Active clearance of chest tubes is associated with reduced postoperative complications and costs after cardiac surgery: a propensity matched analysis

Yvon Baribeau 1*, Benjamin Westbrook 1, Yanick Baribeau 2, Simon Maltais 3, Edward M. Boyle 4 and Louis P. Perrault 5

Abstract

Background: Chest tubes are routinely used to evacuate shed mediastinal blood in the critical care setting in the early hours after heart surgery. Inadequate evacuation of shed mediastinal blood due to chest tube clogging may result in retained blood around the heart and lungs after cardiac surgery. The objective of this study was to compare if active chest tube clearance reduces the incidence of retained blood complications and associated hospital resource utilization after cardiac surgery.

Methods: Propensity matched analysis of 697 consecutive patients who underwent cardiac surgery at a single center. 302 patients served as a baseline control (Phase 0), 58 patients in a training and compliance verification period (Phase 1) and 337 were treated prospectively using active tube clearance (Phase 2). The need to drain retained blood, pleural effusions, postoperative atrial fibrillation, ICU resource utilization and hospital costs were assessed.

Results: Propensity matched patients in Phase 2 had a reduced need for drainage procedures for pleural effusions (22% vs. 8.1%, \( p < 0.001 \)) and reduced postoperative atrial fibrillation (37 to 25%, \( P = 0.011 \)). This corresponded with fewer hours in the ICU (43.5 [24–79] vs 30 [24–49], \( p < 0.001 \)), reduced median postoperative length of stay (6 [4–8] vs 5 [4–6.25], \( p < 0.001 \)) median costs reduced by $1831.45 (−3580.52; 82.38, \( p = 0.04 \)) and the mean costs reduced by an average of $2696 (−6027.59; 880.93, 0.116).

Conclusions: This evidence supports the concept that efforts to actively maintain chest tube patency in early recovery is useful in improving outcomes and reducing resource utilization and costs after cardiac surgery.

Trial registration: Clinicaltrial.gov, NCT02145858, Registered: May 23, 2014.

Keywords: Chest tube, Cardiac surgery, Critical care, Postoperative atrial fibrillation, Pleural effusion, Costs

Background

In the early hours after heart surgery shed mediastinal blood accumulates until the postoperative bleeding stops. Shed mediastinal blood is evacuated by chest tubes positioned around the heart and lungs connected to external blood collection canisters set to suction. Chest tube clogging, however, can lead to un-evacuated shed mediastinal retained around the heart and lungs [1, 2]. This can contribute to the development of tamponade, hemothorax, or bloody pericardial and pleural effusions. Patients with retained blood have more complications including postoperative atrial fibrillation (POAF) and acute kidney injury (AKI) as well as utilization of more intensive care unit (ICU) resources and longer length of stay [1, 3–6]. In many cases, chest tubes are milked and stripped to attempt to clear the lumens of any clogging that can be visualized at the bedside [7]. However, these approaches have been shown to be ineffective and may be potentially harmful [8]. Active tube clearance (ATC) of drainage catheters was...
developed to allow a bedside mechanism for chest tube clearance of clot in the ICU during early recovery [9]. ATC has been shown to reduce interventions for retained blood as well as reduce the incidence of POAF during the index hospitalization after surgery [5, 10–12]. The purpose of this study was to determine if active tube clearance (ATC) might reduce the incidence of retained blood, as well as other associated hospital resources and costs after cardiac surgery.

Materials and methods

This study included 639 consecutive patients undergoing adult cardiac surgery performed by two surgeons (YB and BW) at the New England Heart and Vascular Institute, Catholic Medical Center (CMC), Manchester, NH. The study protocol was registered (NCT02145858) and was approved by the CMC Institutional Review Board (CARD2015–6). Data was collected from our prospectively collected institutional Society of Thoracic Surgeons (STS) database. Additional analysis was supplemented with administrative data using ICD and CPT codes to obtain hospital costs. Patients were divided into those consecutive adult cardiac surgery patients who received conventional chest tubes only (Phase 0, n = 302), an ATC training and compliance verification segment (Phase 1, n = 58) and a consecutive cohort treated with ATC (Phase 2, n = 337). Aspirin was continued preoperatively, while thienopyridines (ADP inhibitors), and warfarin were generally held 5 to 7 days before the operation and GP IIb/IIIa were withheld within 1 day of surgery. In patients with preoperative ADP inhibitors needing urgent surgery, a thromboelastogram was performed and surgery allowed when the platelet inhibition level less than 50%. β–blockade was used in all suitable cases before and after the index procedure and amiodarone was not given prophylactically.

In all groups, all CABG patients were implanted with one 24 Fr chest tube in the retrosternal position, and one 24 Fr chest tube in the pleural space, if opened. All valve and other cases were implanted with 2 retrosternal 24 Fr chest tubes, and one in the pleural space, if opened. In Phase 0, when tube clots were identified, chest tube milking was carried out on an as needed basis at the nurses’ discretion. An ATC system (PleuraFlow Active Clearance Technology; ClearFlow, Inc., Anaheim, CA) was then introduced in Phase 1 and Phase 2. ATC is a chest tube clearance apparatus with a mechanism to actively keep the entire inner lumen of the chest tube clear of obstructing blood clot or fibrinous debris [9]. ATC was actuated every 15 min for the first 8 h, then every 30 min for the next 16 h, and then once an hour and as needed thereafter [5, 13]. No data was collected while the protocol was introduced and training completed (Phase 1). Other than the use of ATC in Phase 2, there were no other differences in the size, placement location or management of chest tubes during this study. Mediastinal chest tubes were removed 24 h postoperatively or when drainage volume was less than 50 mL during the previous 8 h. Pleural chest tubes were removed 48 h postoperatively or when drainage volume was less than 200 mL during the past 24 h.

