Outcome differences between surgeons performing first and subsequent coronary artery bypass grafting procedures in a day: a retrospective comparative cohort study

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ABSTRACT

Background With increasing surgical workload, it is common for cardiac surgeons to perform coronary artery bypass grafting (CABG) after other procedures in a workday. To investigate whether prior procedures performed by the surgeon impact the outcomes, we compared the outcomes between CABGs performed first versus those performed after prior procedures, separately for on-pump and off-pump CABGs as they differed in technical complexity.

Methods We conducted a retrospective cohort study of patients undergoing isolated CABG in China from January 2013 to December 2018. Patients were categorised as undergoing on-pump and off-pump CABGs. Outcomes of the procedures performed first in primary surgeons' daily schedule (first procedure) were compared with subsequent ones (non-first procedure). The primary outcome was an adverse events composite (AEC) defined as the number of adverse events, including in-hospital mortality, myocardial infarction, stroke, acute kidney injury and reoperation. Secondary outcomes were the individual components of the primary outcome, presented as binary variables. Mixed-effects models were used, adjusting for patient and surgeon-level characteristics and year of surgery.

Results Among 21 866 patients, 10 109 (16.1% as non-first) underwent on-pump and 11 757 (29.6% as non-first) off-pump CABG. In the on-pump cohort, there was no significant association between procedure order and the outcomes (all p>0.05). In the off-pump cohort, non-first procedures were associated with an increased number of AEC (adjusted rate ratio 1.29, 95% CI 1.13 to 1.47, p<0.001), myocardial infarction (adjusted OR (OR_{adj}) 1.43, 95% CI 1.13 to 1.81, p=0.003) and stroke (OR_{adj} 1.73, 95% CI 1.18 to 2.53, p=0.005) compared with first procedures. These increases were only found to be statistically significant when the procedure was performed by surgeons with <20 years' practice or surgeons with a preindex volume <700 cases.

Conclusions For a technically challenging surgical procedure like off-pump CABG, prior workload adversely affected patient outcomes.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Increased workload adversely affects surgical outcomes. However, whether prior procedures performed by the surgeon in a workday impact the outcomes of on-pump and the technically more complex off-pump coronary artery bypass grafting (CABG) remains unclear.

WHAT THIS STUDY ADDS

⇒ For off-pump CABG, prior surgical workload has negative impacts on patient outcomes, particularly if procedures were performed by less experienced or lower volume surgeons. These findings were consistent across several patient subgroups and multiple sensitivity analyses.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE AND/OR POLICY

⇒ Daily schedules should ensure that complex procedures are assigned first in a surgeon's shift, while taking patient and surgeon characteristics into account.

INTRODUCTION

With increasing surgical workload, surgeons often have multiple operations in a day, especially in countries where surgical resources are relatively scarce.[1–3] Extended work hours and excessive workload have been proved to bring negative influences on patient outcomes.[4–7] Therefore, various measures to evaluate workload and strategies to reduce workload impacts have been suggested.[8 9] However, whether prior procedures performed by the surgeon in a workday will affect surgical outcomes remains unclear, which could be instructive in arranging surgeons' daily workflow patterns.

Coronary artery bypass grafting (CABG), the standard of care for patients with extensive coronary artery disease, has been among the most common and major surgical procedures.[10] In a CABG procedure, the most critical and challenging step is performing a surgical anastomosis between autologous vessel grafts and coronary arteries, which requires extremely high mental concentration and great physical strength of the surgeon. To achieve the precision requirement for a successful CABG, the heart is typically arrested with a cardiopulmonary bypass (CPB) machine to support the circulation. The off-pump procedure, however, has also evolved as another option that the anastomosis is performed on a beating heart without CPB,[11] which avoids the adverse effect from cardiac arrest and CPB, but adds to the complexity and difficulty of the procedure. Thus, the off-pump CABG is considered to be more technically challenging than the on-pump CABG (with CPB).[12–14] Considering on-pump and off-pump CABGs are two procedures with similar surgical process but different complexity, prior workload may have varying impacts on them. It is highly necessary to examine the association between the procedure order and outcomes, with on-pump and off-pump CABGs regarded as two typical clinical scenarios.

The purpose of this study was to examine whether intraday workload (ie, prior procedures conducted on the same day) would affect the outcomes after CABG, accounting for surgical complexity. We compared the outcome differences between the first CABG and subsequent ones performed in a day, for on-pump CABG and off-pump CABG separately. We also investigated the effect across different patient health conditions and surgeon experience.

