

# Robot-assisted coronary artery bypass surgery: a systematic review and meta-analysis of comparative studies

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**Background:** Robot-assisted coronary bypass (RCAB) surgery has been proposed as an alternative to conventional coronary artery bypass grafting (C-CABG) for managing coronary heart disease, but the evidence on its performance compared to other existing treatments is unclear. The aim of this study was to assess, through a systematic review of comparative studies, the safety and clinical effectiveness of RCAB compared to C-CABG and other minimally invasive approaches for the treatment of coronary heart disease.

**Methods:** We conducted a systematic review of primary studies in the English-language literature comparing RCAB to existing treatment options (C-CABG, minimally invasive direct coronary artery bypass [MIDCAB] and port-access coronary artery bypass [PA-CAB]) following Cochrane Collaboration guidelines. Meta-analyses were performed where appropriate.

**Results:** We reviewed 13 studies: 11 primary studies of RCAB (v. C-CABG in 7, v. MIDCAB in 3 and v. PA-CAB in 1) and 2 multicentre database studies (RCAB v. non-RCAB). The overall quality of the evidence was low. Most studies showed no significant benefit of RCAB over other treatments in a majority of outcome variables. Meta-analyses showed that RCAB had lower rates of pneumonia or wound infection than C-CABG, and shorter intensive care unit length of stay than C-CABG or MIDCAB. Individual studies showed that RCAB had some better outcomes than C-CABG (ventilation time, transfusion, postoperative pain, hospital length of stay) or MIDCAB (transfusion, postoperative pain, time to return to normal activities, physical functioning and hospital length of stay). The review of the database studies showed that RCAB was statistically superior to non-RCAB approaches in postoperative pain, renal failure, transfusion, reoperation for bleeding, stroke and hospital length of stay; however, the difference between the 2 groups in several of these outcomes was small.

**Conclusion:** Although the findings from this review of comparative studies of RCAB appear promising and suggest that RCAB may offer some benefits to patients, in the absence of randomized controlled trials, these results should be interpreted cautiously.

**Contexte :** Le pontage aortocoronarien assisté par robot (PACAR) a été proposé comme solution de rechange au pontage aortocoronarien classique (PACC) pour la prise en charge des coronaropathies, mais on manque de données probantes claires comparant son efficacité à celle d'autres traitements. La présente étude visait à évaluer, dans le cadre d'une revue systématique d'études comparatives, la sûreté et l'efficacité clinique du PACAR, comparative-ment à celles du PACC et d'autres interventions à effraction minimale visant le traitement des coronaropathies.

**Méthodes :** Nous avons réalisé une revue systématique d'études primaires publiées en anglais comparant le PACAR à d'autres options thérapeutiques (PACC, pontage aortocoronarien direct à effraction minimale [PACDEM] et pontage aortocoronarien par voie percutanée [PACVP]) selon les lignes directrices de la Collaboration Cochrane, et avons réalisé des méta-analyses lorsque c'était approprié.

**Résultats :** Nous avons retenu 13 études : 11 études primaires sur le PACAR (comparativement à 7 études sur le PACC, à 3 études sur le PACDEM et à 1 étude sur le PACVP) et 2 études multicentriques fondées sur des bases de données (PACAR contre tout autre type de PAC). Dans l'ensemble, les données probantes étaient considérées de faible qualité. Selon la plupart des études, le PACAR ne présentait aucun avantage significatif par rapport aux autres traitements, et ce, pour la majorité des issues. Les méta-analyses ont montré que le PACAR était associé à des taux de pneumonie et d'infection de la plaie plus faibles que le PACC, de même qu'à une durée d'hospitalisation en soins intensifs plus courte que le PACC et le PACDEM. Des études individuelles ont montré que le PACAR donnait lieu à de meilleures issues pour certains paramètres que le PACC (temps de

ventilation, besoin de transfusion, douleur postopératoire et durée d'hospitalisation) et que le PACDEM (besoin de transfusion, douleur postopératoire, temps nécessaire pour la reprise des activités normales, fonctionnement physique et durée d'hospitalisation). La revue des études fondées sur des bases de données a indiqué que le PACAR était supérieur, sur le plan statistique, aux autres types de PAC en ce qui a trait à la douleur postopératoire, à l'insuffisance rénale, au besoin de transfusion, à la réalisation d'une autre chirurgie en raison de saignements, à l'accident vasculaire cérébral et à la durée d'hospitalisation; cependant, pour plusieurs de ces paramètres, les différences entre les 2 groupes étaient petites.

**Conclusion :** Bien que les résultats de cette revue d'études comparatives sur le PACAR semblent prometteurs et laissent penser que cette intervention comporte des avantages pour les patients, ils devraient être interprétés avec prudence étant donné l'absence d'études cliniques randomisées.

**T**raditionally, coronary artery bypass grafting (CABG) was performed via conventional sternotomy and with a cardiopulmonary machine (i.e., conventional coronary artery bypass grafting [median sternotomy] [on pump] [C-CABG(on)]). Later, off-pump techniques (median sternotomy) (C-CABG [off]) and other minimally invasive procedures performed through a minithoracotomy (minimally invasive direct coronary artery bypass [MIDCAB] and port-access coronary artery bypass [PA-CAB]) were developed. Most recently, the introduction of the da Vinci system has led to new robotic surgical approaches (robotic coronary artery bypass [RCAB]), including robot-assisted direct coronary artery bypass and totally endoscopic coronary artery bypass.

A 2016 systematic review of comparative and noncomparative studies of robot-assisted direct coronary artery bypass, totally endoscopic coronary artery bypass and MIDCAB showed acceptable and comparable perioperative mortality rates for all procedures.<sup>1</sup> The authors reported on intraoperative details as well as postoperative outcomes and concluded that, despite the limitations of clinical evidence available at the time, findings from their review should be considered a useful benchmark for future studies.

Owing to the lack of evidence about the advantages of RCAB over other surgical techniques, its uptake is still challenged by several limitations, including concern over intraoperative conversion, anastomosis time and anastomotic patency, heterogeneity of clinical outcomes, evolving instrumentation and cost.<sup>1,2</sup> The aim of the present study was to assess, through a systematic review of comparative studies only, the safety and clinical effectiveness of RCAB compared to C-CABG and other minimally invasive approaches (MIDCAB and PA-CAB) for the treatment of coronary heart disease.

## METHODS

We conducted a systematic review of published peer-reviewed primary studies comparing RCAB to C-CABG, MIDCAB or PA-CAB following Cochrane guidelines.<sup>3</sup>

## Literature search

We conducted a comprehensive literature search to identify relevant primary studies comparing RCAB to C-CABG, MIDCAB or PA-CAB. We developed structured search strategies and applied them to the following bibliographic databases: PubMed (MEDLINE and other sources), Embase, Web of Science, Clinical Trials.gov, The Cochrane Library, CINAHL, EconLIT, PsycINFO, and the Centre for Reviews and Dissemination (DARE, NHS EED and HTA). The strategies combined relevant key words with controlled vocabulary terms (Medical Subject Headings and Emtree terms) such as coronary artery bypass, robotic surgical procedures and minimally invasive surgical procedures. Keywords included robotic surgery, robot-assisted surgery and da Vinci. Full details of the literature search are presented in Appendix 1 (available at [canjsurg.ca/013318-a1](http://canjsurg.ca/013318-a1)). The initial search was performed in October 2017. We performed monthly update searches in PubMed and Google scholar alerts throughout the project to capture any additional studies published after the initial search; the last update was completed in April 2018. All searches were limited to human studies reported in English. No study design filters were applied.

For completeness, we conducted a manual search of the reference lists of relevant papers located through the electronic searches. Results from each of the searches were compiled and entered into a single Reference Manager v. 12 (Thomson ResearchSoft) database, after which duplicate citations were removed.

## Study selection

Two reviewers (F.H., F.N.) independently screened the titles and abstracts of all citations to identify studies for full-text review. Both reviewers retrieved and assessed the full-text papers for inclusion and exclusion according to the eligibility criteria (Table 1). Disagreement was resolved through discussion.

**Table 1. Study eligibility criteria for review on safety and clinical effectiveness of robotic coronary artery bypass**

Parameter	Inclusion criteria	Exclusion criteria
Setting	Publication in English Any health care facility performing procedure	Abstract Non-English language
Participants	Adults (age > 18 yr) eligible for CABG	Animals, cadavers
Intervention	RCAB with the da Vinci surgical system RAD CAB with the da Vinci surgical system TECAB with the da Vinci surgical system	Other robotic systems
Comparator	Conventional coronary bypass graft (median sternotomy) on pump or off pump MIDCAB PA-CAB	Percutaneous coronary intervention
Outcomes	Anesthesia time, anastomosis time, angina, aortic clamp time Complications (intraoperative and postoperative), cardiopulmonary bypass time, emergency department visits Graft stenosis/failure, harvest duration time, intensive care unit stay, late MI, late stroke Length of hospital stay, long-term pain, death, operating time, postoperative pain Quality of life, readmission, reoperation for bleeding, revascularization, short-term pain Time to return to normal activities, transfusion, ventilation time, survival	Studies without any defined clinical outcomes Studies with no relevant clinical outcomes
Study design	Randomized and nonrandomized controlled trials Cohort studies Case-control studies	Expert reviews Editorials and opinion Case series Case reports Single-arm trials

CABG = coronary artery bypass grafting; MI = myocardial infarction; MIDCAB = minimally invasive direct coronary artery bypass; PA-CAB = port-access coronary artery bypass; RAD CAB = robot-assisted direct coronary artery bypass; RCAB = robot coronary bypass; TECAB = totally endoscopic coronary artery bypass.