Phase 0 patients were then compared with Phase 2 for the primary endpoint of retained blood interventions after the index procedure. Retained blood is a previously described composite endpoint that encompasses any postoperative re-intervention to treat one or more of the following in the first 30 days after an initial index procedure: Re-exploration for bleeding with washout of retained blood, pleural interventions-percutaneous (thoracocentesis or supplemental chest tube placed after surgery), pleural interventions-surgical (thoracotomy or thoracoscopy for hemothorax after surgery), or pericardial interventions (pericardial window or pericardiocentesis) [1, 4, 5, 11]. All patients were monitored continuous telemetry from index surgery for 3 days in CABG only patients, and through hospital discharge for all other patients. Consistent with the STS definition, POAF was defined as an episode of atrial fibrillation/flutter lasting longer than one hour and/or requiring treatment at any time between post index surgery through hospital discharge. Patients who had a documented history of atrial fibrillation/flutter prior to surgery were excluded from the POAF sub analysis. Acute Kidney Injury (AKI) was defined by KDIGO stage [14]. Chest tube output was measured on an hourly basis until chest tube removal. Hospital costs were provided by the hospital’s finance department. Cost were defined as total cost data for Phase 0 and Phase 2 subjects from the time of admission to the time of discharge.

Statistical analysis

Table 1 describes the summary statistics, standardized difference calculation, and the statistical tests used for each variable. The non-symmetrically distributed continuous variables tended to have long right tails, and so the analysis calculated standardized differences after log-transforming these variables. The subscripts 0 and 2 refer to Phase 0 and Phase 2 and the symbols $\bar{X}$, $s$, $m$, $q_1$, $q_3$, $c$, $f$, and $\hat{p}$ refer to the following sample statistics: mean, standard deviation, median, first quartile, third quartile, total count, frequency, and proportion. The analysis matched the patients from Phase 0 and Phase 2 in a one-to-one fashion using the pairmatch function from the R package optmatch. This matching combined propensity score matching based on the variables given in Table 2 with forced matching on ADP inhibitors, glycoprotein IIb/IIIa inhibitors, and procedure type.
Hospital cost data are reported as both median and mean values. Confidence intervals for the cost differences between Phase 2 and Phase 0 were obtained via bootstrapping for the mean and via quantile regression for the median. A two-sided \( p \)-value \( \leq 0.05 \) was considered statistically significant.

**Results**

Unmatched patient characteristics and outcomes are presented in Tables 2, 3 and 4. After propensity matching, 260 of 302 patients in Phase 0 were selected for comparison with 260 matched patients in Phase 2. The propensity matching balanced the Phase 0 and Phase 2 patients with respect to the demographic and pre/intra-operative characteristics (Table 5). In Phase 2 more than 1 ATC were used in select cases resulting in an average of 1.2 ATC inserted per patient in the retrosternal position over an open pericardium. The overall incidence of retained blood in matched Phase 0 patients through the first 30 days at baseline (Phase 0) was 23% (60/260), with a 59% reduction.

---

**Table 1** Summary of statistical methods based on the types of variables

| Type of variable X | Summary statistics | Standardized difference | Statistical test for unmatched data | Statistical test for matched data |
|--------------------|--------------------|-------------------------|------------------------------------|----------------------------------|
| Symmetric continuous variable | \( \bar{X} \pm s \) | \( \frac{\bar{X}_1 - \bar{X}_0}{\sqrt{s_1^2 + s_0^2}} \) | Independent samples t-test | Paired samples t-test |
| Non-symmetric continuous variable | \( m [q_1 - q_3] \) | The standardized difference defined above for lnX | Wilcoxon’s rank sum test | Wilcoxon’s signed rank test |
| Count variable | \( c \) | Standardized difference for symmetric continuous variable | Independent samples t-test | Paired samples t-test |
| Binary variable | \( f \left( \frac{p}{\%} \right) \) | \( \frac{p_2 - p_0}{\sqrt{(p_2(1-p_2) + p_0(1-p_0)))}/2} \) | Fisher’s exact test | McNemar’s test |

---

**Table 2** Demographic and Pre/Intra-operative Characteristics (Unmatched)

| Variable (mean n, %) | All (n = 639) | P0 (n = 302) | P2(n = 337) | \( p \) value |
|----------------------|---------------|--------------|-------------|---------------|
| Age (years) | 66 ± 11.6 | 67 ± 10.2 | 65.1 ± 12.6 | 0.036 |
| Gender (male) | 441 (69%) | 205 (68%) | 236 (70%) | 0.61 |
| Weight (kg) | 89 ± 20 | 88 ± 20 | 90 ± 21 | 0.13 |
| Diabetes | 274 (43%) | 118 (39%) | 156 (46%) | 0.078 |
| Hypertension | 515 (81%) | 243 (80%) | 272 (81%) | 1 |
| Prior PCI | 155 (24%) | 70 (23%) | 85 (25%) | 0.58 |
| NYHA I | 329 (51%) | 162 (54%) | 167 (50%) | 0.3 |
| NYHA II, III or IV | 310 (49%) | 140 (46%) | 170 (50%) | 0.3 |
| Preop atrial arrhythmia | 131 (21%) | 59 (20%) | 72 (21%) | 0.62 |
| Preop IABP | 50 (7.8%) | 25 (8.3%) | 25 (7.4%) | 0.77 |
| ADP inhibitors | 55 (8.6%) | 37 (12%) | 18 (5.3%) | 0.0027 |
| Preop Aspirin | 621 (97%) | 300 (99%) | 321 (95%) | 0.0015 |
| Preop Warfarin | 6 (0.94%) | 3 (0.99%) | 3 (0.89%) | 1 |
| GIIb/IIIa | 7 (1.1%) | 7 (2.3%) | 0 (0%) | 0.0051 |
| First Time Surgery | 601 (94%) | 284 (94%) | 317 (94%) | 1 |
| Reoperation | 38 (5.9%) | 18 (6%) | 20 (5.9%) | 1 |
| Operative Status (Elective) | 269 (42%) | 130 (43%) | 139 (41%) | 0.69 |
| Operative Status (Non Elective) | 370 (58%) | 172 (57%) | 198 (59%) | 0.69 |
| CABG | 359 (56%) | 167 (55%) | 192 (57%) | 0.69 |
| Valve | 79 (12%) | 49 (16%) | 30 (8.0%) | 0.0056 |
| CABG + Valve | 78 (12%) | 38 (13%) | 40 (12%) | 0.81 |
| Other | 123 (19%) | 48 (16%) | 75 (22%) | 0.045 |
| CPB (yes) | 295 (46%) | 140 (46%) | 155 (46%) | 0.94 |