METHODS

Study design

Data of patients undergoing CABG at a cardiovascular specialty hospital with the annual CABG volume exceeding 4500 cases in China from 1 January 2013 through 31 December 2018 were collected through the hospital electronic health record (EHR) system. Data audit and quality measures have been reported previously.[15 16] Briefly, we established an EHR-derived database by linking the structured EHR to a registry database to enable real-time data collection, including baseline patient characteristics, surgical records and in-hospital outcomes. To assure the accuracy of the linkage, 5% of patients were randomly selected and all variables of these patients were compared between the original EHR and EHR-derived database, and the EHR-derived data were 100% consistent with the original records.

Study population

This study included all consecutive patients aged 18 years or older who underwent isolated, elective CABG, which meant that patients undergoing emergent CABG, CABG combined with valvular surgeries or other cardiovascular surgeries were not included. All the CABG surgeries were performed according to the operating standards (online supplemental method 1). Patients who were converted from off-pump to on-pump procedure during the surgery (n=736) were excluded as their outcomes were influenced by both procedures, and it was inappropriate to include them into either cohort. Other exclusion criteria included: (1) patients treated by surgeons after night shift in the preceding overnight hours (00:00 to 07:00, n=175) to avoid bias from extra preceding workload; and (2) patients without surgeon information (n=4). Patients were categorised as undergoing on-pump and off-pump CABGs by the use of CPB, and the association between intraday procedure order and patient outcomes was assessed in both CABG cohorts separately.

Procedure order and study group

Procedure order was determined within work hours (from 08:00 to 19:00) in a single day, when all the elective CABG procedures were performed. All surgical procedures (included but not limited to CABG) performed by the surgeon were taken into account to determine the order, regardless of whether the surgeon served as a primary surgeon or an assistant. More details on the duties of the primary surgeon and surgical team during the surgery are described in online supplemental method 1.

'First procedure' was defined as the CABG surgery being the first procedure of the primary surgeon in a day, whereas other CABG surgeries were also assigned their number in the ordering but included as the 'non-first procedure' considering the lower volumes observed for the third or later procedures (figure 1). Thus, in both on-pump and off-pump CABG cohorts, the patients were further divided into 'first procedure' and 'non-first procedure' groups separately.

Outcome measures

The primary outcome was an adverse events composite (AEC), including in-hospital all-cause mortality, non-fatal myocardial infarction (MI), non-fatal stroke, acute kidney injury (AKI) and reoperation, which are widely used for evaluating the quality of CABG procedures.[17–19] The AEC was expressed as the number of adverse events that occurred during the index hospitalisation, and the analysis was at the individual patient level with each type of the adverse event being counted only once.[20] Secondary outcomes

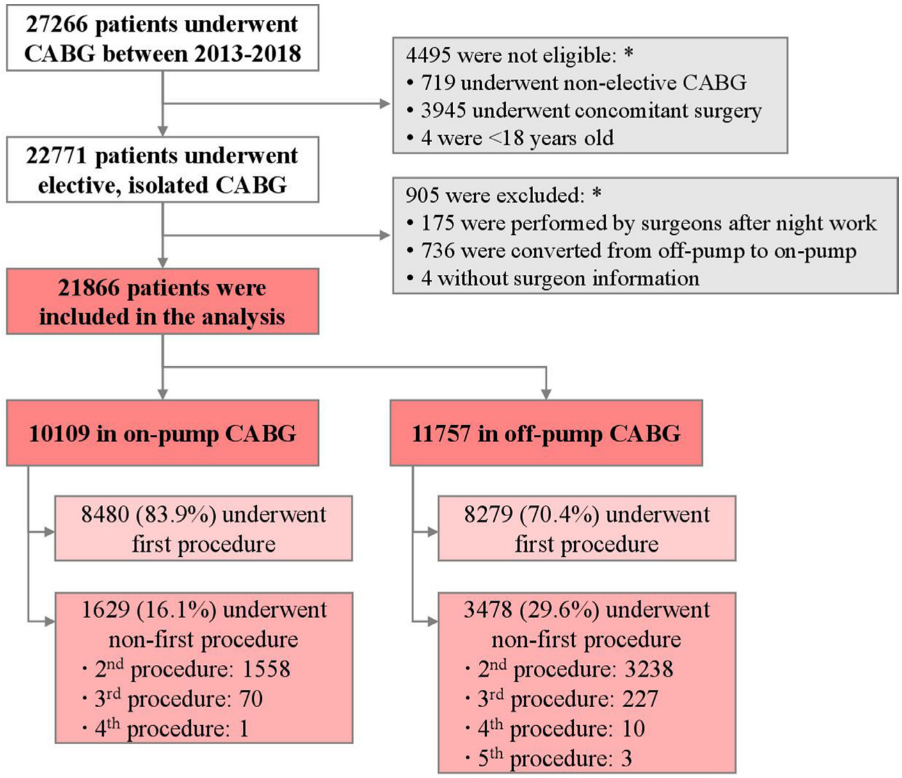

Figure 1 Study flow chart. The flow chart shows detailed inclusion and exclusion criteria for this study as well as corresponding patient numbers. *Multiple exclusions may apply to one patient so that the number in each criterion adds up greater than the total ineligible or excluded patients in the grey boxes. CABG, coronary artery bypass grafting.

