

OBJECTIVES: Ineffective drainage can lead to retained blood syndrome (RBS), bleeding-associated complications and more postoperative atrial fibrillation (AF). The present study compares outcomes of conventional, active tube clearance (ATC) and portable digital drainage systems after myocardial revascularization.

METHODS: Data from 1222 patients undergoing elective myocardial revascularization with or without a concomitant aortic or mitral valve procedure were considered; data from 1065 patients were retrieved and data from 1049 patients were analysed retrospectively.

Patients who received conventional treatment were compared to those treated with ATC and portable digital drainage. Propensity weighting, including comorbidities, medication and perioperative characteristics, was applied for outcome assessment.

RESULTS: In propensity-adjusted patients, 14.6% of conventional patients had interventions for RBS, with 4.1% underdoing early re-exploration for bleeding. In the ATC group, 6.9% required interventions for RBS [odds ratio (OR) 0.43, $P < 0.001$] with a 3.7% re-exploration rate. Patients in the portable digital drainage group had RBS in 5.1% (OR 0.31, $P < 0.001$) with a 1.2% rate of re-exploration (OR 0.29, $P < 0.001$). Postoperative AF dropped by 37% from 29.8% in the conventional to 18.7% in the portable digital drainage cohort (OR 0.31, $P < 0.001$). In-hospital mortality was similar with 1.6% (6 of 369) in the conventional versus 1.1% (2 of 188) in the ATC versus 0.8% (4 of 492) in the portable digital drainage cohort ($P = 0.358$).

CONCLUSIONS: Active tube clearance and portable digital drainage cohorts had fewer RBS interventions. In addition, portable digital drainage was associated with reduced early re-exploration for bleeding and lower postoperative AF. Immediately effective chest drainage is crucial to minimize RBS complications postoperatively.

Keywords: Active tube clearance • Chest tube management • Portable digital drainage • Postoperative atrial fibrillation • Re-exploration for bleeding • Retained blood syndrome

ABBREVIATIONS

AF	Atrial fibrillation
ATC	Active tube clearance
ATX	Aortic cross-clamp
CABG	Coronary artery bypass grafting
CDU	Conventional drainage unit
CI	Confidence interval
CKD	Chronic kidney disease
COPD	Chronic obstructive pulmonary disease
ICU	Intensive care unit
LVEF	Left ventricular ejection fraction
OR	Odds ratio
PDDS	Portable digital drainage system
POAF	Postoperative atrial fibrillation
RBS	Retained blood syndrome

INTRODUCTION

Shed mediastinal blood is independently associated with adverse outcomes due to excessive blood loss and fluid accumulation around the heart and lungs after cardiac surgery [1]. If poorly evacuated, retained blood can significantly increase morbidity and mortality [2, 3]. To prevent blood retention, chest tubes are positioned in the mediastinal, pericardial and pleural cavities; however, they are prone to clogging, which can impair drainage efficiency and lead to complications [4]. Because the majority of bleeding occurs within the first 4 h, with bleeding volumes declining logarithmically [5], combined with intensive efforts to minimize blood loss, the maintenance of chest tube patency at this point is of paramount importance to optimize patient recovery.

Complications associated with chest tubes have given rise to the development of active tube clearance (ATC) technologies, which have been shown to reduce retained blood syndrome (RBS), re-exploration for bleeding and postoperative atrial fibrillation (POAF) [6–9]. However, a recent study failed to show any advantage of ATC over conventional chest drainage [10], questioning current understanding and proposed solutions for optimal evacuation of retained blood after cardiac surgery. Recently, an advanced portable digital drainage system (PDDS) has been safely applied in cardiac operations, with improved chest tube management and appealing patient mobility [11]. Leveraging the experience gained through a previous ATC study [6], our goal was to assess the clinical performance of ATC and PDDS compared to that of a conventional chest drainage unit (CDU) system in an elective myocardial revascularization cohort.

PATIENTS AND METHODS

The study protocol conformed to the ethical guidelines of the 1975 Declaration of Helsinki. The study was registered and approved by the institutional review board of the Paracelsus Medical University Nuremberg on 10 December 2021. Informed consent was waived due to the study's retrospective design, which utilized routinely obtained de-identified clinical and laboratory data.

Eligible subjects were consecutive patients with stable coronary artery disease, documented sinus rhythm without a history of atrial fibrillation (AF), enrolled for first-time coronary artery bypass grafting (CABG) using cardiopulmonary bypass (CPB) alone or in combination with aortic and/or mitral valve procedures through a median sternotomy at the Department of Cardiac Surgery, Klinikum Nürnberg, Paracelsus Medical University, Nuremberg, Germany. Between January 2016 and April 2019, a total of 1222 patients were screened. Patients were allocated with respect to the system received. The CDU was the standard system of choice throughout January 2016–December 2017. The ATC (PleuraFlow, ClearFlow Inc., Anaheim, CA, USA) was an alternative system of choice, used at the surgeon's discretion from January through June, 2016. The PDDS (Thopaz+, Medela AG, Baar, Switzerland) was introduced in January 2018 and since then uniformly applied. Consecutive patients receiving PDDS from January 2018 through April 2019 comprised the PDDS cohort. To briefly describe the principles of each drainage system, the CDU system is characterized by a water-seal chamber, which acts as a one-way valve and a manometer, to monitor the subatmospheric pressure applied to the pleural cavity. This system is connected to a wall suction unit to maintain subpressures. The ATC system is a special chest tube with a chest clearance apparatus and a mechanism to actively keep the entire inner diameter of the chest tube clear of obstructing blood clots or fibrinous debris. Care providers periodically advance the external shuttle magnetically coupled to the inner clearance loop back and forth within the catheter to maintain sterility while the tube is cleared. The PDDS is a remote digital system that actively regulates and monitors the suction. This system is not dependent on the wall suction apparatus and is typically already activated in the operating room. In all patients, a pressure of −20 cm H_2O