### Data extraction

Each reviewer independently extracted information from studies using a standard data extraction form. The elements extracted were study design, setting, methods, sample size, baseline characteristics, details of the intervention and comparator, and outcome measures. Data extraction was cross-checked by the 2 reviewers, and disagreements were resolved through discussion.

### Assessment of study quality

We used the Cochrane Collaboration Risk of Bias Tool to critically appraise any randomized trials. We appraised the methodologic quality of nonrandomized trials with the Newcastle–Ottawa Scale,<sup>4</sup> a visual tool containing 8 items over 3 domains: selection (4 items), to determine the representativeness of participants and assess the presence of selection bias; comparability (1 item), to determine the presence or control of confounding variables; and outcome/exposure (3 items), to determine the adequacy of ascertainment of outcomes and follow-up. Each item in the selection and outcome domains can be awarded a maximum of 1 star, and the item on comparability up to 2 stars. Three possible ratings can be given to studies: poor quality (0 stars in the comparability domain, or 0 or 1 star in the selection or outcome domain), fair quality (2 stars in the selection domain) or good quality (3 or 4 stars in the selection domain).

We used the GRADEpro tool (Grading of Recommendations Assessment, Development and Evaluation)<sup>5</sup> to assess the overall quality of the body of evidence for key

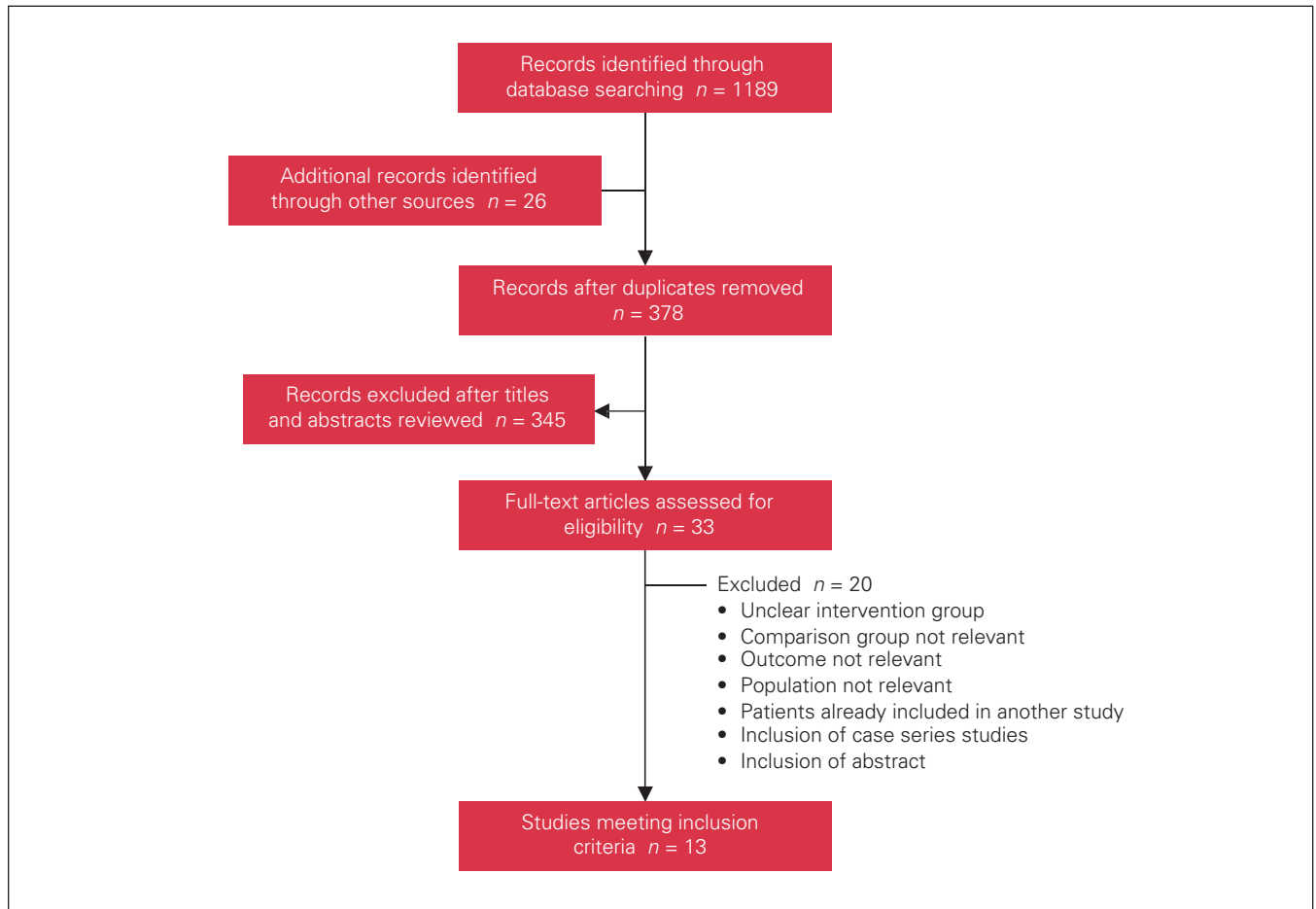
outcomes. With this tool, the quality of outcomes is rated over 6 domains: study design, risk of bias, inconsistency, indirectness, imprecision and other factors, including publication bias, a large effect size, a dose–response gradient and other plausible confounders. This approach can yield 4 grades, ranging from very low to high confidence in the overall quality of evidence. In the current study, the GRADE assessment of the quality of evidence was based on the following outcomes: length of hospital stay, late myocardial infarction (MI), late stroke, overall survival, postoperative pain score, readmission rate within 30 days and revascularization rate.

### Data analysis and synthesis

We tabulated data extracted from included studies to facilitate quantitative and qualitative analysis. Data were assessed for potential meta-analysis.

Characteristics of included studies and findings were synthesized narratively.

We conducted meta-analyses using a random-effects model<sup>6</sup> to calculate the summary statistics. A *p* value of < 0.05 was considered statistically significant. We pooled studies reporting continuous data using the mean difference between surgical groups, and those reporting categorical data using odds ratio. We assessed heterogeneity using the *I*<sup>2</sup> statistic. When heterogeneity was 50% or more,<sup>3</sup> it was considered substantial, and the studies were not pooled. In cases of multiple studies published from an institution with overlap of patients and the same outcome measures, we included only the most recent publication



**Fig. 1.** Flow diagram showing study selection.

and largest sample in the synthesis. We used RevMan software version 5.3 (The Nordic Cochrane Centre, The Cochrane Collaboration) to conduct the meta-analyses.

## RESULTS

In total, 1215 citations were retrieved through the literature searches, and 33 full-text articles were assessed (Fig. 1). Of these, 13 were included in the review.<sup>7-19</sup> Detailed descriptions of included and excluded studies can be found in Appendix 1.

Seven of the 13 studies were conducted in the United States, 2 in France, 1 in Germany, 1 in China, 1 in Taiwan and 1 in Turkey. Two studies were based on national databases,<sup>10,11</sup> and the remaining 11 studies were single-centre.<sup>7-9,12-19</sup> Patients were selected between 1998 and 2014, and sample sizes ranged from 38 to 966 211. Seven studies compared RCAB to C-CABG, on or off pump,<sup>7,12-17</sup> 3 studies compared RCAB to MIDCAB,<sup>17-19</sup> and 1 study compared RCAB to PA-CAB.<sup>9</sup> The 2 multi-centre studies investigated differences between robotic and nonrobotic CABG.<sup>10,11</sup> None of the studies were randomized controlled trials. Three were prospective

cohorts,<sup>7,17,19</sup> and the remainder were retrospective cohorts. Four studies were propensity score matched.<sup>11-13,16</sup>

### Study quality

With the GRADEpro tool, the quality of studies comparing RCAB to other surgical modalities (C-CABG, MID-CAB and PA-CAB) was rated as low to very low (Table 2). With the Newcastle–Ottawa Scale, quality was rated as good in 1 study,<sup>11</sup> fair in 2,<sup>12,13</sup> and poor in 10.<sup>7-10,14-19</sup>

### Selection bias

In 5 studies, the selection of patients for the control and intervention groups was unclear or not the same.<sup>8,9,12,16,17</sup> Three of the 5 did not state whether the eligibility criteria were the same between the RCAB group and the control group.<sup>12,16,17</sup>