included the individual components of the primary outcome mentioned above, expressed as binary variables (yes/no). MI was defined as an absolute rise in cardiac troponin to over 70 times the 99th percentile upper reference limit (URL), or an increase in creatine kinase - muscle/brain (CK-MB) to over 10 times the 99th percentile URL. Stroke was defined as brain, spinal cord or retinal cell death attributable to focal arterial ischaemia. AKI was defined as any one of the following: (1) an increase in the serum creatinine level over three times the latest preoperative value; (2) a serum creatinine level reaching 4.0 mg/dL with a minimum increase of 0.5 mg/dL relative to the last preoperative value; and (3) a new postoperative dialysis. Reoperation was defined as the re-exploration for mediastinal bleeding either in the intensive care unit (ICU) or operating room. Detailed definitions of the outcomes are further described in online supplemental method 2.

Patient and surgeon characteristics

Patient characteristics were collected and some were selected as covariates for risk adjustment because they were previously shown to be risk factors among patients undergoing CABG in China,[21] including (1) demographic characteristics: age, sex; (2) comorbidities: body mass index, angina, estimated glomerular filtration rate (eGFR); (3) medical history: history of chronic obstructive pulmonary disease, MI, stroke, cardiac surgery, percutaneous coronary intervention; and (4) cardiovascular status: New York Heart Association (NYHA) class, preoperative left ventricular ejection fraction (LVEF), left main disease, number of lesions and aortic calcification. Covariates for each model are listed in online supplemental table 2. Other characteristics that were not included in the multivariable regression models (following the general principle of variable selection, like sample size, collinearity or clinical importance) but were often reported in other cardiovascular studies were also listed in table 1, and they were also used to predict the propensity score in the sensitivity analysis (see below).

All surgeons performed first and non-first CABG procedures. Surgeon characteristics including years in practice and CABG volume before the index procedure were calculated dynamically for each patient as surgeon-level covariates. Years in practice was defined as the number of years a surgeon served as a cardiac surgeon until the date of the index CABG procedure. The CABG volume was defined as the cumulative number of CABGs a surgeon had performed from the year 2012 to the date of the index CABG procedure. The annual CABG volume in 2012 was included to indicate a surgeon's surgical experience at baseline.

Statistical analyses

We performed the analyses in the on-pump and off-pump CABG cohorts separately. The patient and

Table 1 Patient demographic and clinical characteristics

	Overall	On-pump CABG cohort (n=10 109)			Off-pump CABG cohort (n=11 757)		
		First procedure (n=8480)	Non-first procedure (n=1629)	P value*	First procedure (n=8279)	Non-first procedure (n=3478)	P value*
Age, mean (SD), years	61.2 (8.6)	60.8 (8.5)	60.5 (8.5)	0.33	61.7 (8.8)	61.2 (8.6)	**0.005**
Female, n (%)	4975 (22.8)	1893 (22.3)	388 (23.8)	0.19	1887 (22.8)	807 (23.2)	0.63
BMI, mean (SD), kg/m²†	25.7 (3.0)	25.8 (3.0)	25.7 (3.1)	0.94	25.6 (3.0)	25.6 (3.1)	0.65
Smoking, n (%)	12 117 (55.4)	4578 (54.0)	866 (53.2)	0.54	4683 (56.6)	1990 (57.2)	0.51
Diabetes, n (%)	4952 (22.6)	2017 (23.8)	353 (21.7)	0.06	1820 (22.0)	762 (21.9)	0.93
Hypertension, n (%)	13 957 (63.8)	5418 (63.9)	1069 (65.6)	0.18	5291 (63.9)	2179 (62.7)	0.20
Hyperlipidaemia, n (%)	16 128 (73.8)	6178 (72.9)	1176 (72.2)	0.58	6172 (74.6)	2602 (74.8)	0.76
Prior COPD, n (%)	139 (0.6)	44 (0.5)	10 (0.6)	0.63	57 (0.7)	28 (0.8)	0.50
Prior MI, n (%)	8189 (37.5)	3209 (37.8)	633 (38.9)	0.44	3085 (37.3)	1262 (36.3)	0.32
Prior stroke, n (%)	1684 (7.7)	632 (7.5)	122 (7.5)	0.96	648 (7.8)	282 (8.1)	0.61
Prior PCI, n (%)	1233 (5.6)	433 (5.1)	89 (5.5)	0.55	523 (6.3)	188 (5.4)	0.06
Prior cardiac surgery, n (%)	828 (3.8)	322 (3.8)	59 (3.6)	0.73	309 (3.7)	138 (4.0)	0.54
Angina, n (%)	18 491 (84.6)	7032 (82.9)	1352 (83.0)	0.94	7061 (85.3)	3046 (87.6)	**0.001**
NYHA III/IV, n (%)	6923 (31.7)	2367 (27.9)	502 (30.8)	**0.017**	2809 (33.9)	1245 (35.8)	0.05
eGFR, median (IQR), mL/min/1.73 m²‡	91.6 (78.1–107.0)	92.0 (78.4–107.5)	91.2 (78.4–106.6)	0.41	91.5 (77.8–106.5)	91.2 (78.4–107.2)	0.40
PAD, n (%)	2790 (12.8)	881 (10.4)	146 (9.0)	0.08	1194 (14.4)	569 (16.4)	**0.007**
LM disease, n (%)	4145 (19.0)	1580 (18.6)	284 (17.4)	0.25	1633 (19.7)	648 (18.6)	0.17
Three-vessel disease, n (%)	13 296 (60.8)	5692 (67.1)	1116 (68.5)	0.27	4507 (54.4)	1981 (57.0)	**0.012**
Preoperative LVEF, mean (SD)	61.1 (7.4)	60.9 (7.6)	60.6 (7.8)	0.16	61.3 (7.2)	61.5 (6.9)	0.17
Aortic calcification, n (%)	1774 (8.1)	437 (5.2)	110 (6.8)	**0.009**	863 (10.4)	364 (10.5)	0.95
EuroSCORE >3, n (%)	4990 (22.8)	1727 (20.4)	304 (18.7)	0.33	2075 (25.1)	884 (25.4)	0.69