(−9.8 Pa) was applied. All patients underwent cardiac operations using the same pre-, intra- and postoperative protocols, including haemostasis, anti-aggregation and anticoagulation, described in detail previously [6]. Briefly, antiplatelet therapy with acetylsalicylic acid was skipped 1 day before the operation, adenosine-diphosphate receptor antagonists were discontinued 5 days (clopidogrel, ticagrelor) or 7 days (prasugrel) preoperatively, respectively. Perioperatively, the patients received thromboprophylaxis with non-fractionated heparin before surgery and after mobilization with low-molecular-weight heparin. The protocol was similar in all groups.

Exclusion criteria were operative emergency, reoperative status, atrial fibrillation and/or ablation and/or left atrial appendage amputation, ascending aortic surgery in general, hypothermia with selective cerebral perfusion, intra-aortic balloon pump or extracorporeal life support requirement at any time, history of pulmonary embolism, deep vein thrombosis or anticoagulation with in/direct oral anticoagulant, severely impaired left ventricular ejection fraction (LVEF) ≥30%, re-exploration for reason other than bleeding and/or tamponade or a second CPB run.

All patients were fitted with at least one 28 Fr chest tube in the anterior mediastinum. We do not routinely open the pleura to harvest the mammary artery, but when we do, the surgeons place a pleural 28 Fr chest tube. Posterior pericardial 24 Fr chest tubes were placed at the surgeon's discretion. In case of clotting of the tubes, first, a milking procedure was performed (only manually in order to avoid extensive subatmospheric pressures). If these manoeuvres remained unsuccessful, suction of the tubes was performed under sterile conditions. Chest tubes were removed on postoperative day 2 or later in case the amount of serous fluid drained in the last 12 h was <150 ml. Blake or channel-type drains were not used in any patient in this study. All patients were treated with tranexamic acid. An institutional trigger to transfuse for a haemoglobin level of 7.5 g/dl to 8 g/dl was adhered to in this study. Platelet concentrates were transfused by blood loss of >200 ml every hour for at least 2 h and/or documented impaired thrombocyte function. Patient blood management was performed in accordance with the recommendations of Meybohm *et al.* [12]. Cardiac surgery- associated acute kidney injury was defined as any of the following: an increase in serum creatinine by ≥0.3 mg/dl within 48 h; or an increase in serum creatinine to ≥1.5 times the baseline value, within 7 days of surgery; excluding urine criteria [13]. Stroke was defined as a neurologic event with an appropriate correlate on computed tomography or magnetic resonance imaging. Routine prospectively collected pseudo-anonymized demographical and clinical data, echocardiographic findings and intraoperative details were retrieved retrospectively from our institutional cardiac surgery database SAP (Waldorf, Germany) and THG-QIMS (Terraconnect, Nottuln, Germany). Postoperative treatment and data acquisition were performed as part of routine patient care.

The primary outcomes measured were POAF and interventions for RBS, whereby RBS encompassed complications created by retained intrathoracic blood and subsequent inflammation after cardiac surgery. Clinically, RBS was a composite outcome comprising any of the following interventions: re-exploration for bleeding and/or tamponade with washout of retained blood; pericardial interventions (pericardial window or pericardiocentesis); percutaneous pleural interventions (thoracentesis or supplemental chest tube placed postoperatively); and surgical pleural interventions (thoracoscopy or thoracotomy for haemothorax postoperatively). Early re-exploration was defined as occurring in the first 48 h with chest tubes in place to discriminate from any subsequent events after chest tube removal. The institutional trigger for immediate take back for re-exploration was haemodynamic instability reflected by an increasing requirement for inotropic support, threatening cardiac tamponade and/or excessive chest tube drainage exceeding 400 ml in 1 hour, 500 ml over 2 hours and 600 ml over 3 successive hours despite adequately corrected coagulopathy. Patients who had interventions for more than 1 component of RBS were counted only once. Patients who had a diagnosis of pleural or pericardial effusion or haemothorax or haemopneumothorax but did not undergo a specific invasive intervention were excluded. To classify the degrees of severity of the bleeding, the definition of universal perioperative bleeding [14] was divided into 5 categories, taking into account postoperative blood loss, the need to re-explore for bleeding and the use of packed red blood cells (RBCs) and other blood products.