Abbreviations: Coronary Artery Bypass Surgery (CABG), Cardiopulmonary Bypass (CPB), Glycoprotein GIIb/IIIa inhibitor (GIIb/IIIa), Intra Aortic Balloon Pump (IABP), New York Heart Association (NYHA), Percutaneous Cardiac Interventions (PCI)
to 9.6% (25/260) in the matched Phase 2 patients ($P < 0.001$). (Table 6) The number needed to treat for this RBS reduction was 7.4 [95% CI 5–14.6, $p = 0.001$].

The rate of percutaneous pleural interventions was similarly reduced in the analysis from 22% in Phase 0 to 8.1% ($P < 0.001$) in Phase 2. Patients in Phase 2 had a reduced number of pleural interventions. (139 vs 53, $p = 0.002$). The other less common components of the retained blood composite such as re-exploration for bleeding, pericardial drainage procedures, surgical pleural drainage procedures were not significantly different between phases. Phase 2 patients had a 32.4% reduced incidence of POAF (37% in Phase 0 to 25% in Phase 2; $p = 0.011$) (Table 5). The NNT for the reduction in POAF was 8.7 [CI 4.9–43.6, $p = 0.014$]. There was a reduction in KDIGO stage 1 AKI from 30 to 17% ($P = 0.0014$) and total chest tube output was significantly lower in Phase 2. (1152 ml vs 1037.50 mL, $p = 0.02$). There were no statistically significant reductions in hospital mortality, cardiac arrest, or permanent stroke. (Table 5) Additionally, there was a marked reduction total ICU hours (43 [24–79] vs 29.75 [24–49], $p < 0.001$); ICU stay > 3 days 27% vs 12%, $< 0.001$), time on the ventilator in hours (9.1 [5–20] vs 7.3 [4.9–17.2], $p 0.004$). (Table 7) Postoperative length of stay was reduced by 1 day from 6 [4–8] to 5

### Table 3 Postoperative Outcomes (Unmatched)

| Variable (mean or mean, n, %) | P0 (n = 302) | P2 (n = 337) | $p$ value |
|-----------------------------|-------------|-------------|----------|
| RB (composite)              | 72 (24%)    | 31 (9.2%)   | < 0.001  |
| Re-exploration              | 6 (2%)      | 3 (0.89%)   | 0.32     |
| Pleural Intervention-Percutaneous | 69 (23%) | 25 (7.4%)   | < 0.001  |
| Pleural Intervention- Surgical | 2 (0.66%)  | 1 (0.3%)    | 0.6      |
| Pericardial Intervention    | 4 (1.3%)    | 4 (1.2%)    | 1        |
| # Pleural Effusion drained  | 168         | 59          | 0.001    |
| POAF                        | 93 (37%) (n = 251) | 67 (25%) (n = 270) | 0.0032   |
| Cardiac arrest              | 8 (2.6%)    | 8 (2.4%)    | 1        |
| Postoperative blood products used | 72 (24%) | 61 (18%)    | 0.079    |
| CTO (mL) first 24 h         | 740 [561.3–975] | 680 [532–910] | 0.016    |
| Total CTO (mL)              | 1136 [834.3–1645] | 1040 [760–1430] | 0.041    |
| Total CT (days)             | 3 [3–4]     | 2 [2–2]     | < 0.001  |
| Infection (any)             | 39 (13%)    | 14 (4.2%)   | < 0.001  |
| Surgical site deep          | 0 (0%)      | 0 (0%)      | 1        |
| Surgical site superficial   | 0 (0%)      | 0 (0%)      | 1        |
| Surgical site mediastinitis | 0 (0%)      | 0 (0%)      | 1        |
| Pneumonia                   | 20 (6.6%)   | 6 (1.8%)    | 0.0022   |
| Septicemia                  | 4 (1.3%)    | 0 (0%)      | 0.049    |
| UTI                         | 11 (3.6%)   | 4 (1.2%)    | 0.064    |
| C. Diff                     | 3 (0.99%)   | 2 (0.59%)   | 0.67     |
| Highest postop- creatinine  | 1.1 [0.905–1.4] | 1 [0.83–1.33] | < 0.001  |
| AKI Stage 1                 | 85 (28%) (n = 299) | 67 (20%) (n = 332) | 0.02     |
| AKI Stage 2                 | 8 (2.7%)    | 8 (2.4%)    | 1        |
| AKI Stage 3                 | 4 (1.3%)    | 3 (0.9%)    | 0.71     |
| Postop-renal dialysis       | 7 (2.3%)    | 2 (0.59%)   | 0.092    |
| Stroke                      | 2 (0.66%)   | 4 (1.2%)    | 0.69     |
| Mortality                   | 7 (2.3%)    | 9 (2.7%)    | 0.81     |