*The χ^2 test is used for categorical variables and the Kruskal-Wallis test is used for continuous variables between first and non-first procedure groups in specific CABG cohorts. Those achieving a statistically significant level of 0.05 are in bold.
†BMI=weight (kg)/(height [m])^2.
‡eGFR (mL/min/1.73 m^2)=186×(serum creatinine level [mg/dL])$^{-1.154}$×(age [years])$^{-0.203}$.
BMI, body mass index; CABG, coronary artery bypass grafting; COPD, chronic obstructive pulmonary disease; eGFR, estimated glomerular filtration rate; EuroSCORE, European System for Cardiac Operative Risk Evaluation; LM, left main; LVEF, left ventricular ejection fraction; MI, myocardial infarction; NYHA, New York Heart Association; PAD, peripheral artery disease; PCI, percutaneous coronary intervention.

surgeon characteristics between first and non-first procedure groups were compared, with the χ^2 test used for categorical variables and the Kruskal-Wallis test for continuous variables. The completeness of patient-level variables ranged from 96% to 100% (online supplemental table 1). For those key variables with missing data, we implemented multiple imputation with the Markov Chain Monte Carlo method, and the predictors included other variables of patient demographic characteristics, comorbidities and medical history with 100% completeness listed in online supplemental table 1. The final imputed value was an average of 20 imputations for all analyses.

To investigate the AEC difference between first and non-first procedure groups, assuming a Poisson distribution for the number of adverse events, we fitted a mixed-effects model with a Poisson link function and surgeon-specific random intercepts to model the AEC as a function of procedure order (non-first procedure vs first procedure; when examining the potential 'dose-effect' relationship between the number of prior procedures performed by the surgeon and patient outcomes, we compared the third or later procedure, the second procedure vs the first procedure). Rate ratios (RR) were calculated to present the outcome differences. For each individual adverse event (binary outcome), we fitted separate mixed-effects models with a logit link function and surgeon-specific random intercepts, with ORs estimated. All models were adjusted for patient and surgeon-level characteristics listed in the online supplemental table 2, also including an interval time variable corresponding to the date of surgery (2013 (time=0) through 2018 (time=6)) to represent annual changes in outcomes.

To test whether prior workload had greater impact in clinically high-risk subsets,[10 21] we repeated the analysis for AEC in eight prespecified patient subgroups defined by age (<65 or ≥65 years), sex, diabetes, eGFR (<60 or ≥60 mL/min/1.73 m^2), LVEF (<50% or ≥50%), prior MI, three-vessel disease and European System for Cardiac Operative Risk Evaluation (≤3 or >3). Since surgeons' skill and experience may overwhelm the effect of workload, we further repeated the analyses in two surgeon subgroups defined by years in practice (<20 or ≥20 years), and the CABG volume (<700 or ≥700 cases) before the index procedure.