POAF was defined as the occurrence of an irregular heart rhythm, without detectable P waves, lasting more than 30 s [15], obtained from a standard 12-lead electrocardiogram or recorded by bedside continuous rhythm monitoring with automatic arrhythmia detection (HP 1205A, Hewlett-Packard, Andover, MA, USA) until postoperative day 4. A standard 12-lead electrocardiogram was recorded daily thereafter until the day of discharge and in the case of a clinical suspicion suggestive of POAF. All patients received routine postoperative antiarrhythmic prophylaxis with β blockers to target heart rates at 70–80 beats per min, except for those who were bradycardic (heart rates less than 50 beats per min), required epicardial pacing, had an atrioventricular block or were receiving β agonists. Further measures included potassium substitution to maintain levels above 4.5 mmol/l, magnesium supplementation and careful administration of diuretics to prevent excessive fluid shifts. If POAF occurred, electrolyte correction and fluid restitution were performed as appropriate, followed by administration of β blockers and finally amiodarone to allow for a medical conversion. Patients with POAF persisting for more than 12 h and/or with haemodynamic instability received electrical cardioversion. Systemic anticoagulation was used in case of POAF lasting more than 24 h or in case of recurrent episodes.

Secondary outcomes included in-hospital deaths, intensive care unit (ICU) length of stay and chest tube drainage volumes in the first 6, 12 and 24 h.

MEASUREMENT AND ANALYSIS

Results are presented as medians (interquartile ranges) or frequencies (percentages) unless otherwise specified. The 3 groups were compared using the Kruskal-Wallis rank sum test for continuous variables and the χ^2 or Fisher's exact test for categorical variables. In addition, an adjustment was made using propensity weighting [16] calculated with the following confounders: age; antiplatelet agents (aspirin, ADP P2Y12 inhibitor, glycoprotein IIb/IIIa inhibitor); complexity of the operation (CABG alone vs with a valve); CPB and aortic cross-clamp (ATX) times; liver disease; LVEF; preoperative non-fractionated heparin; preoperative haematocrit) and platelet count; placement of a posterior pericardial chest tube; arterial hypertension; beta blocker; chronic kidney disease (CKD); and chronic obstructive pulmonary disease (COPD). Pairwise odds ratios (ORs) between the 3 cohorts were also calculated for RBS, POAF and early re-exploration for bleeding using univariable and multivariable logistic regression. All statistical analyses were performed using CRAN R (https://www.R-project.org/, version 4.1.0, The R Foundation for Statistical Computing, Vienna, Austria); a *P*-value of less than 0.05 was considered statistically significant.

RESULTS

From the 1222 initially identified patients, 1065 had preoperatively confirmed normal sinus rhythm. A conventional CDU system with continuous wall suction (−20 cm H_20) was applied in 377, ATC in 191 and PDDS in 497 patients. Sixteen patients who had altered courses of surgery due to complications other than bleeding and/or tamponade, dying in the early perioperative period or receiving intra-aortic balloon pump and/or mechanical circulatory support (8 in the CDU, 3 in the ATC and 5 in the PDDS cohorts) were excluded from the final analysis. The cause of death perioperatively and thus the reason for exclusion from the analysis was rupture of the ascending aorta with subsequent tamponade in 1 patient with a PDDS and aortic dissection with reoperation and heart failure in 1 patient with ATC. Thus, the final cohort comprised 188 patients with ATC, 369 with CDU and 492 patients with a PDDS (Fig. 1).

In non-adjusted analyses, patients with a CDU had the lowest platelet counts and the lowest incidence of COPD (Table 1) [17]. The single retrosternal drainage tube was the predominant mode of drain placement in patients with ATC (Table 1). Patients with a PDDS had less CKD but higher platelet counts and incidence of COPD. Aspirin was prescribed less frequently in the PDDS group. Both CPB and ATX times were longest and the proportion of posterior pericardial chest tube placement was highest in the PDDS cohort (Table 1).

After adjustment by propensity weighting, COPD remained lowest in the CDU cohort; however, platelet counts and isolated CABG became comparable across the groups (Table 1). Insertion of a single retrosternal drainage tube remained most frequent in the ATC cohort, also after adjustment. In the PDDS cohort, less frequent CKD and peripheral arterial occlusive disease rates persisted after adjustment, whereby prescription rates of aspirin became comparable across the groups. Both CPB and ATX times remained longest and the proportion of posterior pericardial chest tube placement highest in the PDDS cohort, also after adjustment (Table 1).

Primary outcomes

Before propensity weighting adjustment, lowest early and any re-exploration for bleeding (1.2%, $P = 0.032$ and 1.4%, $P = 0.006$, respectively) and the lowest incidence of POAF (18.7%, $P < 0.001$) were observed in the PDDS cohort (Table 2). Furthermore, RBS-associated interventions occurred less often in patients with ATC (6.9%) and PDDS (5.1%) than in those with CDU (14.6%, $P < 0.001$, Table 2). After adjustment, RBS-associated interventions remained less frequent in both the PDDS cohort with an OR of 0.31 [95% confidence interval (CI) 0.19, 0.51] and the ATC cohort with an OR of 0.43 (95% CI 0.22, 0.79, $P < 0.001$), whereas PDDS remained associated with a reduced requirement for early re-exploration for bleeding [OR 0.29 (95% CI 0.10, 0.72), $P = 0.032$], as well as a reduced incidence of POAF [OR 0.54 (95% CI 0.39, 0.74), $P < 0.001$] (Fig. 2).