### Table 4 ICU and Hospital Length of Stay (unmatched)

| Variable (median or mean %) | P0 (n = 302) | P2 (n = 337) | $p$ value |
|-----------------------------|-------------|-------------|----------|
| ICU time (Hrs.)             | 44.5 [24–83] | 30 [24–49] | < 0.001  |
| ICU stay > 3 days           | 82 (27%)    | 43 (13%)   | < 0.001  |
| Total time on ventilator (Hrs.) | 8.7 [5–19.7] | 8.2 [5.0–17.5] | 0.27     |
| Ventilation > 24 h.         | 49 (16%)    | 39 (12%)   | 0.11     |
| Hospital LOS (d)            | 8 [5–11]    | 7 [5–10]   | 0.017    |
| Post-op LOS (d)             | 6 [4–8]     | 5 [4–7]    | < 0.001  |

Abbreviations: Retained Blood (RB), Postoperative atrial fibrillation (POAF); Chest tube output (CTO); Chest tube (CT), Urinary Tract Infection (UTI), Clostridium difficile (C.Diff), Acute Kidney Injury (AKI)
the mean costs (Table 9) reduced by an average of -$2696 were reduced by -$1831.45 (− heart surgery patients [2, 15]. Chest tube stripping, milkingeters, occurring in up to 36% of prospectively evaluated blood comes in contact with the inside of drainage cath-trauma. Chest tube clogging can develop when shed ting to clear blood and air from the mediastinal and Chest tubes are used routinely in the intensive care set-

Discussion

Chest tubes are used routinely in the intensive care setting to clear blood and air from the mediastinal and pleural spaces after cardiac and thoracic surgery and trauma. Chest tube clogging can develop when shed blood comes in contact with the inside of drainage catheters, occurring in up to 36% of prospectively evaluated heart surgery patients [2, 15]. Chest tube stripping, milking and open suction have been utilized in an attempt to prevent chest tube clogging, but its safety and efficacy are not shown when reviewed in meta-analysis of randomized trials [8]. In particular, a major issue for chest tube stripping and milking is the potential for the high

[4–6.25], (P < 0.001). The matched median costs (Table 8) were reduced by -$1831.45 ([$−3580.52; $82.38], p = 0.04) the mean costs (Table 9) reduced by an average of -$2696 ([$−6027.59; $880.93], p = 0.116).

Retained blood as an endpoint is defined as any postoperative intervention to remove blood, blood clot or bloody fluid after cardiac surgery [4]. This includes taking a patient back to washout mediastinal clot or hemothorax, inserting an additional chest tube in the ICU, thoracentesis or pericardial drainage for bloody effusions. Sirch, et al., previously demonstrated a 43% relative risk reduction in retained blood in an all comers population of cardiac surgery patients treated with ATC, and Maltais, et al., reported a 59% reduction in retained blood in a mechanical assist cohort of patients [5, 11]. Likewise in this study, we noted a 59% relative risk reduction in retained blood in matched patients.

The primary driver of the reduction in the retained blood composite endpoint were interventions to drain pleural effusion by thoracentesis. In this series over the course of 30 days, 22% of Phase 0 patients required at least one pleural intervention which was reduced to 8.1% in patients in Phase 2. The majority of early pleural effusions are known to be bloody and inflammatory after cardiac surgery [18, 19]. By minimizing retained blood in the pericardium and pleural spaces there could be less of an inflammatory process driving fluid exudation from the inflamed mesothelium during recovery [4]. Although there was a trend toward reduced take back for re-exploration for bleeding for washout of mediastinal clot the sample sizes were too small for statistical comparison [20].

In this study, as also seen by Sirch, et al., the volume of bleeding (measured as chest tube output) was significantly less in Phase 2 patients at 24 h and in total [5]. While this may seem counter intuitive, it suggest there may be an advantage of more rapidly clearing shed mediastinal blood to prevent on going microvascular bleeding from the cut surfaces in the early hours after surgery. Tissue plasminogen activator (t-PA) is known to significantly accumulate in shed mediastinal blood, which can promote on going microvascular bleeding within the postsurgical space if not promptly evacuated by chest tubes [21]. Therefore perhaps having shed mediastinal blood more effectively evacuated could leave

| Variable (mean n, %) | Phase 0 (n = 260) | Phase 2 (n = 260) | p value |
|----------------------|-------------------|-------------------|---------|
| Age (years)          | 66.7 ± 10.1       | 66 ± 11.6         | .4      |
| Gender (male)        | 177 (68%)         | 177 (68%)         | 1       |
| Weight (kg)          | 88 ± 21           | 90 ± 21           | .33     |
| Diabetes             | 106 (41%)         | 107 (41%)         | 1       |
| Hypertension         | 209 (80%)         | 213 (82%)         | .73     |
| Prior PCI            | 61 (23%)          | 66 (25%)          | .67     |
| NYHA Class I         | 139 (53%)         | 133 (51%)         | .63     |
| NYHA Class II, III or IV | 121 (47%) | 127 (49%) | .63 |
| Preoperative atrial arrhythmia | 51 (20%) | 49 (19%) | .91 |
| Preoperative IABP    | 19 (7.3%)         | 22 (8.5%)         | .74     |
| ADP inhibitors       | 18 (6.9%)         | 18 (6.9%)         | 1       |
| Preoperative Aspirin | 258 (99%)         | 257 (99%)         | 1       |
| Preoperative Warfarin| 3 (1.2%)          | 3 (1.2%)          | 1       |
| GIIa/Illla           | 0 (0%)            | 0 (0%)            | 1       |
| First Time Surgery   | 244 (94%)         | 246 (95%)         | .86     |
| Reoperation          | 16 (6.2%)         | 14 (5.4%)         | .86     |
| Operative Status (Elective) | 112 (43%) | 117 (45%) | .71 |
| Operative Status (Non-elective) | 148 (57%) | 143 (55%) | .71 |
| CABG                 | 147 (57%)         | 154 (59%)         | .54     |
| Valve                | 30 (12%)          | 30 (12%)          | 1       |
| CABG + valve         | 35 (13%)          | 32 (12%)          | .78     |
| Other procedure      | 48 (18%)          | 44 (17%)          | .7      |
| CPB (yes)            | 114 (44%)         | 119 (46%)         | .69     |

Abbreviations: Coronary Artery Bypass Surgery (CABG), Cardiopulmonary Bypass (CPB), Glycoprotein GIIb/Illa inhibitor (GIIb/Illa), Intra Aortic Balloon Pump (IABP), New York Heart Association (NYHA), Percutaneous Cardiac Interventions (PCI)
less t-PA remaining in contact with these tissues, facilitating a more rapid achievement of microvascular hemostasis in this time period.