In 2 studies, patients were selected for the intervention and control groups based on availability of the technology and patient's and surgeon's preference.<sup>8,9</sup> With the exception of those based on national databases,<sup>10,11</sup> all of the studies failed to show that the selected cohort was representative of the general population with coronary artery

**Table 2. GRADE (Grading of Recommendations Assessment, Development and Evaluation)<sup>5</sup> assessment of included studies**

Outcome	No. of participants (studies)*	Certainty of evidence (GRADE)	Relative effect (95% CI)	Expected absolute effects	
				Risk per 1000 with C-CABG†	Risk difference with RCAB
Length of hospital stay	1066 (7)	⊕○○○ Very low‡§¶	—	Not pooled	Not pooled
Late myocardial infarction	286 (1)	⊕○○○ Very low**††	Not estimable	41	41 fewer per 1000 (41 fewer to 41 fewer)
Late stroke	200 (1)	⊕⊕○○ Low††	Not estimable	20	20 fewer per 1000 (20 fewer to 20 fewer)
Overall survival	286 (1)	⊕○○○ Very low††‡‡	Not estimable	707	707 fewer per 1000 (707 fewer to 707 fewer)
Postoperative pain score	187(2)	⊕○○○ Very low§§¶¶	—	Not pooled	Not pooled
Readmission rate	484 (2)	⊕○○○ Very low¶¶††	Not pooled	Not pooled	Not pooled
Revascularization rate	524 (3)	⊕○○○ Very low††‡‡‡‡	Not estimable	27	27 fewer per 1000 (27 fewer to 27 fewer)

C-CABG = conventional coronary artery bypass grafting (median sternotomy); CI = confidence interval; RCAB = robotic coronary artery bypass.  
 \*Observational in all cases.  
 †The risk in the intervention group (and its 95% CI) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI).  
 ‡Most studies failed to control for confounding variables.  
 §Mean difference varied from 1 to 7 days.  
 ¶Lack of information on surgeon's experience.  
 \*\*Lack of control for confounding variables, study at high risk of selection bias.  
 ††Low event rate.  
 ‡‡Study at high risk of selection bias.  
 §§Lack of control for confounding variables, study at high risk of performance bias.  
 ¶¶Small sample.

disease. In all studies, medical records or institutional databases provided information on patients' baseline characteristics.

### Confounding

Four studies used propensity scoring to match patients and controls for potential imbalances in age, cardiac comorbidities and noncardiac comorbidities.<sup>11–13,16</sup> The other studies did not attempt to control for confounding variables during selection of patients or at the statistical analysis stage.

### Detection and attrition bias

Apart from 1 study that used self-reported measurements,<sup>17</sup> investigators extracted information on outcome measures from medical records and institutional databases. Most studies had an appropriate follow-up time, since they measured operative and perioperative outcomes. However, in 4 studies examining long-term outcomes, patients were followed for a short period, or the follow-up time differed between the intervention and control groups.<sup>8,9,11,18</sup> The presence of attrition bias was unclear in 4 studies, as the investigators did not report the number of patients lost to follow-up.<sup>8,9,14,17</sup> Further details on GRADE and methodological quality assessment are presented in Appendix 1.

### Patient characteristics

With 1 exception,<sup>14</sup> the mean or median age across studies ranged from 55 to 70 years (Table 3). The majority of participants (59%–100%) were men. The mean or median

left ventricular ejection fraction ranged from 52% to 64%. Most studies included only elective cases of CABG.

### Surgical procedure

- Procedure: Two single-centre studies used the da Vinci system for totally endoscopic coronary artery bypass<sup>9,15</sup> (Appendix 1, Supplemental Table S1). In the remaining single-centre studies, robotic-assisted direct coronary artery bypass, in which the anastomosis is performed manually, was used.<sup>7,8,12–14,16–19</sup> Nineteen percent to 22% of patients in the national database studies who had RCAB underwent surgery with the use of a cardiopulmonary bypass machine (on pump).<sup>10,11</sup> All patients in the remaining studies underwent RCAB off pump. Six of the comparative studies included patients who had C-CABG(on),<sup>7,12–15,17</sup> and 1 included those who had C-CABG(off) only.<sup>16</sup> Most procedures involved the use of the internal thoracic artery as the graft.
- Number of grafts: Two studies were limited to patients with single-vessel coronary heart disease,<sup>14,15</sup> and 1 study excluded them.<sup>16</sup> Where reported, the mean or median number of grafts for RCAB ranged from 1 to 3, whereas the mean or median number of grafts for C-CABG was 3 or 4. In 1 study of MIDCAB, there was a statistically significantly higher proportion of patients with 1 graft in the MIDCAB group than in the RCAB group.<sup>18</sup> The remaining studies comparing RCAB to MIDCAB or PA-CAB provided no information on the difference in number of grafts between groups.