Sensitivity analyses

We performed several sensitivity analyses to test the robustness of our findings. First, we aimed to take into account possible confounding by indication as some high-risk patients may be more likely performed as a non-first procedure. We therefore included all patient characteristics (online supplemental table 1) in a multivariable logistic regression model to estimate the propensity for patients to undergo a non-first procedure. The inverse probability of treatment weighting (IPTW) was used based on the inverse of the propensity score and the mixed-effects model analyses repeated. We also performed a 1:1 propensity score matching to form matched on-pump and off-pump CABG cohorts by matching first and non-first patients treated by the same surgeon with similar propensity score using the greedy nearest neighbour matching algorithm, with a calliper width at 0.01 according to the absolute value of the difference between propensity scores. Second, we took the surgeon and assistant as pairs and restricted the analysis to the pairs who had ever performed both first and non-first procedures, with at least five CABG cases in total. The pair identifiers were used as the random intercepts in mixed-effects models rather than the surgeon, thus reducing bias from assistants. Finally, we restricted the analysis to the surgeries that started after 11:00 in case that circadian variation of patients or surgical teams could influence the outcomes.

All statistical tests were two sided, with a significance level of 0.05. We conducted all the analyses using SAS software V.9.4 (SAS Institute).

RESULTS

Study cohorts

Among 27 266 consecutive patients undergoing CABG during the study period, 21 866 were included in the final analysis (table 1). The mean age was 61.2 (SD 8.6) years and 22.8% were female. There were 10 109 patients in the on-pump cohort and 16.1% underwent non-first procedures; 11 757 patients in the off-pump cohort and 29.6% underwent non-first procedures.

In the on-pump CABG cohort, patients in the non-first procedure group had higher prevalence of NYHA III/IV (non-first vs first: 30.8% vs 27.9%) and aortic calcification (6.8% vs 5.2%) compared with the first procedure group, indicating higher risk of worse patient outcomes. In the off-pump CABG cohort, patients who underwent non-first procedures were younger (61.2 vs 61.7 years), and had higher prevalence of angina (87.6% vs 85.3%), peripheral artery disease (16.4% vs 14.4%) and three-vessel disease (57.0% vs 54.4%) than those who underwent a first procedure. Apart from the above, patient characteristics were similar between the first and non-first procedures in the on-pump and off-pump CABG cohorts (table 1).

Overall, 47 primary surgeons were included. Surgeons in the non-first procedure group had higher preindex CABG volume in both on-pump and off-pump CABG cohorts, and longer years in practice in the off-pump cohort (p<0.001, online supplemental table 3).

Primary outcome

In the on-pump CABG cohort, 8480 patients undergoing first procedures had 1173 AEC in total, and 1629 patients undergoing non-first procedures had 208 AEC (table 2 and online supplemental figure 1). The number of adverse events per 1000 hospitalisations was 127.7 (non-first) vs 138.3 (first). There was no significant difference in AEC between the two groups after risk adjustment (adjusted rate ratio (RR_{adj}) 0.90, 95% CI 0.77 to 1.06, p=0.19; table 2).

In the off-pump CABG cohort, 8279 patients undergoing first procedures had 759 adverse events in total (patients with AEC: one event, 658; two events, 44; ≥three events, 4), and 3478 patients undergoing non-first procedures had 390 events (one event, 319; two events, 28; three events, 5). The number of adverse events per 1000 hospitalisations was 112.1 (non-first) vs 91.7 (first). After risk adjustment, undergoing a non-first procedure was associated with an increased number of AEC (RR_{adj} 1.29, 95% CI 1.13 to 1.47, p<0.001; table 2). Further stratifying non-first procedures, it was shown that the third or later procedure (accounting for 6.9% of all non-first procedures) was associated with a higher rate (RR_{adj} 1.35, 95% CI 0.89 to 2.04, p=0.16) relative to first procedures than second procedures (RR_{adj} 1.28, 95% CI 1.12 to 1.46, p<0.001), but did not reach a statistical significance (online supplemental figure 2).

Secondary outcomes

In the on-pump CABG cohort, there was no statistically significant difference between the first and

Table 2 Outcome differences associated with non-first versus first procedure groups in the on-pump and off-pump CABG cohorts

Outcome	On-pump CABG cohort (n=10 109)				Off-pump CABG cohort (n=11 757)			
	First procedure (n=8480)	Non-first procedure (n=1629)	RR_{adj}*/OR_{adj}† (95% CI)	P value	First procedure (n=8279)	Non-first procedure (n=3478)	RR_{adj}*/OR_{adj}† (95% CI)	P value
AEC, n (%)*			0.90 (0.77 to 1.06)	0.19			1.29 (1.13 to 1.47)	**<0.001**
One event	984 (11.6)	165 (10.1)			658 (7.9)	319 (9.2)		
Two events	71 (0.8)	17 (1.0)			44 (0.5)	28 (0.8)		
Three events	13 (0.2)	3 (0.2)			3 (0.0)	5 (0.1)		
Four events	2 (0.0)	0 (0.0)			1 (0.0)	0 (0.0)		
Death, n (%)	32 (0.4)	10 (0.6)	1.44 (0.79 to 2.62)	0.23	16 (0.2)	12 (0.3)	2.01 (0.94 to 4.27)	0.07
MI, n (%)	379 (4.5)	71 (4.4)	0.84 (0.64 to 1.09)	0.19	204 (2.5)	114 (3.3)	1.43 (1.13 to 1.81)	**0.003**
Stroke, n (%)	98 (1.2)	11 (0.7)	0.57 (0.31 to 1.06)	0.08	57 (0.7)	40 (1.2)	1.73 (1.18 to 2.53)	**0.005**
AKI, n (%)	559 (6.6)	98 (6.0)	0.93 (0.72 to 1.21)	0.60	362 (4.4)	178 (5.1)	1.23 (1.00 to 1.51)	0.054
Reoperation, n (%)	105 (1.2)	18 (1.1)	0.83 (0.50 to 1.38)	0.48	120 (1.4)	46 (1.3)	0.92 (0.64 to 1.32)	0.65