Retained blood is recognized as an important trigger for POAF in susceptible individuals after heart surgery [22–24]. Blood not evacuated from the pericardial space coagulates, generating thrombin that recruits neutrophils which promote a localized inflammatory response on the surface of the atrium that is highly pro-oxidant and inflammatory [6]. In patients who have susceptible atrial substrate this oxidative response can trigger POAF [23]. In the present study, there was a 32.4% reduction in

| Table 6 Postoperative Outcomes (Matched) | Phase 0 (n = 260) | Phase 2 (n = 260) | p value |
|----------------------------------------|------------------|------------------|---------|
| Retained Blood (composite)             | 60 (23%)         | 25 (9.6%)        | <.001   |
| Re-exploration                         | 6 (2.3%)         | 2 (0.77%)        | .29     |
| Pleural Intervention-Percutaneous      | 57 (22%)         | 21 (8.1%)        | <.001   |
| Pleural Intervention- Surgical          | 2 (0.77%)        | 0 (0%)           | .25     |
| Pericardial Intervention               | 4 (1.5%)         | 4 (1.5%)         | 1       |
| # Pleural Effusions drained            | 139              | 53               | .002    |
| POAF                                   | 79 (37%) (n = 214)| 55 (25%) (n = 216)| .011    |
| Cardiac arrest                         | 8 (3.1%)         | 5 (1.9%)         | .58     |
| Postoperative blood products used      | 60 (23%)         | 48 (18%)         | .2      |
| CT output (mL) first 24 h              | 753 [584–975]    | 678 [539–950]    | .038    |
| Total CT output (mL)                   | 1152 [854–1656]  | 1038 [760–1431]  | .020    |
| Total CT (days)                        | 3 [3–4]          | 2 [2–2]          | <.001   |
| Infection (any)                        | 37 (14%)         | 10 (3.8%)        | <.001   |
| Surgical site deep                     | 0 (0%)           | 0 (0%)           | 1       |
| Surgical site superficial              | 0 (0%)           | 0 (0%)           | 1       |
| Surgical site mediastinitis           | 0 (0%)           | 0 (0%)           | 1       |
| Pneumonia                              | 20 (7.7%)        | 4 (1.5%)         | .0022   |
| Septicemia                             | 4 (1.5%)         | 0 (0%)           | .062    |
| UTI                                    | 10 (3.8%)        | 4 (1.5%)         | .18     |
| C. Diff                                | 3 (1.2%)         | 1 (0.38%)        | .62     |
| Highest postoperative creatinine       | 1.1 [1–1.4]      | 1.0 [0.8–1.2]    | <.001   |
| AKI Stage 1                            | 78 (30%) (n = 257)| 44 (17%) (n = 256)| .0014   |
| AKI Stage 2                            | 7 (2.7%) (n = 257)| 4 (1.6%) (n = 256)| .55     |
| AKI Stage 3                            | 3 (1.2%) (n = 257)| 1 (0.39%) (n = 256)| .62     |
| Postoperative renal dialysis           | 7 (2.7%)         | 0 (0%)           | .0078   |
| Stroke                                 | 2 (0.77%)        | 2 (0.77%)        | 1       |
| Mortality                              | 7 (2.7%)         | 7 (2.7%)         | 1       |

Abbreviations: Postoperative atrial fibrillation (POAF); Chest tube (CT), Urinary Tract Infection (UTI), Clostridium difficile (C.Diff), Acute Kidney Injury (AKI),

| Table 7 ICU and Hospital Length of Stay (Matched) | Phase 0 (n = 260) | Phase 2 (n = 260) | p value |
|---------------------------------------------------|------------------|------------------|---------|
| Total ICU time (Hrs.)                             | 43.5 [24–79.25]  | 29.75 [24–49]    | <.001   |
| ICU stay > 3 days                                  | 70 (27%)         | 31 (12%)         | <.001   |
| Total time on ventilator (Hrs.)                    | 9.1 [5–20]       | 7.3 [4.9–17.2]   | .004    |
| Ventilation > 24 h                                 | 44 (17%)         | 27 (10%)         | .037    |
| Total hospital length of stay (d)                  | 7.5 [5–11]       | 7 [5–10]         | .045    |
| Total post-op length of stay (d)                   | 6 [4–8]          | 5 [4–6.25]       | <.001   |

Abbreviations: Intensive Care Unit (ICU), Hours (Hrs), Length of Stay (LOS), Postoperative (Post-op); days (d)
POAF. This is consistent with the studies by Sirch, where patients treated with ATC had a 30% reduction in POAF, and St. Onge, where there was a 34% reduction in POAF [5, 12]. This could have a significant impact on hospital resource utilization, as POAF is known to significantly increase hospital costs [25].

AKI is a well-recognized complication of cardiac surgery in the postoperative period [14]. In this study, patients with ATC had lower postoperative creatinine levels as well as a significant reduction in the need for postoperative dialysis. The calculated KDIGO stage I AKI rate was 30% during Phase 0, controls, dropping to 17% in Phase 2 (P = 0.0014). There was a trend towards a reduction in KDIGO stage II and III AKI, but the sample sizes were too small for this analysis. This study was not designed to specifically study these endpoints or the mechanism by which this may occur. However, several mechanisms can be considered such as a reduction in hypotension from tamponade or hypoxia from effusions might put less stress on the kidneys during recovery. Additionally, perhaps if there is less retained blood there is less reabsorption of oxidized products of which are known to contribute to AKI [26]. AKI imposes a sizable financial burden for hospitals and thus reducing this outcome could contribute to a reduction of overall hospital costs [27]. Further studies are indicated to more specifically evaluate this endpoint and the possible mechanisms of how ATC might be an additional adjunct to help minimize AKI after heart surgery.