**Table 3. Characteristics of participants**

Study and country	Sample size	Age, mean $\pm$ SD or median (IQR), yr	Male gender, no. (%) of participants	Diabetes, no. (%) of participants	Chronic obstructive pulmonary disease, no. (%) of participants	Peripheral vascular disease, no. (%) of participants	Left ventricular ejection fraction, mean $\pm$ SD or median (IQR), %
<b>RCAB v. C-CABG</b>							
Lewi et al., <sup>7</sup> 2018	RCAB 28 C-CABG(om) 10	RCAB 61.6 $\pm$ 10.8 C-CABG(om) 61.8 $\pm$ 8.1	RCAB 18 (64) C-CABG(om) 10 (100)†	RCAB 10 (36) C-CABG(om) 7 (70)	RCAB 1 (4) C-CABG(om) 0 (0)	RCAB 2 (7) C-CABG(om) 2 (20)	RCAB 52.6 $\pm$ 12.3 C-CABG(om) 58.9 $\pm$ 6.9
Su et al., <sup>8</sup> 2018	RCAB 139 C-CABG 147	RCAB 66 (59–72) C-CABG 70 (60–77)†	RCAB 115 (83) C-CABG 123 (84)	RCAB 68 (49) C-CABG 69 (47)	NR	RCAB 24 (17) C-CABG 33 (22)	RCAB 58 (45–60) C-CABG 45 (32–59)†
Lewi et al., <sup>12</sup> 2016	RCAB 141 C-CABG(om) 141	RCAB 64.7 $\pm$ 12.8 C-CABG(om) 64.4 $\pm$ 9.9	RCAB 95 (67) C-CABG(om) 99 (70)	RCAB 71 (50) C-CABG(om) 67 (48)	RCAB 20 (14) C-CABG(om) 22 (16)	NR	< 35% RCAB 4 (3)‡ C-CABG(om) 4 (3)‡
Read et al., <sup>13</sup> 2016	RCAB 142 C-CABG(om) 142	RCAB 64.2 $\pm$ 12.6 C-CABG(om) 63.9 $\pm$ 10.3	RCAB 96 (68) C-CABG(om) 104 (73)	RCAB 73 (51) C-CABG(om) 69 (49)	RCAB 22 (15) C-CABG(om) 23 (16)	RCAB 22 (15) C-CABG(om) 23 (16)	RCAB 54 $\pm$ 10 C-CABG(om) 53 $\pm$ 11
Ezelsoy et al., <sup>14</sup> 2015	RCAB 35 C-CABG(om) 35	RCAB 58.6 $\pm$ 10.3 C-CABG(om) 61.3 $\pm$ 8.9	RCAB 25 (71) C-CABG(om) 16 (46)†	RCAB 10 (29) C-CABG(om) 15 (43)	RCAB 1 (3) C-CABG(om) 8 (23)†	RCAB 2 (6) C-CABG(om) 1 (3)	RCAB 62.7 $\pm$ 6.0 C-CABG(om) 54.9 $\pm$ 6.2†
Zaouter et al., <sup>15</sup> 2015	RCAB 38 C-CABG(om) 33	RCAB 64 $\pm$ 10 C-CABG(om) 67 $\pm$ 11	RCAB 33 (87) C-CABG(om) 22 (67)†	RCAB 14 (37) C-CABG(om) 17 (52)	RCAB 7 (18) C-CABG(om) 5 (15)	RCAB 5 (13) C-CABG(om) 6 (18)	RCAB 56 $\pm$ 12 C-CABG(om) 54 $\pm$ 11
Poston et al., <sup>16</sup> 2008	RCAB 100 C-CABG(off) 100	RCAB 61.8 $\pm$ 9.4 C-CABG 66.2 $\pm$ 10.1	RCAB 72 (72) C-CABG 63 (63)	RCAB 32 (32) C-CABG 43 (100)	NR	RCAB 28 (28) C-CABG 26 (26)	< 35% RCAB 20 (20)‡ C-CABG(off) 23 (23)‡ 35%–50% RCAB: 28 (28)‡ C-CABG(off): 27 (27)‡ > 50% RCAB: 52 (52)‡ C-CABG(off): 50 (50)‡
Bucerius et al., <sup>17</sup> 2002	RCAB 24 C-CABG(om) 93	RCAB 65.3 $\pm$ 6.6 C-CABG 63.9 $\pm$ 9.0§	RCAB 16 (67) C-CABG 70 (75)§	NR	NR	NR	RCAB 64.4 $\pm$ 11.4 C-CABG 58.2 $\pm$ 14.2§
<b>RCAB v. MIDCAB</b>							
Gong et al., <sup>18</sup> 2016	RCAB 71 MIDCAB 61	RCAB 66.5 $\pm$ 11.3 MIDCAB 67.9 $\pm$ 9.1	RCAB 48 (68) MIDCAB 43 (70)	RCAB 23 (32) MIDCAB 20 (33)	RCAB 4 (6) MIDCAB 3 (5)	RCAB 26 (37) MIDCAB 20 (33)	RCAB 59.0 $\pm$ 9.6 MIDCAB 57.5 $\pm$ 6.4
		HCR subgroup	HCR subgroup	HCR subgroup	HCR subgroup	HCR subgroup	HCR subgroup
		RCAB (n = 34) 67.8 $\pm$ 8.1 MIDCAB (n = 12) 63.6 $\pm$ 8.1	RCAB (n = 34) 26 (76) MIDCAB (n = 12) 7 (58)	RCAB (n = 34) 12 (35) MIDCAB (n = 12) 7 (58)	RCAB (n = 34) 2 (6) MIDCAB (n = 12) 1 (8)	RCAB (n = 34) 6 (18) MIDCAB (n = 12) 3 (25)	RCAB (n = 34) 59.0 $\pm$ 8.6 MIDCAB (n = 12) 57.5 $\pm$ 6.4
Bachinsky et al., <sup>19</sup> 2012, US	RCAB 25 MIDCAB 27	RCAB 63.2 $\pm$ 10.5 MIDCAB 66.8 $\pm$ 10.7	RCAB 20 (80) MIDCAB 16 (59)	RCAB 9 (36) MIDCAB 13 (48)	NR	RCAB 3 (12) MIDCAB 3 (11)	RCAB 55.3 $\pm$ 10.4 MIDCAB 51.5 $\pm$ 12.0
Bucerius et al., <sup>17</sup> 2002	RCAB 24 MIDCAB 73	RCAB 65.3 $\pm$ 6.6 MIDCAB 61.6 $\pm$ 9.9§	RCAB 16 (67) MIDCAB 55 (75)§	NR	NR	NR	RCAB 64.4 $\pm$ 11.4 MIDCAB 62.8 $\pm$ 18.2§
<b>RCAB v. PA-CAB</b>							
Jegaden et al., <sup>9</sup> 2011	RCAB 59 PA-CAB 48	RCAB 59 $\pm$ 12 PA-CAB 55 $\pm$ 9	RCAB 53 (90) PA-CAB 44 (92)	NR	NR	NR	RCAB 57 $\pm$ 8 PA-CAB 58 $\pm$ 11
<b>RCAB v. non-RCAB</b>							
Whellan et al., <sup>10</sup> 2016	RCAB 9862 Non-RCAB 956 349	RCAB 64 (56–72) Non-RCAB 65 (57–73)†	RCAB 7156 (73) Non-RCAB 706 981 (74)†	RCAB 3,542 (36) Non-RCAB 395 168 (41)†	NR	RCAB 1224 (12) Non-RCAB 137 583 (14)†	RCAB 55 (49–60) Non-RCAB 55 (45–60)†
Cavallaro et al., <sup>11</sup> 2015, US	RCAB 464 Non-RCAB 464	RCAB (n = 275) 64.6 $\pm$ 11.3 Non-RCAB (n = 275) 64.2 $\pm$ 11.6	RCAB (n = 275) 193 (70) Non-RCAB (n = 275) 185 (67)	RCAB (n = 275) 96 (35) Non-RCAB (n = 275) 110 (40)	1 bypass RCAB (n = 275) 43 (16) Non-RCAB (n = 275) 44 (16)	1 bypass RCAB (n = 275) 28 (10) Non-RCAB (n = 275) 34 (12)	NR
		$\geq 2$ bypasses RCAB (n = 189) 63.9 $\pm$ 10.6 Non-RCAB (n = 189) 63.8 $\pm$ 11.2	$\geq 2$ bypasses RCAB (n = 189) 152 (80) Non-RCAB (n = 189) 151 (80)	$\geq 2$ bypasses RCAB (n = 189) 26 (14) Non-RCAB (n = 189) 26 (14)	$\geq 2$ bypasses RCAB (n = 189) 30 (16) Non-RCAB (n = 189) 14 (7)		

C-CABG(off) = conventional coronary artery bypass grafting (median sternotomy) (off pump); C-CABG(om) = C-CABG (on pump); HCR = hybrid coronary revascularization; IQR = interquartile range; MIDCAB = minimally invasive direct coronary artery bypass; non-RCAB = nonrobotic coronary artery bypass; NR = not reported; PA-CAB = port-access coronary artery bypass; RCAB = robotic coronary artery bypass; SD = standard deviation.  
 †P  $\leq$  0.05.  
 ‡Reported as number (%) of participants.  
 §p value based on the overall differences between RCAB, MIDCAB and C-CABG.

**Table 4. Safety**

Study and country	Intraoperative complications, no. (%) of participants			Postoperative complications, no. (%) of participants		
	Conversion to C-CABG	Myocardial infarction	Stroke	Atrial fibrillation	Infection	Renal failure
<b>RCAB v. C-CABG</b>						
Leyvi et al., <sup>7</sup> 2018 US	NR	RCAB 0 (0) C-CABG(on) 0 (0)	RCAB 1 (4) C-CABG(on) 0 (0)	NR	RCAB 1 (4)* C-CABG(on) 2 (20)*	NR
Su et al., <sup>8</sup> 2018 Taiwan	RCAB 0 (0) C-CABG NA	NR	NR	NR	NR	NR
Leyvi et al., <sup>12</sup> 2016 US	RCAB 2 (1) C-CABG(on) NA	RCAB 0 (0) C-CABG(on) 0 (0)	RCAB 0 (0) C-CABG(on) 2 (1)	NR	RCAB 0 (0)† C-CABG(on) 4 (3)†	RCAB 1 (1) C-CABG(on) 1 (1)
Raad et al., <sup>13</sup> 2016 US	NR	NR	RCAB 0 (0) C-CABG 4 (3)	NR	RCAB 0 (0)* C-CABG 3 (2)*	RCAB 0 (0) C-CABG(on) 1 (1)
Ezelsoy et al., <sup>14</sup> 2015 Turkey	RCAB 0 (0) C-CABG NA	NR	NR	RCAB 5 (14)‡ C-CABG 6 (17)‡	RCAB 0 (0)§ C-CABG(on) 7 (20)§	RCAB 0 (0)¶ C-CABG(on) 2 (6)¶
Zaouter et al., <sup>15</sup> 2015 France	RCAB 2 (5) (graft failure) C-CABG(on) NA	NR	RCAB 0 (0) C-CABG(on) 1 (3)	RCAB 7 (18) C-CABG(on) 3 (9)	RCAB 0 (0)* C-CABG(on) 1 (3)* RCAB 0 (0)§ C-CABG(on) 2 (6)§	NR
Poston et al., <sup>16</sup> 2008 US	NR	RCAB 1 (1)** C-CABG(off) 7 (7)**	RCAB 0 (0)** C-CABG(off) 2 (2)**	RCAB 12 (12)** C-CABG(off) 20 (20)**	RCAB 0 (0)†† C-CABG(off) 2 (2)††	NR
Bucerius et al., <sup>17</sup> 2002 Germany	NR	NR	NR	NR	NR	NR
<b>RCAB v. MIDCAB</b>						
Gong et al., <sup>18</sup> 2016 China	RCAB 3 (4) MIDCAB 2 (3)	RCAB 1 (1) MIDCAB 2 (3) <i>HCR subgroup</i> RCAB ( <i>n</i> = 34) 1 (3) MIDCAB ( <i>n</i> = 12) 0 (0)	NR	RCAB 2 (3)‡ MIDCAB 9 (15)‡ <i>HCR subgroup</i> RCAB ( <i>n</i> = 34) 2 (6) MIDCAB ( <i>n</i> = 12) 1 (8)	RCAB 0 (0)* MIDCAB 1 (2)*	RCAB 1 (1) MIDCAB 2 (3) <i>HCR subgroup</i> RCAB ( <i>n</i> = 34) 0 (0) MIDCAB ( <i>n</i> = 12) 1 (8)
Bachinsky et al., <sup>19</sup> 2012 US	NR	RCAB 15 (60) MIDCAB 24 (92)	NR	RCAB 4 (16) MIDCAB 8 (30)	NR	NR
Bucerius et al., <sup>17</sup> 2002 Germany	NR	NR	NR	NR	NR	NR
<b>RCAB v. PA-CAB</b>						
Jegaden et al., <sup>9</sup> 2011 France	RCAB 0 (0) PA-CAB 0 (0)	RCAB 2 (3) PA-CAB 1 (2)	RCAB 0 (0) PA-CAB 1 (2)	NR	NR	NR
<b>RCAB v. non-RCAB</b>						
Whellan et al., <sup>10</sup> 2016 US	NR	NR	RCAB 53 (1) Non-RCAB 10 973 (1)	NR	NR	RCAB 210 (2) Non-RCAB 27 505 (3)
Cavallaro (2015) <sup>11</sup> USA	NR	NR	<i>1 bypass</i> RCAB ( <i>n</i> = 275) 0 (0) Non-RCAB ( <i>n</i> = 275) 4 (1) <i>≥ 2 bypasses</i> RCAB ( <i>n</i> = 189) 9 (5) Non-RCAB ( <i>n</i> = 189) 9 (5)	NR	<i>1 bypass</i> RCAB ( <i>n</i> = 275) 11 (4) Non-RCAB ( <i>n</i> = 275) 13 (5) <i>≥ 2 bypasses</i> RCAB ( <i>n</i> = 189) 2 (1) Non-RCAB ( <i>n</i> = 189) 8 (4)	<i>1 bypass</i> RCAB ( <i>n</i> = 275) 12 (4)¶ Non-RCAB ( <i>n</i> = 275) 23 (8)¶ <i>≥ 2 bypasses</i> RCAB ( <i>n</i> = 189) 12 (6)¶ Non-RCAB ( <i>n</i> = 189) 11 (6)¶