AEC indicates adverse events composite, which is defined as the number of any adverse events that occurred, including death, myocardial infarction, stroke, acute kidney injury or reoperation.

*For the adverse events composite (AEC, count variable), the 'n (%)' presents the number of patients with given number of events and the percentage of those patients among specific procedure group. A mixed-effects model with a Poisson link function and surgeon-specific random intercepts is fitted, adjusting for the patient risk factors and surgeon characteristics mentioned in the Methods section and listed in online supplemental table 2. The adjusted rate ratio (non-first vs first) is estimated, and when it achieves a statistically significant level of 0.05, the p value is in bold.

†For every individual event (binary variable; ie, death, MI, stroke, AKI and reoperation), a mixed-effects model with a logit link function and surgeon-specific random intercepts is fitted, also adjusting for the patient and surgeon characteristics listed in online supplemental table 2. The adjusted OR (non-first vs first) for each outcome is estimated, and when it achieves a statistically significant level of 0.05, the p value is in bold.

AKI, acute kidney injury; CABG, coronary artery bypass grafting; MI, myocardial infarction; OR_{adj}, adjusted OR; RR_{adj}, adjusted rate ratio.

non-first procedure groups for any individual outcomes (table 2).

In the off-pump CABG cohort, non-first procedure group was associated with higher odds of MI (3.3% vs 2.5%, adjusted OR (OR_{adj}) 1.43, 95% CI 1.13 to 1.81, p=0.003) and stroke (1.2% vs 0.7%, OR_{adj} 1.73, 95% CI 1.18 to 2.53, p=0.005) than the first procedure group, but were similar in both groups for all other outcomes (death, AKI and reoperation) (table 2).

Subgroup analyses

The AEC did not differ between first and non-first procedures in the on-pump CABG cohort among all the patient or surgeon subgroups (figure 2). However,