To better understand potential underlying pre-existing substrate and pathophysiological contributors, the following parameters were analysed in the ATC, CDU and PDDS subcohorts developing

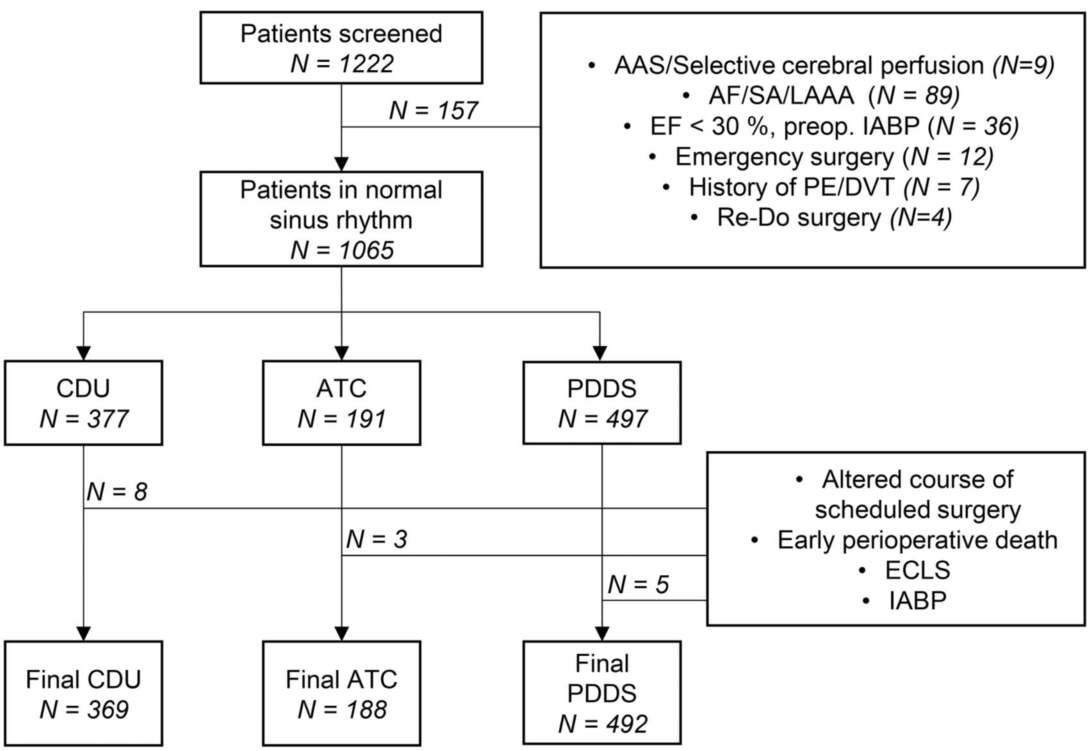


Figure 1: Flow chart of patient selection protocol for the study. AAS: ascending aortic surgery; AF: atrial fibrillation; ATC: active tube clearance; CDU: chest drainage unit (wall suction); DVT: deep vein thrombosis; ECLS: extracorporeal life support; EF: ejection fraction; IABP: intra-aortic balloon pump; LAAA: left atrial appendage amputation; PDDS: portable digital drainage system; PE: pulmonary embolism; preop: preoperative; Re-Do surgery: repetitive surgical revascularization; SA: surgical ablation.

Table 1: Comparison of demographic and operative characteristics for portable digital drainage, conventional and active tube clearance drainage system (17)

	PDDS	CDU	ATC	*P*-value	*P*-adjusted
N	492	369	188		
Age, median [IQR]	67.0 [60.0, 73.0]	68.0 [61.0, 75.0]	68.5 [61.0, 75.0]	0.188	0.268
Female gender, *n* (%)	98 (19.9)	70 (19)	43 (22.9)	0.548	0.858
BMI, median [IQR]	28.1 [25.5, 31.1]	27.4 [24.9, 30.9]	27.8 [25.2, 30.2]	0.202	0.270
CHA_2DS_2VASc score, median [IQR]	3.0 [2.0, 4.0]	3.0[2.0, 4.0]	3.0 [2.0, 4.0]	0.144	0.174
Aspirin, *n* (%)	345 (70.3)	286 (77.5)	145 (77.1)	0.032	0.053
Glycoprotein IIb/IIIa inhibitor, *n* (%)	4 (0.8)	5 (1.4)	2 (1.1)	0.742	0.510
ADP P2Y12 inhibitor, *n* (%)	61 (12.4)	40 (10.8)	30(16)	0.224	0.831
HMWH iv, *n* (%)	118 (24.0)	92 (24.9)	37(19.7)	0.367	0.720
Preoperative platelets ($10^3/\mu L$), median [IQR]	217 [190, 250]	209 [166, 250]	219 [192, 256]	0.002	0.750
LVEF%, median [IQR]	60 [55, 60]	60 [55, 60]	60 [55, 60]	0.454	0.595
Hypertension, *n* (%)	467 (94.9)	347 (94.0)	179 (95.2)	0.794	0.999
History of MI, *n* (%)	153 (31.1)	121 (32.8)	60 (31.9)	0.870	0.870
Diabetes mellitus, *n* (%)	160 (32.5)	118 (32)	73 (38.8)	0.224	0.751
COPD, *n* (%)	72 (14.6)	10 (2.7)	11 (5.9)	<0.001	<0.001
CKD, *n* (%)	9 (1.8)	26 (7.4)	12 (6.8)	<0.001	0.001
PAOD, *n* (%)	85 (17.3)	83 (23.7)	40 (22.7)	0.054	0.015
Preoperative dialysis, *n* (%)	3 (0.6)	6 (1.6)	4 (2.1)	0.196	0.073
INR preoperatively	1.0 [1.0, 1.0]	1.0 [1.0, 1.0]	1.0 [1.0, 1.0]	0.05	0.076
Child-Pugh A, *n* (%)	6 (1.2)	6 (1.6)	4 (2.1)	0.094	0.128
Child-Pugh B, *n* (%)	0 (0.0)	1 (0.3)	0 (0.0)	0.398	0.390
Preoperative Hct %, median [IQR]	41 [40, 44]	42 [39, 44]	41 [38, 43]	0.259	0.183
Beta blocker, *n* (%)	340 (69.1)	264 (71.5)	146 (77.7)	0.087	0.203
Combined CABG + valve	30 (6.1)	33 (8.9)	13 (6.9)	0.276	0.793
CPB (min)	75.5 [62.0, 93.0]	72.0 [55.0, 88.0]	70.5 [58.0, 86.0]	0.001	0.001
Aortic cross-clamp (min)	44.5 [36.0, 55.2]	42.0 [32.0, 53.0]	42.0 [33.8, 52.2]	0.003	0.002
Ratio left pleura open/closed	0.79	1.24	1.04	0.003	0.001
Pericardial chest tube combination, *n* (%)	220 (44.7)	78 (21.1)	7 (3.7)	<0.001	<0.001