C-CABG = conventional coronary artery bypass grafting (median sternotomy); C-CABG(off) = C-CABG (off pump); C-CABG(on) = C-CABG (on pump); HCR = hybrid coronary revascularization; MIDCAB = minimally invasive direct coronary artery bypass; NA = not applicable; non-RCAB = nonrobotic coronary artery bypass; NR = not reported; PA-CAB = port-access coronary artery bypass; RCAB = robotic coronary artery bypass.

\*Wound infection.  
†Deep sternal wound infections.  
‡Arrhythmia.  
§Pneumonia.  
¶Acute renal failure.  
\*\*Within 30 days.  
††Major infection.

- **Surgeons:** In 4 studies, surgical procedures in the control and intervention groups were performed by a single surgeon or surgical team.<sup>7,14,16,19</sup> One of the remaining studies simply described surgeons as being experienced with robotic technology,<sup>12</sup> and the rest provided no information on surgeon experience.
- **Hybrid coronary revascularization:** Some patients with multivessel coronary heart disease who underwent a minimally invasive procedure also had a percutaneous coronary intervention. Where reported, the rates of hybrid coronary revascularization in studies of minimally invasive non-robot-assisted procedures ranged from 0% to 48%.<sup>7,12,15,18</sup> In 1 study of RCAB, all patients had a percutaneous coronary intervention for other coronary vessels.<sup>18</sup> Across studies, the timing of percutaneous coronary intervention varied between 0 (i.e., performed at the same time) and 14 days after CABG. Most hybrid coronary revascularization procedures were performed with drug-eluting stents.

### Safety

- **Conversion to C-CABG:** Six studies reported rates of conversion to C-CABG from RCAB ranging from 0% to 5% (Table 4).<sup>8,9,12,14,15,18</sup> One study comparing RCAB and MIDCAB showed no differences in rates between these 2 approaches.<sup>18</sup> Jegaden and colleagues<sup>9</sup> compared conversion rates of RCAB and PA-CAB, and reported none in either group.
- **Postoperative complications:** One study comparing RCAB to C-CABG(on) showed no differences in rates,<sup>7</sup> but Poston and colleagues<sup>16</sup> reported that patients who underwent RCAB had lower rates of major complications than those who underwent C-CABG(off). One national database study showed significantly higher rates of major complications in the nonrobotic group than in the robotic group.<sup>10</sup>
- **Myocardial infarction:** Three studies compared MI rates between RCAB and C-CABG.<sup>7,12,16</sup> Rates ranged from 0% to 7%, and no differences between groups were found. One of the 2 studies comparing RCAB and MIDCAB showed no significant difference in MI rates between the 2 groups.<sup>15</sup> The second study showed significantly lower rates with RCAB; however, this difference disappeared after adjustment for baseline covariates with a propensity score model.<sup>19</sup> The single study of PA-CAB showed similar rates of MI as for RCAB.<sup>9</sup>
- **Stroke:** Postoperative stroke rates were provided in 4 studies of patients who underwent RCAB or C-CABG.<sup>7,13,15,16</sup> A meta-analysis of 3 studies on RCAB versus C-CABG(on) showed no significant difference between the 2 procedures (Fig. 2). The single study on RCAB versus C-CABG(off) also showed no significant difference.<sup>16</sup> In 1 study comparing RCAB and PA-CAB, stroke rates were 0% and 2%, respectively

(*p* value not reported).<sup>9</sup> No studies reported postoperative stroke rates among patients who underwent MIDCAB, but the 2 national database studies compared rates between robotic and nonrobotic procedures.<sup>10,11</sup> Although both studies showed lower rates for stroke, only 1 showed a significant difference between groups, favouring RCAB.<sup>11</sup>

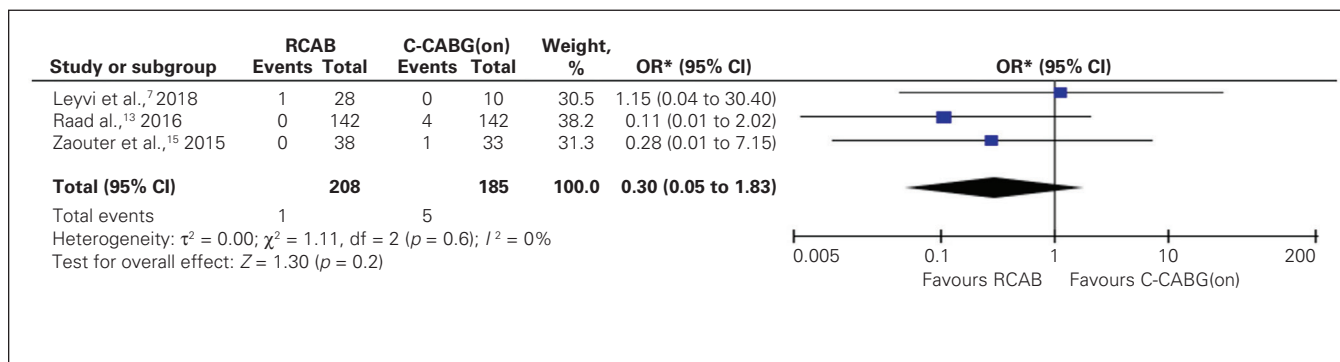
- **Atrial fibrillation:** Rates of atrial fibrillation varied from 9% to 20%, and no significant differences between patients who underwent RCAB versus C-CABG were reported.<sup>14-16</sup> One study comparing patients who had RCAB as well as a percutaneous coronary intervention to those who had MIDCAB showed no significant differences in atrial fibrillation rates (16% v. 30%).<sup>19</sup> However, in 1 other study of the same comparators that showed no significant differences among patients who underwent hybrid coronary revascularization, significantly higher rates of arrhythmia were observed in the MIDCAB group than in the RCAB group.<sup>18</sup>
- **Infection:** Of the studies comparing RCAB and C-CABG, 3 provided information on wound infection,<sup>7,13,15</sup> 2 provided information on pneumonia<sup>14,15</sup> and 1 provided information on major infections.<sup>16</sup> Meta-analyses showed that RCAB was associated with significantly lower rates of wound infection (Fig. 3) and pneumonia (Fig. 4) than C-CABG(on). There was no significant difference in rates of major infections between RCAB and C-CABG(off). One study of MIDCAB versus RCAB presented rates of wound infection after CABG; no significant differences were found.<sup>18</sup> None of the studies reported on infection rates after PA-CAB. However, 1 national database study showed no significant difference in infection rates between patients who underwent robotic and those who underwent nonrobotic surgery.<sup>11</sup>
- **Renal failure:** Three studies comparing RCAB to C-CABG showed postoperative renal failure rates ranging from 0% to 6%.<sup>12-14</sup> The pooled estimate of studies on RCAB and C-CABG(on) showed no differences between approaches (Fig. 5). One study of MIDCAB versus RCAB showed no significant differences in renal failure rates.<sup>18</sup> One national database study showed a significant difference, favouring robotic over nonrobotic CABG.<sup>10</sup> However, the other national database study showed no significant difference in renal failure rates.<sup>11</sup>

### Outcomes

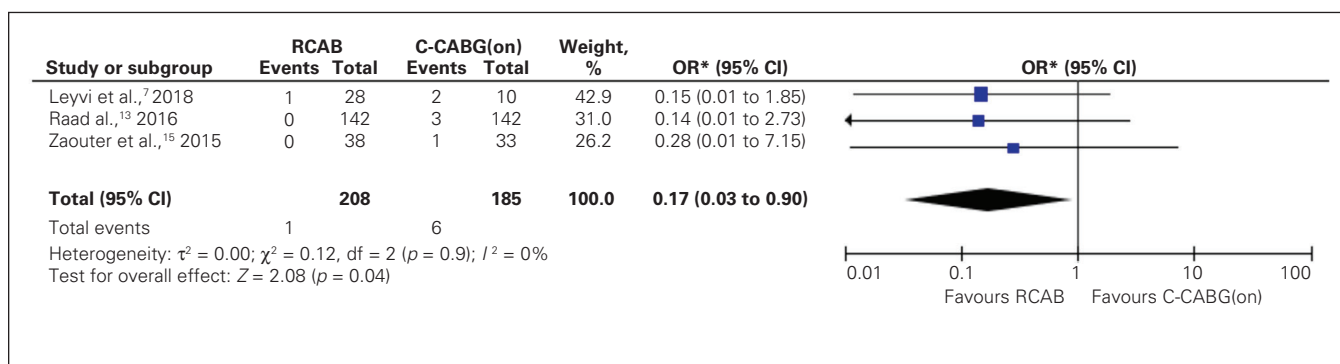
#### Operative outcomes

- **Cardiopulmonary bypass time:** One national database study showed no significant difference in cardiopulmonary bypass time between arrested-heart robotic and nonrobotic procedures (88 min v. 90 min, *p* = 0.2).<sup>10</sup> The remaining studies used off-pump techniques during RCAB.