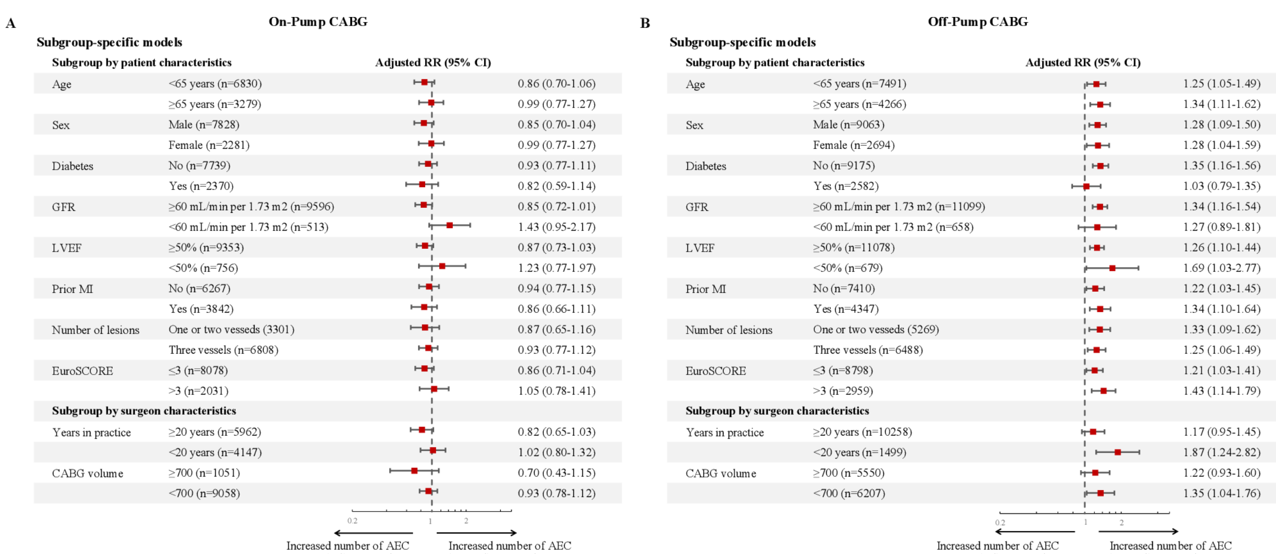

Figure 2 Association between procedure order and adverse events composite (AEC) in the patient and surgeon subgroups of the on-pump and off-pump CABG cohorts. The forest plots show the subgroup-specific RRs for the AEC in patients of non-first procedure group compared with patients of first procedure group, adjusting for the patient and surgeon characteristics. Panels (A) and (B) show the subgroup-specific RRs in the on-pump and off-pump CABG cohorts, respectively. A RR of greater than 1 indicates an increased number of adverse events for non-first procedure group in specific subgroups. The horizontal lines indicate 95% CIs. CABG, coronary artery bypass grafting; EuroSCORE, European System for Cardiac Operative Risk Evaluation; eGFR, estimated glomerular filtration rate; LVEF, left ventricular ejection fraction; MI, myocardial infarction; RR, rate ratio.

in the off-pump CABG cohort, the number of AEC increased significantly among most patient subgroups, except for patients with diabetes, or with eGFR <60 mL/min/1.73 m^2. In surgeon subgroups, a non-first procedure was associated with an increased AEC only when the procedure was performed by surgeons with <20 years in practice (RR_{adj} 1.87, 95% CI 1.24 to 2.82, p=0.003) or a preindex CABG volume <700 cases (RR_{adj} 1.35, 95% CI 1.04 to 1.76, p=0.02).

Sensitivity analyses

The results were robust and confirmed the primary findings across all sensitivity analyses. In the IPTW-weighted cohorts, similar results were obtained on an increased AEC (RR_{adj} 1.28, 95% CI 1.14 to 1.45, p<0.001) associated with undergoing a non-first procedure in the off-pump CABG. Moreover, the odds of death and AKI were now significantly increased in addition to increased odds on MI and stroke (online supplemental table 5). In the 1:1 propensity score-matched cohorts (3084 patients in the on-pump CABG cohort and 6882 in the off-pump), patient characteristics were well balanced between matched first and non-first procedure groups (online supplemental table 4). Non-first procedures were also associated with increased AEC (RR_{adj} 1.32, 95% CI 1.13 to 1.54, p<0.001), MI and stroke in the off-pump cohort (online supplemental table 5). For the analysis based on 316 surgeon–assistant pairs, including 8600 on-pump and 11 185 off-pump CABGs, the non-first procedure was associated with increased AEC (RR_{adj} 1.29, 95% CI 1.14 to 1.47, p<0.001; online supplemental table 6), death, MI and stroke in the off-pump cohort. Among 4992 patients undergoing off-pump CABG after 11:00, the non-first group was also associated with increased AEC (RR_{adj} 1.30, 95% CI 1.04 to 1.64, p=0.02; online supplemental table 7) and MI. As for reoperation, no significant association was observed in any of the sensitivity analyses. Besides, in the on-pump cohort, undergoing a non-first procedure was associated with a significantly lower odds on stroke in several analyses (online supplemental tables 5 and 6).

DISCUSSION

In this retrospective comparative study, procedure order of the surgeon in a day did not impact the outcomes after on-pump CABG, but patients undergoing a non-first off-pump CABG procedure had increased adverse events compared with those undergoing a first procedure. The results for off-pump CABG were found across most patient subgroups but only for less experienced and lower volume surgeons, as well as being robust across multiple sensitivity analyses.

Outcome differences among scheduled surgeries during routine work hours should not be neglected, especially when increased workload or inappropriate arrangement could be possible reasons. Nevertheless, evidence is still scarce on surgeons' prior workload impact on subsequent procedures, with inconclusive results of existing studies.[7 22–24] Lee *et al*[22] found that preceding endoscopic procedures impacted polyp detection, independent of surgical time, and detection rates declined as time passed during an endoscopist's schedule. However, Bagrodia *et al*[7] demonstrated that performing several urological procedures consecutively was irrelevant to worse outcomes. Gruskay *et al*[23] observed that postoperative infection was associated with the case order of decompression procedures but not for fusion procedures in spine surgery. The controversy may partly be attributed to the procedure type and selected outcome indicators. Nevertheless, all these studies implied the importance of daily schedule drafting and rational work arrangement.