Patients with ATC had a reduction in hospital resource utilization including a reduction in ICU hours, ICU stays of over 3 days, and reduced incidence of

| Table 8 | Median Index Hospitalization Costs by Department, using Quantile Regression (Matched) |
|---------|---------------------------------------------------------------|
| Department | P0 Costs (95% CI) | P2 Costs (95% CI) | Difference (P2-P0) | p value |
| Cardiology | $9.74 (7.29, 12.19) | $13.20 (10.57, 15.83) | $3.46 (−0.13, 7.05) | 0.0591 |
| Laboratory | $968.86 (881.95, 1055.77) | $734.63 (665.03, 804.23) | $−234.23 (−345.58, −122.88) | < 0.0001 |
| Other | $1112.88 (1044.25, 1181.51) | $1764.89 (1733.14, 1796.64) | $652.01 (576.39, 727.63) | < 0.0001 |
| Radiology | $378.97 (335.58, 422.36) | $264.36 (239.27, 289.45) | $−114.61 (−164.73, −64.49) | < 0.0001 |
| Step Down/Ward | $2591.52 (2426.63, 2756.41) | $2621.32 (2455.39, 2787.25) | $29.80 (−204.13, 263.73) | 0.8025 |
| Respiratory | $420.71 (341.32, 500.10) | $250.22 (212.49, 287.95) | $−170.49 (−258.39, −82.59) | 0.0002 |
| ICU | $2710.08 (2369.00, 2756.41) | $1782.60 (1420.70, 2144.50) | $−927.48 (−1424.78, −430.18) | 0.0003 |
| Operating Room - Index | $1215.12 (1182.92, 13,199.12) | $12,359.89 (11,907.61, 12,884.17) | $113.78 (−750.24, 897.71) | 0.7826 |
| Blood Bank | $120.14 (71.77, 168.51) | $73.10 (51.45, 94.75) | $−47.04 (−100.04, 5.96) | 0.0818 |
| OR/Anesthesia | $525.61 (516.73, 534.49) | $511.53 (503.17, 519.89) | $−14.08 (−26.27, −1.89) | 0.0237 |
| Pharmacy | $2181.44 (2010.88, 2352.00) | $1430.57 (1325.98, 1535.16) | $−750.87 (−950.94, −550.80) | < 0.0001 |
| Total | $25,072.80 (23,662.97, 26,482.63) | $23,241.35 (22,206.16, 24,276.54) | $−1831.45 (−3580.52, −82.38) | 0.0402 |

| Table 9 | Mean Index Hospitalization Costs ($) by Department, with 95% CI from bootstrapping (Matched) |
|---------|---------------------------------------------------------------|
| Department | P0 Costs (95% CI) | P2 Costs (95% CI) | Difference (P2-P0) | p value |
| Cardiology | $323.00 (177.44, 498.57) | $457.36 (202.86, 780.58) | $134.36 (−194.43, 491.74) | 0.466 |
| Laboratory | $1111.94 (1021.96, 1203.00) | $900.76 (831.97, 975.97) | $−211.18 (−316.80, −99.11) | < 0.0001 |
| Other | $1508.14 (1377.42, 1658.83) | $1875.89 (1767.38, 2005.89) | $367.75 (169.65, 550.74) | < 0.0001 |
| Radiology | $1018.82 (844.36, 1206.31) | $577.06 (473.02, 702.34) | $−441.75 (−654.92, −234.25) | < 0.0001 |
| Step Down/Ward | $2955.18 (2724.31, 3,223.20) | $3012.16 (2685.25, 3,387.11) | $56.98 (−346.97, 484.92) | 0.760 |
| Respiratory | $856.63 (678.98, 1037.94) | $696.12 (440.17, 730.86) | $−160.51 (−511.17, −46.08) | 0.020 |
| ICU | $4887.07 (4020.89, 5802.31) | $3919.07 (3110.13, 4965.25) | $−968.00 (−2199.04, 365.86) | 0.156 |
| Operating Room | $14,024.07 (13,528.39, 14,538.16) | $13,631.57 (13,086.79, 14,125.95) | $−392.50 (−1028.30, 309.46) | 0.244 |
| Blood Bank | $811.35 (616.39, 1022.17) | $571.44 (393.92, 776.12) | $−239.91 (−510.83, 31.15) | 0.088 |
| OR/Anesthesia | $548.80 (536.12, 562.48) | $313.82 (251.51, 453.23) | $−235.98 (−449.25, −22.72) | 0.074 |
| Pharmacy | $3175.06 (2724.31, 3,223.20) | $2259.84 (1858.48, 2818.09) | $−915.22 (−1595.18, −263.73) | 0.014 |
| Total | $31,549.19 (29,149.07, 34,144.06) | $28,852.59 (26,677.52, 31,341.75) | $−2696.59 (−6027.70, 880.93) | 0.116 |
prolonged intubation (defined as > 24 h). There was a statistically significant reduction in infections, primarily driven by a reduction in pneumonia and sepsis. Patients in Phase 2 had a 1 day reduced total and hospital post-operative length of stay, again, which could have significant hospital resource use implications (measured in costs, not charges) [5, 12]. This suggests that ATC is economically justifiable for hospitals, even after including the costs of acquiring the technology. In the United States, ATC costs approximately $395 per unit, and in this study it was implemented as a preventative measure in all patients. Our program performs 700 cardiac cases on a yearly basis. Assuming that 700 cases a year utilizing 1.2 ATC per case, the yearly costs to implement ATC is $331,800. A median net savings of $1831 per patient over 700 patients would result in a net recuperation of $1,281,700 per year for the hospital. A mean net savings of $2696 per patient over 700 patients would result in a net recuperation of $1,887,200 per year for the hospital. Both of these sums provide a considerable margin for cost effectiveness from a hospital purchasing perspective. This important administrative consideration is crucial in the current healthcare environment which endeavors to increase healthcare value by reducing complications and costs [28, 29].