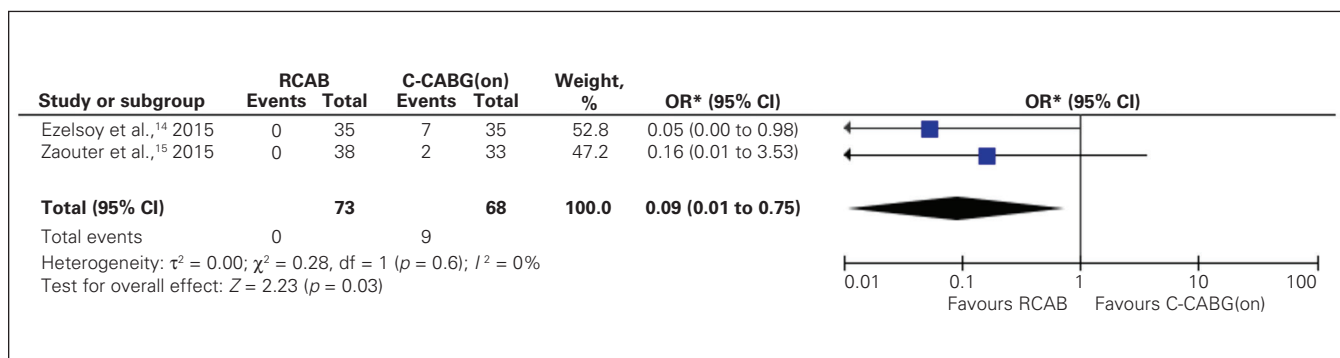




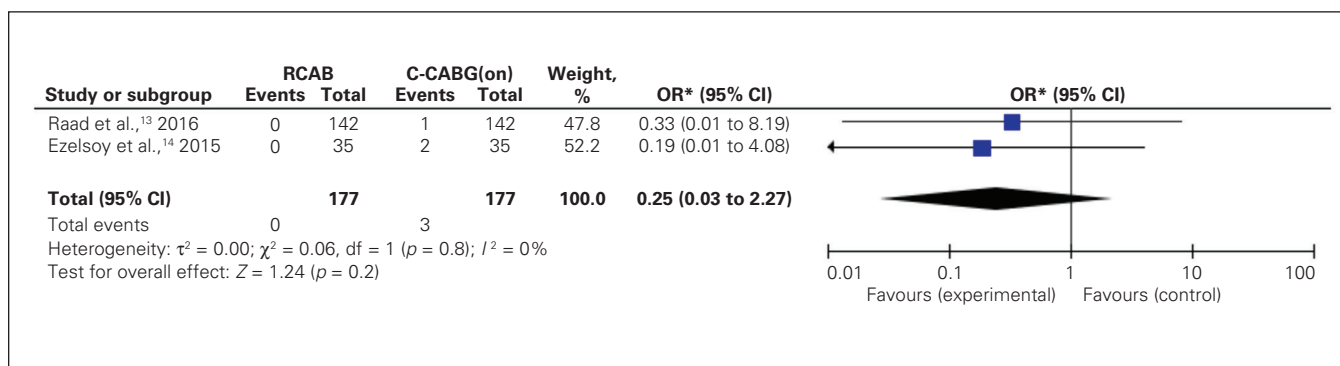
**Fig. 2.** Meta-analysis of postoperative stroke from comparative studies of robotic coronary artery bypass (RCAB) versus conventional coronary artery bypass grafting (on pump) (C-CABG[on]). \*IV random. CI = confidence interval; OR = odds ratio.



**Fig. 3.** Meta-analysis of wound infection from comparative studies of robotic coronary artery bypass (RCAB) versus conventional coronary artery bypass grafting (on pump) (C-CABG[on]). \*Mantel-Haenszel random. CI = confidence interval; OR = odds ratio.



**Fig. 4.** Meta-analysis of pneumonia from comparative studies of robotic coronary artery bypass (RCAB) versus conventional coronary artery bypass grafting (on pump) (C-CABG[on]). \*Mantel-Haenszel random. CI = confidence interval; OR = odds ratio.



**Fig. 5.** Meta-analysis of renal failure from comparative studies of robotic coronary artery bypass (RCAB) versus conventional coronary artery bypass grafting (on pump) (C-CABG[on]). \*Mantel-Haenszel random. CI = confidence interval; OR = odds ratio.

- Harvest duration time: None of the studies compared harvest duration time between RCAB and other surgical approaches. One study indicated that the mean harvest time for the RCAB group was 48 minutes.<sup>14</sup>
- Anastomosis time: Zaouter and colleagues<sup>15</sup> reported an average anastomosis time of 60 minutes during RCAB. There were no studies comparing anastomosis time between CABG techniques.

#### Postoperative outcomes

- Ventilation time: In 6 studies comparing RCAB and C-CABG, the investigators reported on differences in mean ventilation time<sup>7,13-17</sup> (Table 5). The mean time for RCAB ranged from 0.4 to 16 hours, whereas the mean time for C-CABG ranged from 3 to 14 hours. In 4 of these studies, mean ventilation times were significantly longer for patients who underwent C-CABG than for those who had RCAB.<sup>7,13,14,16</sup> For MIDCAB, different results were reported in 2 studies. One showed that a significantly higher proportion of patients who underwent RCAB than underwent MIDCAB had been extubated within 6 hours or less after surgery,<sup>18</sup> whereas the second study showed no significant difference between the 2 approaches.<sup>17</sup> In a study of RCAB versus PA-CAB, the mean ventilation times for RCAB and PA-CAB were 5 hours and 8 hours, respectively;<sup>9</sup> the investigators did not provide the statistical significance of the results. One national database study showed that a significantly higher proportion of patients in the non-robotic group than in the robotic group required ventilation beyond 24 hours.<sup>10</sup>
- Intensive care unit stay: Seven studies of RCAB versus C-CABG reported on differences in intensive care unit (ICU) stay.<sup>7,8,12,14-17</sup> A meta-analysis of 2 studies showed that stays were significantly longer after C-CABG(on) (Fig. 6). The pooled estimate of 3 studies on MIDCAB showed shorter ICU stay after RCAB (Fig. 7).
- Transfusion: Three studies compared transfusion rates between RCAB and C-CABG(on).<sup>7,12,15</sup> One showed no significant difference,<sup>7</sup> whereas 2 showed significantly lower rates in the RCAB group.<sup>12,15</sup> Transfusion rates with RCAB and C-CABG(on) ranged from 4% to 26% and from 20% to 58%, respectively. Two studies comparing RCAB to MIDCAB showed different results regarding transfusion rates.<sup>18,19</sup> In 1 study, rates were similar (15% v. 18%,  $p = 0.7$ ),<sup>18</sup> whereas in the other, they were significantly higher for MIDCAB (67% v. 12%).<sup>19</sup> One national database study showed significantly higher transfusion rates among patients who underwent nonrobotic CABG for single and multiple bypasses than among those who underwent robotic CABG.<sup>11</sup>
- Reoperation for bleeding: Rates of reoperation for bleeding were low (0%–8%). In three studies, they were similar for patients who underwent C-CABG and

those who had RCAB.<sup>13,15,16</sup> One study comparing RCAB and MIDCAB provided information on the number of patients requiring reoperation due to bleeding; no significant differences were found between groups.<sup>18</sup> In the single study of PA-CAB versus RCAB, rates of 2% and 8% for PA-CAB and RCAB, respectively, were reported ( $p$  value not provided).<sup>9</sup> One national database study showed that the difference of 0.3% in rates was statistically significant and was in favour of the robotic group.<sup>10</sup>