Our study took CABG as a specific clinical scenario, one of the complicated but protocolised cardiac surgeries, to study whether prior procedures could impact patient outcomes. The procedure order in a day for a surgeon was regarded as a metric to study surgeon workload and workflow pattern. Additionally, we tested our hypothesis in the on-pump and off-pump CABGs separately, giving full consideration to the technical differences. Meaningful results were found that for off-pump CABG, surgical performance was influenced by preceding procedures performed by the surgeon, as it was associated with an increased number of adverse events. Moreover, the outcome of the third or later procedure may deteriorate further, as suggested by the higher point estimate although it did not reach statistical significance in the current sample. But for on-pump CABG, there was no significant association between the procedure order and outcomes. We considered the explanation for the difference between procedures may be the high technical demand and concentration required for off-pump CABG made it more susceptible to be affected by the fatigue status of primary surgeons. It is reasonable to assume that physical and cognitive fatigue have greater detrimental impact on the performance of surgeons who have performed more procedures before the index surgery. Apart from the primary composite endpoint, non-first procedures were also associated with higher odds of MI and stroke after off-pump CABG, the most devastating complications and common causes of early and late mortality after CABG.[25–27] As there is growing research investigating the surgery time or operative hours on surgical outcomes,[28–30] our study adds new evidence on evaluating the workload impact during regular work hours.

The findings were robust across multiple sensitivity analyses. Both the IPTW and the propensity score matching method to reduce confounding by indication resulted in estimates very close to the primary analysis. For concerns on the possible bias from the assistant, surgeon–assistant pairs were used as random

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effects instead of primary surgeons alone, and results were consistent. As for other surgical team members like anaesthesiologists, nurses or perfusionists, they were scheduled for the entire day and hardly changed during the daytime surgeries. Considering that inconclusive discussions remain on the natural circadian variability in surgical performance,[31–34] the analysis on surgeries performed after 11:00 demonstrated the procedure order still had a consistent negative impact on outcomes after off-pump CABG. Additionally, higher odds of death and AKI also reached statistical significance in some sensitivity analyses. Larger sample size is needed to confirm the findings particularly for events that occur infrequently such as death. As for reoperation, we hypothesise that the lack of a significant association among primary and sensitivity analyses was because reoperation-related processes, such as sternal closure and haemostasis, were performed by assistant rather than primary surgeons. We also found that in the on-pump cohort, non-first procedure was associated with lower odds of stroke in some sensitivity analyses. This should be interpreted with caution since some risk factors for stroke after on-pump CABG such as aorta atheroma or carotid artery disease were not recorded in our study, and may bias the result.

The subgroup analyses further enriched our findings. In most high-risk subsets, the primary findings were consistent for both on-pump and off-pump CABGs, which ensured that the effect of procedure order was not driven by a narrow patient group. The association between procedure order and outcomes after off-pump CABG was non-significant in patients with diabetes or low eGFR. Since these subgroups indicated more severe patients, we hypothesise the outcomes were largely and primarily determined by patient conditions so that the effect of procedure order was relatively small in that context. Interesting findings were observed in surgeon-specific subgroup analyses, as the association was only found for less experienced and lower volume surgeons, which indicates that accumulating surgical experience and skills might outweigh the adverse effect of workload.

There are some clinical implications of our study. Surgeons performing multiple surgeries in a day is common in clinical settings. The number of prior procedures can be a new metric of workload, and may have similar impact on outcomes among other clinical specialisations or surgical procedures. Our study suggests that better arrangement on daily schedules can be an actionable and cost-effective approach to balance the workload without major changes on existing infrastructure, for example, prioritising more difficult and complex procedures first, while also taking patient characteristics and surgeon experience into account.

Our study has several potential limitations. First, as an observational study, unmeasured confounders may affect the results. However, we have made every effort to achieve sufficient adjustment using patient and surgeon characteristics, and tried several methods to reduce confounding. Though we still lack information on receiving teams in the wards and ICUs, the personnel distribution among different wards and ICUs is similar and they provide equal care to the patients regardless of the procedure order. There are no data to distinguish between on-pump arrest and on-pump beating CABG, but hardly any on-pump CABG was performed with a beating heart in our hospital. Second, as a retrospective analysis, we cannot estimate surgeons' extra workload other than recorded procedures, such as working on medical records, or measure their subjective fatigue by standard scales. Moreover, we did not choose the operative time to represent the workload because primary surgeons usually perform key surgical steps only, and the operative time does not really capture their exact operating time. Third, we chose a composite endpoint as our primary outcome that has both advantages and disadvantages.[35] Though without formal validation, the composite is widely used in related fields and we carefully interpreted the composite and individual endpoints. Last, we took CABG (representing technically complicated surgeries) and in-hospital outcomes as a specific scenario to study this question, and the study was limited to a single hospital, which may limit the generalisation of study findings. Further research in different clinical settings is required to unravel the mechanism for the observed findings, and longer term effects need to be taken into account.

In conclusion, procedure order of the surgeon in a day impacts patient outcomes after off-pump CABG, as undergoing a non-first procedure was associated with higher rates of in-hospital events, but outcomes of on-pump CABG did not appear to be affected by procedure order. Further research is needed to unravel the underlying mechanism and put forward quality-improving measures, such as improvement in the daily workflow patterns.

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