There are several limitations to this study. First, data were generated from a nonrandomized, prospectively collected observational cardiac surgical database supplemented by retrospective chart reviews. These cases, however, represented a 100% census of all cardiac surgical procedures occurring during the duration of this study, which could have limited the potential for selection bias. Second, the endpoint of retained blood relies on the analysis of patients who had interventions performed, rather than by direct imaging for retained blood. This has the disadvantage of being more dependent on the subjective decision of the operating surgeon to intervene to evacuate retained blood. On the other hand, this strictly represents the experience of only two operating surgeons who have internally consistent practice patterns. Imaging may be more likely to include retained blood of uncertain clinical significance, while relying on the definition that requires specific invasive intervention for retained blood may represent a more clinically meaningful endpoint with quality improvement ramifications. Finally, although we implemented an ATC protocol for all patients undergoing cardiac surgery in our program, it is important to note that sub populations of patients such as those having CABG only, on pump vs off pump CAGB, valve surgery, reoperations and more complex combined procedures have different risks and patterns of postoperative bleeding and thus may have differing clinical responses to a clinical protocol. Further studies are needed that are statistically powered to examine these different cardiac surgery populations so that the outcomes with this approach can be better defined and protocols more specifically developed to best serve these patients.

**Conclusion**

The use of ATC is associated with a reduction in retained blood, POAF, AKI, blood loss, ICU and hospital resource utilization and median costs. This supports the concept that efforts to actively maintain chest tube patency in the ICU after heart surgery improve outcomes and are economically justified to help reduce hospital resource utilization after cardiac surgery.

**Abbreviations**

$\$: US Dollar; ADP: Adenosine diphosphate receptor inhibitors; AKI: Acute kidney injury; ATC: Active tube clearance; C Diff: Clostridiun difficile Infection; CAGB: Coronary Artery Bypass Surgery; CPT: Current procedural terminology code; CT: Chest tube; CTO: Chest tube output; d: day; GP: Glycoprotein; Hrs: Hours; IABP: Intra aortic balloon pump; ICD: International classification of diseases code; ICU: Intensive Care Unit; KDIGO: Kidney Disease Improving Global Outcomes; LOS: Length of Stay; NYHA: New York Heart Association; PCI: Percutaneous Intervention; POAF: Post-operative atrial fibrillation; POD: Postoperative day; t-PA: Tissue plasminogen activator; UTI: Urinary tract infection

**Acknowledgments**

The authors acknowledge Corey Powell, Ph.D., for his expert statistical analysis, David J. Cohn, MD, (Director of Cardiovascular Research, St. Luke’s Mid American Heart Institute), Elizabeth Magnuson, Sc.D. (Director of Health Economics and Technology Assessment, St. Luke’s Mid America Heart Institute), and Khaja Chinnakondepalli, Ms. Sc (Statistician, Health Economics and Technology Assessment, St. Luke’s Mid America Heart Institute) for their advising on and statistical analysis of economic data.

**Authors’ contributions**

Study Concept and Design: Yv Baribeau, Perrault, Maltais. Acquisition, analysis or interpretation of data: Yv Baribeau, Westbrook, Ya Baribeau. Drafting of Manuscript: Yv Baribeau, Boyle. Critical Revision of manuscript for important intellectual content: All Authors. Statistical Analysis: Yv Baribeau, Powell, Magnuson, Administrative, technical or material support: Yv Baribeau, Supervision: Yv Baribeau, Perrault, Maltais. All authors read and approved the final manuscript.

**Funding**

This study was supported by an unrestricted grant to the hospital for additional data collection from ClearFlow, Inc., who played no role in the collection and entry of data to the study database. The hospital purchased the ATC product for this study. The study site investigators (YvB and BW) had full freedom of investigation including the ability to analyze independently from the sponsor, and sole authority to make the final decision regarding publication.

**Availability of data and materials**

Data are available upon request.

**Ethics approval and consent to participate**

Ethics approval provided by the Institutional Review Board with a waiver of informed consent.

**Consent for publication**

Not applicable.

**Competing interests**

YvB received partial funding from ClearFlow, Inc, in the form of an unrestricted grant to support data collection for this study. EB is a consultant.
and equity holder in ClearFlow, Inc. SM is the recipient of a research grant from ClearFlow, Inc., and a Clinical Trial Educator for Medtronic. LPP is a scientific advisor to ClearFlow, Inc. For the remaining of authors, none were declared.

Author details
1Department of Cardiac Surgery, New England Heart and Vascular Institute, Catholic Medical Center, 100 McGregor St, Manchester, NH 03102, USA.
2Department of Anesthesia and Critical Care, Beth Israel Deaconess Medical Center, Boston, MA, USA.
3Department of Cardiothoracic Surgery, Centre Hospitalier Universitaire de Montréal, Montreal, Canada.
4Department of Thoracic Surgery, St. Charles Medical Center, Bend, OR, USA.
5Montreal Heart Institute, Montreal, Canada.