- Postoperative pain: In 4 studies comparing RCAB and C-CABG, pain was measured with different instruments. Pain was assessed through scales in 2 studies, which showed higher pain scores among patients who underwent C-CABG(on) at postoperative day 3–7 than among those who underwent RCAB.<sup>14,17</sup> In a third study, pain was measured through use of narcotic medication; the RCAB group required significantly lower dosages during the hospital stay than the C-CABG group.<sup>13</sup> However, the fourth study showed no differences in duration of incisional pain between patients who underwent RCAB and those who had C-CABG(off) (13 d v. 27 d).<sup>13</sup> Different instruments to measure postoperative pain were also used in 3 studies of MIDCAB versus RCAB.<sup>17-19</sup> In 1 study, a higher proportion of patients who underwent MIDCAB had intercostal pain for 3 days (16% v. 6% for RCAB,  $p = 0.04$ ).<sup>18</sup> In the other 2 studies, scales were used to assess pain.<sup>17,19</sup> One study showed no significant differences in scores between the groups during the hospital stay or on discharge.<sup>19</sup> The second study also showed no differences in pain scores 1–2 days after surgery, but lower scores were observed in the RCAB group than in the MIDCAB group at postoperative days 3–7.<sup>17</sup>

#### Short- and long-term outcomes

- Angina: One study comparing RCAB to MIDCAB provided information on angina rates after the procedure<sup>18</sup> (Table 6). During 22 months (range 12–60 mo) of follow-up, no significant differences were reported. Rates with RCAB and MIDCAB were 6% and 7%, respectively. In the single comparative study on PA-CAB, 3-year angina-free survival rates were 85% for patients who underwent RCAB and 94% for those who underwent PA-CAB ( $p$  value not provided).<sup>9</sup> None of the studies measured angina after C-CABG.
- Late MI: One study showed late MI rates for RCAB and C-CABG of 5% and 4%, respectively; the difference was not statistically significant.<sup>8</sup> Gong and colleagues<sup>18</sup> measured late MI during 22 months of follow-up in patients who went RCAB or MIDCAB and found that the rates were low and were similar for the 2 approaches (3% and 2%). In the single study of RCAB versus PA-CAB, only 1 case (2%) of late MI was observed, in the PA-CAB group.<sup>9</sup>

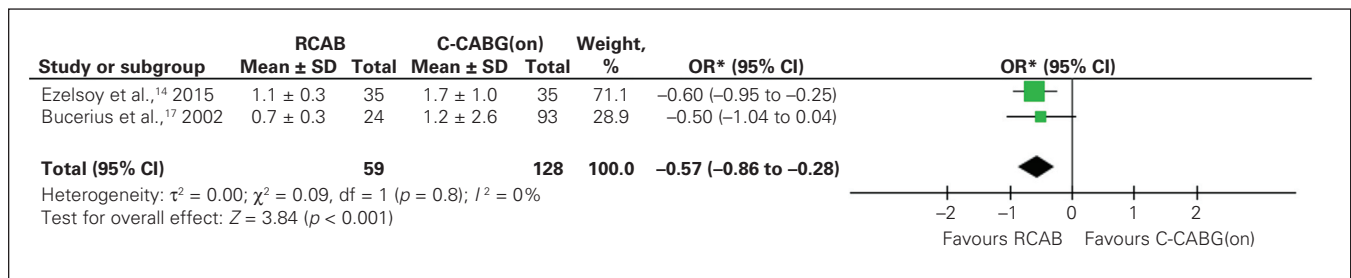
Table 5 (part 1 of 2). Postoperative outcomes

Study and country	Ventilation time, mean ± SD or median (IQR), h*	ICU stay, mean ± SD or median (IQR), h	Transfusion, no. (%) of participants	Reoperation for bleeding, no. (%) of participants	Postoperative pain, mean value ± SD*
<b>RCAB v. C-CABG</b>					
Leyvi et al., <sup>7</sup> 2018 US	RCAB 2.7 (0.7–4.4) C-CABG(on) 6.8 (5.5–8.5)	RCAB 1 (1–2) C-CABG(on) 2 (2–3)	RCAB 1 (4) C-CABG(on) 2 (20)	NR	NR
Su et al., <sup>8</sup> 2018 Taiwan	NR	RCAB 3 (2–4) C-CABG 7 (5–13)	NR	NR	NR
Leyvi et al., <sup>12</sup> 2016 US	NR	RCAB 1.3 (1–2.0) C-CABG(on) 2.2 (1.3–4.0)	RCAB 18 (13) C-CABG(on) 49 (35)	RCAB 2 (1) C-CABG(on) 5 (4)	NR
Raad et al., <sup>13</sup> 2016 US	RCAB 7.3 ± 20.0 C-CABG(on) 10.5 ± 10.0	NR	NR	RCAB 1 (1) C-CABG(on) 3 (2)	MED From procedure to postoperative day 3 RCAB 182 ± 21 C-CABG(on) 253 ± 16† In hospital RCAB 317 ± 30 C-CABG(on) 480 ± 28† Intraoperatively RCAB 127 ± 12 C-CABG(on) 205 ± 13†
Ezelsoy et al., <sup>14</sup> 2015 Turkey	RCAB 4.7 ± 1.2 C-CABG(on) 5.2 ± 1.0	RCAB 1.1 ± 0.3 C-CABG(on) 1.7 ± 1.0	NR	NR	VRS‡ Postoperative day 1 Higher mean score for RCAB§ Postoperative day 3 Higher mean score for C-CABG(on)§
Zaouter et al., <sup>15</sup> 2015 France	RCAB 0.4 ± 0.1¶ C-CABG(on) 2.6 ± 1.9¶	RCAB 0.9 (0.8–1.8) C-CABG(on) 1.9 (1.2–2.0)	RCAB 10 (26) C-CABG(on) 19 (58)	RCAB 0 (0) C-CABG(on) 0 (0)	NR
Poston et al., <sup>16</sup> 2008 US	RCAB 4.8 ± 6.4 C-CABG(off) 12.2 ± 6.2	RCAB 0.9 ± 0.4 C-CABG(off) 2.1 ± 1.1	NR	RCAB 1 (1) C-CABG(off) 6 (6)	Duration of incisional pain in days RCAB 13.1 ± 10.9 C-CABG(off) 26.6 ± 31.4
Bucerius et al., <sup>17</sup> 2002 Germany	RCAB 15.7 ± 4.9 C-CABG(on) 13.8 ± 34.4	RCAB 0.7 ± 0.3 C-CABG(on) 1.2 ± 2.6	NR	NR	VAS Postoperative day 1 RCAB 4.3 ± 2.6 C-CABG(on) 4.4 ± 2.9 Postoperative day 2 RCAB 3.1 ± 2.4 C-CABG(on) 4.5 ± 2.5§ Postoperative day 3 RCAB 2.6 ± 2.4 C-CABG(on) 4.3 ± 2.1** Postoperative day 4 RCAB 2.1 ± 1.7 C-CABG(on) 3.9 ± 2.3† Postoperative day 5 RCAB 2.1 ± 1.7 C-CABG(on) 3.8 ± 2.3** Postoperative day 6 RCAB 1.1 ± 1.3 C-CABG(on) 3.6 ± 2.4† Postoperative day 7 RCAB 0.3 ± 0.6 C-CABG(on) 2.8 ± 2.4†
<b>RCAB v. MIDCAB</b>					
Gong et al., <sup>18</sup> 2016 China	No. (%) of patients < 6 h RCAB 10 (14) MIDCAB 2 (3) 6–12 h RCAB 60 (85) MIDCAB 56 (92) > 12 h RCAB 1 (1) MIDCAB 3 (5)	RCAB 1.3 ± 0.4 MIDCAB 1.5 ± 0.4 HCR subgroup RCAB (n = 34) 1.1 ± 0.3 MIDCAB (n = 12) 1.4 ± 0.2	RCAB 11 (15) MIDCAB 11 (18)	RCAB 1 (1) MIDCAB 1 (2) HCR subgroup RCAB (n = 34) 0 (0) MIDCAB (n = 12) 0 (0)	No. (%) of patients with intercostal pain (incisional pain requiring medication more than once a day for 3 d) RCAB 4 (6) MIDCAB 10 (16)§

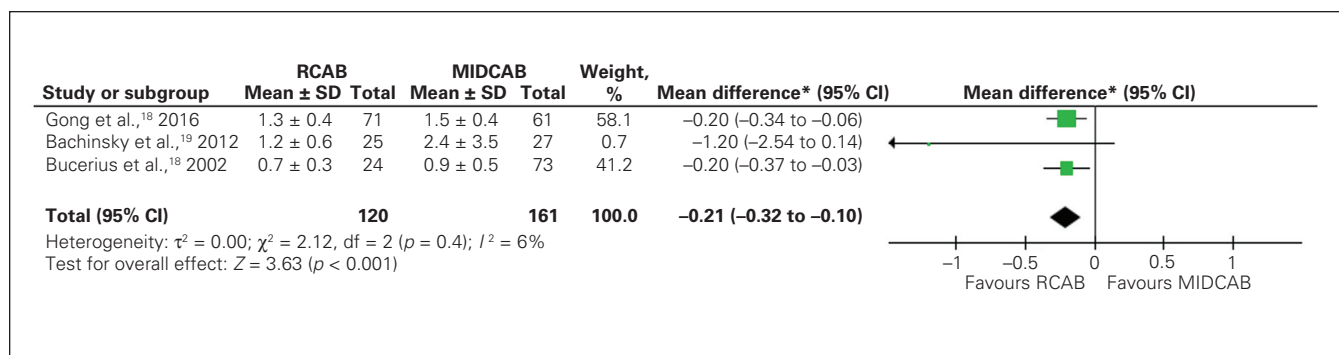
**Table 5 (part 2 of 2). Postoperative outcomes**