The values are expressed as number (%) or median [IQR].

ATC: active tube clearance; BMI: body mass index; CABG: coronary artery bypass grafting; CDU: conventional drainage unit; Child-Pugh: hepatic dysfunction staging ; CKD: chronic kidney disease; COPD: chronic obstructive pulmonary disease; CPB: cardiopulmonary bypass; Hct: hematocrit test; HMWH: high-molecular-weight heparin; IQR: IQR: interquartile range; iv: intravenous; LVEF: left ventricular ejection fraction; MI: myocardial infarction; PAOD: peripheral arterial occlusive disease; PDDS: portable digital drainage system;.

POAF: POAF characteristics including initiation, duration, recurrences, electrical cardioversion requirement and status at discharge; perioperative characteristics like beta blocker administration and transfusion of RBCs, characteristics of the surgical procedure and inflammatory course data. Beta blocker-naive status was identified in 39 (59%) patients in the ATC, in 61 (55.5%) in the CDU and in 57 (62%) patients in the PDDS subcohorts, respectively ($P = 0.411$). The beta-blocker-free interval between preoperative cessation and postoperative readministration was 95.1 (91.4) h in ATC, 74.1 (71.2) h in the CDU and 97.2 (137) h in the PDDS subcohorts ($P = 0.370$), respectively. A biological aortic valve prosthesis was implanted in addition to CABG in 2 (3%) patients with ATC, 11 (10%) with CDU and 8 (8.7%) with PDDS ($P = 0.255$), respectively. A left internal mammary artery was used as a single in situ graft in 64 (97%) patients in the ATC, in 107 (97.2%) patients in the CDU and in 87 (94.6%) patients ($P = 0.297$) in the PDDS cohorts, respectively. A right internal mammary artery was used as an in situ or a radial artery was used as a free graft in 5 (7.6%) patients with ATC, 11 (10%) patients with CDU and 9 (9.8%) patients with PDDS ($P = 0.852$), respectively. The average number of vein grafts performed was 1.4 (0.7) in the ATC, 1.3 (0.7) in the CDU and 1.4 (0.7) in the PDDS subcohorts ($P = 0.521$), respectively. In the POAF subcohort, 46 (69.7%) patients with ATC, 82 (74.5%) with CDU and 62 (67.4%) with PDDS received RBC transfusions. Postoperatively, peak C-reactive protein values were 20.3 (6.5) mg/L in patients with ATC, 20.9 (12.7) mg/L in patients with CDU and 20.6 (7.3) mg/L in patients with PDDS ($P = 0.949$), respectively. Similar peak counts of white blood cells were observed postoperatively in the ATC [13.9×10^9/L (4.2)], the CDU [13.8×10^9/L (5.4)] and the PDDS [13.7×10^9/L (3.4)] cohorts, respectively ($P = 0.989$). The first POAF episode occurred in the ATC 51.7 (25.6), in the CDU 61.6 (36.5) and in the PDDS 60 (30.4) h after the index operation ($P = 0.153$), respectively. POAF recurred in 24 (36.4%) ATC, 36 (32.7%) CDU and 44 (47.8%) PDDS patients ($P = 0.082$), respectively. The cumulative POAF duration was 16.3 (23.3) h in the ATC, 15.3 (15.7) h in the CDU and 20.4 (19.9) h in the PDDS subcohorts ($P = 0.259$), respectively. Electrical cardioversion was applied to restore sinus rhythm in 7 (10.6%) patients with ATC, in 7 (6.4%) patients with CDU and in 8 (8.7%) patients with PDDS ($P = 0.730$), respectively. At discharge, atrial fibrillation persisted in 4 (6.1%) patients with ATC, 4 (3.6%) patients with CDU and 9 patients (9.8%) with PDDS ($P = 0.240$), respectively.