Received: 1 August 2019 Accepted: 20 September 2019

References
1. Balzer F, von Heymann C, Boyle EM, Wernecke KD, Grubitzsch K, Sander M. Impact of retained blood requiring Reintervention on outcomes after cardiac surgery. J Thorac Cardiovasc Surg. 2016;152(2):595–601.
2. Karimov JV, Gillinov AM, Schenck L, Cook M, Kosty Sweeney D, Boyle EM, Fukamachi K. Incidence of chest tube clogging after cardiac surgery: a single-center prospective observational study. Eur J Cardiothoracic Surg. 2013;44(6):1029–36.
3. Tauriainen TKE, Morosin MA, Airaksinen J. Biancari Fausto: outcome after procedures for retained blood syndrome in coronary surgery. European Journal of Cardiothoracic Surgery. 2017;51(6):1078–85.
4. Boyle E, Gillinov A, Cohn W, Levy S, Fischlein T, Perrault L. Retained blood syndrome after cardiac surgery: a new look at an old problem. Innovations. 2015;10(5):296–303.
5. Sirch J, Ledwon M, Püski T, Boyle EM, Pfeiffer S, Fischlein T. Active clearance of chest drainage catheters reduces retained blood. J Thorac Cardiovasc Surg. 2016;151(2):828–32.
6. Keyser PA, Chadik BK, Ravi S, Johnson MS, Mitchell T, Barnes S, Arbabshahi A, Dell'Italia LJ, George DJ, Steele C, et al. Hemoglobin-associated oxidative stress in the pericardial compartment of postoperative cardiac surgery patients. Lab Invest. 2015;95(2):132–42.
7. Halm MA. To strip or not to strip? Physiological effects of chest tube manipulation. Am J Crit Care. 2007;16(6):609–12.
8. Day TG, Penning RR, Gofton K. Is manipulation of mediastinal chest drains useful or harmful after cardiac surgery? Interact Cardiovasc Thorac Surg. 2008;7(5):888–90.
9. Shali S, Boyle EM, Saeed D, Fukamachi K, Cohn WE, Gillinov AM. The active tube clearance system: a novel bedside chest-tube clearance device. Innovations. 2010;5(1):42–7.
10. Engelman DT, Ben Ali W, Williams JB, Perrault LP, Reddy VS, Ailawadi G, et al. Hemoglobin-associated oxidative stress in the pericardial compartment of postoperative cardiac surgery patients. Lab Invest. 2015;95(2):132–42.
11. Radomski FM, Rihal CS, Sopurno A, Nuszkowski J, Agosta F, Chesebro JH, et al: Guidelines for Perioperative Maximal Airway Patency. Innovations. 2010;5(1):42–7.
12. Baribeau M, Mewly M, St-Onge S, Ben Ali W, Bouchard D, Lamarche Y, Perrault LP, Boyle EM, Gillinov AM, Fukamachi K. Improved drainage with active chest tube clearance: evaluation of a downsized chest tube. Ann Thorac Surg. 2011;91(2):580–3.
13. Shiose A, Takaseya T, Fumoto H, Arakawa Y, Horai T, Boyle EM, Gillinov AM, Fukamachi K. Superior chest drainage with an active tube clearance system: evaluation of a downsized chest tube. Ann Thorac Surg. 2010;100(6):685–8.
14. Labidi M, Ballot R, Doinne B, Lacasse Y, Maltais F, Boulet LP. Pleural effusions following cardiac surgery: prevalence, risk factors, and clinical features. Chest. 2009;136(6):1604–11.
15. Light RW, Rogers JT, Moyers JP, Lee YC, Rodriguez RM, Alford WC Jr, Ball SK, Burrus GR, Coltharp WH, Glassford DM Jr, et al. Prevalence and clinical course of pleural effusions at 30 days after coronary artery and cardiac surgery. Ann J Respir Crit Care Med. 2002;166(12 Pt 1):1567–71.
16. Grieshaber P, Heinm N, Herzberg M, Niemann B, Roth P, Boening A. Active chest tube clearance after cardiac surgery is associated with reduced Reexploration rates. Ann Thorac Surg. 2018;105(5):1771–7.
17. Pelletier MP, Sclymoss S, Lee A, Chiu RC. Negative reexploration for cardiac postoperative bleeding: can it be therapeutic? Ann Thorac Surg. 1998;65(4):999–1002.
18. Greenberg JW, Lancaster TS, Schuessler RB, Melby SJ. Postoperative atrial fibrillation following cardiac surgery: a persistent complication. Eur J Cardiothoracic Surg. 2017;53(4):655–72.
19. St-Onge S, Perrault LP, Demers P, Boyle EM, Gillinov AM, Cox J, Melby S. Pericardial blood as a trigger for postoperative atrial fibrillation after cardiac surgery. Ann Thorac Surg. 2018;105(1):321–8.
20. Godek M, Pawliszak W, Hagner W, Zalewski P, Kowalewski J, Paparella D, Catell T, Anismanowicz L, Kowalewski M. Systematic review and meta-analysis of randomized controlled trials assessing safety and efficacy of posterior pericardial drainage in patients undergoing heart surgery. J Thorac Cardiovasc Surg. 2017;153(4):865–75.
21. LaPar DJ, Speir AM, Crosby IK, Fonner E Jr, Brown M, Rich JB, Quader M, Kern J, Krol L, Allavadi G, et al. Postoperative atrial fibrillation significantly increases mortality, hospital readmission, and hospital costs. Ann Thorac Surg. 2014;98(2):527–33.
22. Alshaikh HN, Katz MN, Gani F, Nagarajan N, Canner JK, Kacker S, Najjar PA, Higgins RS, Schneider EB. Financial impact of acute kidney injury after cardiac operations in the United States. Ann Thorac Surg. 2018;105(2):469–75.
23. Engelman DT, Boyle EM Jr, Benjamin EM. Addressing the imperative to evolve the hospital new product value analysis process. J Thorac Cardiovasc Surg. 2018;155(2):682–5.
24. Engelman DT. Surgical economics: MACRA, MIPS, and bundles—lessons learned in the first 3 years of a coronary artery bypass grafting alternative payment model. J Thorac Cardiovasc Surg. 2017;153(2):381–4.

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.