Secondary outcomes

In-hospital mortality was 1.6% in patients with conventional CDU, 1.1% in patients with ACT and 0.8% in patients with PDDS and was similar across cohorts (non-adjusted $P = 0.536$, propensity adjusted $P = 0.358$, Table 2). Of the 12 deceased patients, 2 patients in the CDU cohort, 1 patient in each ACT and PDDS cohort, respectively had undergone re-exploration

Table 2: Propensity weighing adjusted postoperative outcomes for portable digital, conventional and active tube clearance drainage systems

	PDDS	CDU	ATC	*P*-value	*P*-adjusted
Early re-exploration, *n* (%)	6 (1.2)	15 (4.1)	7 (3.7)	0.023	0.032
Re-exploration, *n* (%)	7 (1.4)	19 (5.1)	8 (4.3)	0.006	0.010
Postoperative AF, *n* (%)	92 (18.7)	110 (29.8)	66 (35.1)	<0.001	<0.001
RBS, *n* (%)	25 (5.1)	54 (14.6)	13 (6.9)	<0.001	<0.001
In-hospital deaths, *n* (%)	4 (0.8)	6 (1.6)	2 (1.1)	0.536	0.358
Time to return to op,	8.0 [6.5, 13.5]	6.0 [3.2, 8.8]	18.0 [11.0, 29.5]	0.193	0.123
Surgical bleeding	5 (1.0)	9 (2.4)	3 (1.6)	0.262	0.246
Tamponade	5 (1.0)	14 (3.8)	4 (2.1)	0.022	0.064
Coagulopathy	2 (0.4)	10 (2.7)	5 (2.7)	0.014	0.021
UPBD class 0/1/2/3	365/32/80/15 (74.2/6.5/16.3/3.0)	246/29/65/29 (66.7/7.9/17.6/7.9)	122/10/46/10 (64.9/5.3/24.5/5.3)	0.005	0.009
Drainage 0–6 h (ml)	200 [150, 300]	200 [150, 300]	200 [100, 300]	0.210	0.244
Drainage 6–12 h (ml)	150 [100, 200]	150 [100, 200]	150.0 [100, 225]	0.438	0.184
Drainage 24 h (ml)	550 [400, 700]	550 [400, 750]	550 [430, 750]	0.627	0.563
ICU stay (h)	24.0 [3.0, 48.0]	24.0 [24.0, 72.0]	48.0 [24.0, 72.0]	<0.001	<0.001
Mechanical ventilation (h)	8.5 [6.0, 12.0]	9.0 [7.0, 13.0]	9.0 [7.0, 13.0]	0.869	0.876
New stroke, *n* (%)	5 (1.0)	6 (1.6)	3 (1.6)	0.700	0.261
CSA-AKI, *n* (%)	70 (14.2)	57 (15.4)	22 (11.7)	0.488	0.124
Postoperative dialysis, *n* (%)	6 (1.2)	9 (2.4)	5 (2.7)	0.306	0.354
Pleural intervention, *n* (%)	16 (3.3)	34 (9.2)	2 (1.1)	<0.001	<0.001
Pericardial intervention, *n* (%)	1 (0.2)	4 (1.1)	3 (1.6)	0.119	0.220
Pneumothorax, *n* (%)	8 (1.6)	19 (5.1)	6 (3.2)	0.014	0.006
Postoperative RBCs, *n* (%)	120 (24.4)	125 (33.9)	68 (36.2)	0.001	0.001
Postoperative FFP, *n* (%)	33 (6.7)	21 (5.7)	20 (10.6)	0.090	0.144
Postoperative platelets	27 (5.5)	18 (4.9)	13 (6.9)	0.609	0.535
Postoperative amiodarone (%)	79 (16.1)	62 (17.2)	31 (16.9)	0.902	0.670

The values are expressed as number (%) or median [IQR].

AF: atrial fibrillation; ATC: active tube clearance; CDU: conventional drainage unit; CSA-AKI: cardiac surgery associated acute kidney injury; FFP: fresh frozen plasma; ICU intensive care unit; PDDS: portable digital drainage system; RBC: red blood cell; RBS: retained blood syndrome; UPDB: perioperative bleeding (universal definition; 14).

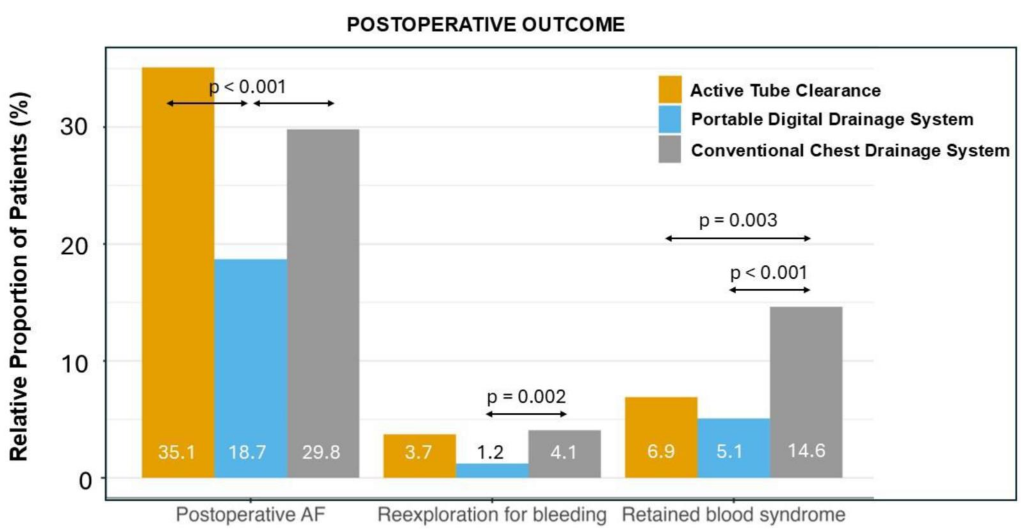


Figure 2: Comparison of active tube clearance, portable digital and conventional drainage system. AF: atrial fibrillation.

for bleeding and/or tamponade. Hourly bleeding volumes were 200 ml, 150 ml and 550 ml in the first 6 h and at 12 and at 24 h across all 3 groups ($P = 0.210$, $P = 0.438$ and $P = 0.627$, respectively) and remained comparable after propensity weighting ($P = 0.244$, $P = 0.184$ and $P = 0.563$, respectively, Table 2). Nevertheless, patients with conventional CDUs had a more pronounced tendency to bleed, as expressed with the universal bleeding definition (14, non-adjusted $P = 0.005$ and adjusted $P = 0.009$, respectively) and a higher proportion of coagulopathic bleeding-associated re-exploration for bleeding (non-adjusted $P = 0.014$ and adjusted $P = 0.021$, respectively) as depicted in Table 2. Significantly lower RBC transfusion rates and shorter ICU and postoperative hospital stays were observed in the PDDS cohort in non-adjusted ($P \leq 0.001$ for all) and adjusted analyses ($P \leq 0.001$ for all), respectively (Table 2).

DISCUSSION

The drainage systems available differ in terms of clinical performance. Although we determined that, similar to our previous study [6], active maintenance of chest tube patency reduced RBS by 53% (from 14.6% to 6.9%), we also observed that the immediate instillation of a PDDS at the time of sternal closure in combination with frequent placement of additional pericardial chest tubes resulted in a 65% reduction in RBS from 14.6% to 5.1%. Furthermore, a 70% reduction in the need for re-exploration for bleeding from 4% to 1.6% and a 37% reduction of POAF from 29.9% to 18.7% were observed in the PDDS cohort.

The rate of RBS requiring intervention varies largely from 9.2% to 22%, reflecting non-uniform definitions and thresholds for interventions across institutions, different placement and sizing of chest tubes, diverse early postoperative anti-/procoagulation and blood management as well as heterogeneous study cohorts [2–12]. As an RBS component with the potentially most devastating consequences, re-exploration for bleeding and/or tamponade turned out to be a major contributor to mortality both in myocardial revascularization [2] and in the general cardiac postsurgical cohort [18, 19]. These negative effects were more pronounced in cases of delayed indication; however, aggressive indication for early re-exploration resulted in a neutral or even favourable impact on mortality [13, 18, 19, 20].

With the rates of re-exploration for bleeding ranging widely in the literature from 1% to 9.9% [2–12], Grieshaber *et al.* [8] reported a 56% reduction in patients receiving ATC in addition to an 18 Fr posterior pericardial chest tube. In an isolated myocardial revascularization cohort, a 6.3% re-exploration-for-bleeding rate was reported with standardized conventional setting of a 30 Fr retrosternal and a 24 Fr posterior pericardial chest tube in place [2]. In this study, more than a 2-fold reduction in early re-exploration for bleeding was observed in the PDDS cohort compared to the CDU cohort with immediate suction directly after sternal closure, application of a 28 Fr retrosternal chest tube and application of an additional 24 Fr retro cardiac chest tube in 44.7% of our patients. On the other hand, the application of a single 28 Fr ATC catheter and an additional 28 Fr posterior pericardial chest tube provided a 3.7% early re-exploration rate in the ATC cohort, which was similar to the situation in the conventionally drained patients. The latter result implies that maintaining chest tubes open in the external portion, without knowing if they are obstructed in the internal portion or already surrounded by a pericardial clot, seems to be insufficient to prevent accumulation of retained blood or subsequent formation of clots.

Conversely, it is plausible to assume that effective drainage of the pericardial space from the very moment of sternal closure onward, when the postoperative bleeding is most intensive, remains a crucial measure to prevent cardiac tamponade. This assumption, however, leaves open the dilemma of whether these observations are attributable to pericardial chest drainage in place or rather to the immediate suction preventing blood from clotting around the heart. Of note, a combination of persisting bleeding and inadequate drainage would facilitate the accumulation of clot around the heart, initiating a vicious cycle with rapidly developing cardiac tamponade already at small bleeding volumes. In this connection, posterior pericardial drainage by a posterior pericardiotomy and/or placement of an additional pericardial chest tube resulted in up to 90% reduction of the odds for tamponade and pericardial effusion [21, 22]. It might therefore be expected that only cardiac drainage providing removal of shed blood from the entire pericardial space immediately at the end of the operation, well before it starts to clot, might lead to comprehensive reduction of re-exploration for bleeding and/or tamponade.

As many as one-third of patients taken back to the operating room for haemostasis and resolution of cardiac tamponade are re-explored without finding a surgical source of bleeding. Furthermore, patients with excessive bleeding, re-explored late (25–28 h), exhibit a 3-fold greater morbidity and 10-fold higher mortality than patients re-explored within the first 4 h [18, 20]. Thus, it is plausible to assume that many returns to the operating room could be avoided by improving effective removal of shed blood during the time when the postoperative coagulopathy is corrected and the patient's bleeding stops. Furthermore, such an effective drainage system would ideally prolong the interval to haemodynamic instability and/or tamponade in the case of excessive surgical bleeding. Importantly, ATC with a single retrosternally placed chest tube and standard wall suction on arrival in the ICU did not result in a reduced rate of re-exploration for bleeding in our study, whereas constant immediate suction with a frequently placed retro cardiac chest tube in the PDDS cohort reduced the need for re-exploration similarly to the reported 73% reduction of re-exploration for bleeding in the randomized study of ATC in combination with a posterior pericardial chest tube [9].

The present study demonstrates a $> 30\%$ reduction in POAF in the PDDS cohort, whereas POAF rates remained comparable in both the conventional and the ATC cohorts. Given that the risk of distant persistent AF is increased 5–8 times in patients with POAF [23, 24], understanding the underlying pathophysiological causal mechanisms is crucial to improving current strategies to reduce the incidence of POAF. Aberrant cardiac autonomic neuromodulation, arrhythmic circuits in the pulmonary veins and/or atria and pericardial effusion have been listed as the leading pathophysiological determinants underlying POAF [15, 24].

Postoperative pericardial effusion and localized pericardial inflammation seem to play pivotal roles in triggering POAF in the first postoperative days directly through mechanical irritation and indirectly through cardiac autonomic modulation derangement [22]. The strategies used to reduce pericardial effusion demonstrated improved surgical outcomes [21, 24, 25]. Specifically, a posterior pericardiotomy incision with or without posterior pericardial chest tube placement resulted in a 58% reduction of POAF [21]; a similarly reduced incidence of POAF was also noted in a large meta-analysis of randomized control trials [24, 25]. Of note, posterolateral pericardial effusion with a cut-off of 10 mm but not anterior pericardial effusion was associated with POAF [25, 26]. The latter implies that the location of the effusion matters and also that even smaller amounts of retained blood might trigger POAF through clot, haemolysis, inflammation with reactive oxygen species and epicardial nervous system activation at the posterolateral aspect of the heart [25, 26]. We speculate that relatively less effective drainage of the posterior pericardium in ATC and conventional systems versus PDDS accounted for the observed diverging rates of POAF in our cohorts.

Limitations

The present study was a retrospective analysis and therefore subject to limitations including investigator bias and errors in manual data extraction from the electronic medical records.

Although the clinical protocols and surgical team remained identical, with comparable complication rates of our previous [6] and present analyses, the potential bias of time due to subsequent study cohorts cannot be completely excluded. In addition, not all relevant factors, such as exact findings at re-exploration for retained blood or the cytology of fluid removed by thoracentesis, were available for inclusion in this analysis. In addition, we did not differentiate the results in regard to the severity of tamponade on re-exploration. The documentation of retained blood relied on interventions and therefore might have been underestimated. Although we carefully documented the pattern and duration of chest tubes in place as well as the quantity of the drainage fluid, the exact causal analysis of the observed differences was not possible because not all of the patients received an additional posterior pericardial chest tube nor was the degree of obstruction [4] determined when the chest tube was removed. Not all possible confounding effects could be neutralized in this analysis, especially the potentially protective role of posterior pericardial chest tube placement for re-exploration or anticipated increased risk for postoperative bleeding complications, especially in patients with chronic renal insufficiency [27]. The present results refer predominantly to the patients undergoing elective myocardial revascularization with preserved LVEF, moderate morbidity and preoperatively checked pro-bleeding diathesis without ongoing anticoagulation. Because RBS can be even more deleterious for higher-risk patients [3], further investigation is warranted to determine the most optimized postinterventional chest cavity drainage management system for higher-risk patients.

CONCLUSION

The present study underscores the fact that the use of different drainage modalities and of various chest placement strategies significantly impacts postoperative outcomes in patients undergoing CABG. Both ATC and PDDS demonstrated superiority over conventional drainage in reducing RBS interventions, with PDDS offering additional benefits in terms of early re-exploration for bleeding, POAF incidence, RBC transfusion requirements and resource utilization reduction. In this regard, adoption of advanced drainage systems including effective immediate drainage of posterior pericardium may play a pivotal role in improving patient outcomes and further optimizing postoperative care in cardiac surgery.

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DATA AVAILABILITY

All relevant data are within the manuscript and its supporting information files.

Author contributions

Jurij M. Kalisnik: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Supervision; Writing—original draft; Writing—review & editing. **Vitalijs Zujs:** Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing—original draft. **Janez Zibert:** Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing—original draft. **Jacob Arne B. Carstensen:** Data curation; Formal analysis; Investigation; Methodology; Project administration. **Jan-Niklas Krohn:** Data curation; Formal analysis; Investigation; Methodology; Project administration. **Islam Batashev:** Data curation; Formal analysis; Investigation; Methodology. **Spela Leiler:** Data curation, Formal analysis; Methodology; Project administration. **Theodor Fischlein:** Conceptualization; Supervision; Writing—review & editing.

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REVIEW