Study and country	Ventilation time, mean ± SD or median (IQR), h*	ICU stay, mean ± SD or median (IQR), h	Transfusion, no. (%) of participants	Reoperation for bleeding, no. (%) of participants	Postoperative pain, mean value ± SD*
Bachinsky et al., <sup>19</sup> 2012 US	NR	RCAB 1.2 ± 0.6 MIDCAB 2.4 ± 3.5	RCAB 3 (12) MIDCAB 18 (67)	NR	Scale of 0–10 During hospital stay RCAB 7.4 ± 1.8 MIDCAB 7.6 ± 1.6 On discharge RCAB 6.4 ± 2.6 MIDCAB 7.5 ± 2.5
Bucerius et al., <sup>17</sup> 2002 Germany	RCAB 15.7 ± 4.9 MIDCAB 9.3 ± 4.9	RCAB 0.7 ± 0.3 MIDCAB 0.9 ± 0.5	NR	NR	VAS Postoperative day 1 RCAB 4.3 ± 2.6 MIDCAB 5.8 ± 2.7 Postoperative day 2 RCAB 3.1 ± 2.4 MIDCAB 2.8 ± 1.1 Postoperative day 3 RCAB 2.6 ± 2.4 MIDCAB 4.2 ± 1.9§ Postoperative day 4 RCAB 2.1 ± 1.7 MIDCAB 3.7 ± 1.9** Postoperative day 5 RCAB 2.1 ± 1.7 MIDCAB 3.4 ± 1.9** Postoperative day 6 RCAB 1.1 ± 1.3 MIDCAB 2.8 ± 2.0** Postoperative day 7 RCAB 0.3 ± 0.6 MIDCAB 2.3 ± 2.1†
<b>RCAB v. PA-CAB</b>					
Jegaden et al., <sup>9</sup> 2011 France	RCAB 4.6 ± 2.4 PA-CAB 8.0 ± 4.0	RCAB 1.0 ± 0.8 PA-CAB 1.7 ± 2.7	NR	RCAB 5 (8) PA-CAB 1 (2)	NR
<b>RCAB v. non-RCAB</b>					
Whellan et al., <sup>10</sup> 2016 US	> 24 h RCAB 548 (6) Non-RCAB 82 620 (9)	NR	NR	RCAB 228 (2) Non-RCAB 19 099 (2)	NR
Cavallaro et al., <sup>11</sup> 2015 US	NR	NR	1 bypass RCAB (n = 275) 37 (13) Non-RCAB (n = 275) 67 (24) ≥ 2 bypasses RCAB (n = 189) 35 (19) Non-RCAB (n = 189) 52 (28)	NR	NR

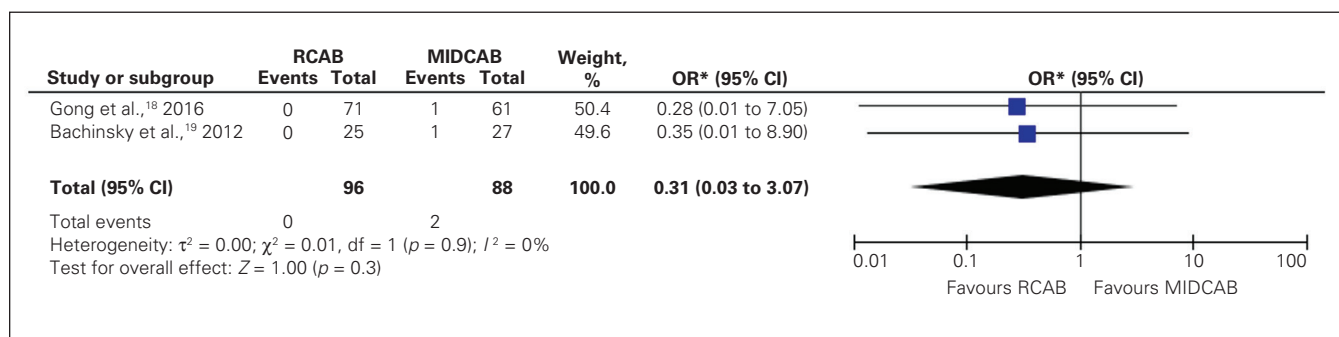
C-CABG = conventional coronary artery bypass grafting (median sternotomy); C-CABG(off) = C-CABG (off pump); C-CABG(on) = C-CABG (on pump); HCR = hybrid coronary revascularization; ICU = intensive care unit; IQR = interquartile range; MED = morphine equivalent dose; MIDCAB = minimally invasive direct coronary artery bypass; non-RCAB = nonrobotic coronary artery bypass; NR = not reported; PA-CAB = port-access coronary artery bypass; RCAB = robotic coronary artery bypass; SD = standard deviation; VAS = visual analogue scale; VRS = verbal rating scale.  
 \*Except where noted otherwise.  
 †p ≤ 0.001.  
 ‡On a scale of 0 to 10.  
 §p ≤ 0.05.  
 ¶Converted from minutes.  
 \*\*p < 0.01.



**Fig. 6.** Meta-analysis of intensive care unit length of stay from comparative studies of robotic coronary artery bypass (RCAB) versus conventional coronary artery bypass grafting (on pump) (C-CABG[on]).\*IV random. CI = confidence interval; SD = standard deviation.



**Fig. 7.** Meta-analysis of intensive care unit length of stay from comparative studies of robotic coronary artery bypass (RCAB) versus minimally invasive direct coronary artery bypass (MIDCAB). \*IV random. CI = confidence interval; SD = standard deviation.



**Fig. 8.** Meta-analysis of 30-day mortality from comparative studies of robotic coronary artery bypass (RCAB) versus minimally invasive direct coronary artery bypass (MIDCAB). \*Mantel-Haenszel random. CI = confidence interval; OR = odds ratio.

- Late stroke: In 1 study comparing RCAB to C-CABG(off)<sup>16</sup> and another comparing RCAB to MIDCAB,<sup>18</sup> the investigators reported on late stroke rates after surgery. There were no significant differences between RCAB and C-CABG(off) or MIDCAB.
- Graft stenosis: One study comparing RCAB and C-CABG(off) presented information on graft stenosis.<sup>16</sup> During 1 year of follow-up, there was only 1 case of stenosis in the entire group. The single study that compared RCAB to PA-CAB indicated that graft stenosis rates were 5% and 0%, respectively.<sup>9</sup>
- Graft failure: Two studies provided information on graft failure after RCAB and C-CABG.<sup>15,16</sup> In 1 study, no significant differences between approaches were found.<sup>15</sup> In the other study, 20 cases of graft failure involving saphenous vein grafts were observed in the C-CABG group.<sup>16</sup> One study presented graft failure rates after RCAB and PA-CAB: rates were low and were similar for the 2 approaches (5% and 0%).<sup>9</sup>
- Revascularization: Differences in revascularization rates between RCAB and C-CABG were provided in 2 studies.<sup>7,16</sup> Both showed low rates and no significant differences between approaches. One study compared revascularization rates for RCAB and MIDCAB, which ranged from 0% to 5%.<sup>18</sup> No significant differences were found. Jegaden and colleagues<sup>9</sup> reported early and late revascularization rates after RCAB and PA-CAB.

The early revascularization rates were 0% for PA-CAB and 7% for RCAB, and the corresponding late revascularization rates were 4% and 5%.

- Death: Four studies comparing RCAB to C-CABG provided information on mortality rates, which ranged from 0% to 29%.<sup>8,12,15,16</sup> Three studies showed no significant differences between surgical groups after 30 days and 1 year of follow-up.<sup>12,15,16</sup> Su and colleagues<sup>8</sup> reported similar rates of in-hospital death after RCAB and C-CABG, but the overall mortality rate was higher for C-CABG. Mortality rates for RCAB and MIDCAB were presented in 2 studies.<sup>18,19</sup> Neither showed significant differences in 30-day mortality rates (Fig. 8), and 1 indicated that rates remained similar throughout 22 months of follow-up.<sup>18</sup> Similarly low mortality rates were found after RCAB and PA-CAB (3% and 0%, respectively).<sup>9</sup> The 2 national database studies showed no significant differences in short-term mortality rates between robotic and nonrobotic CABG.<sup>10,11</sup>
- Survival: One study provided overall survival rates after RCAB and C-CABG.<sup>8</sup> During follow-up of 34–53 months, rates were not significantly different (68% v. 54%). In a study comparing RCAB to MIDCAB, the 5-year overall survival rate was 94% and 88%, respectively, a nonsignificant difference.<sup>18</sup> The single study of PA-CAB showed a 3-year overall survival rate

Table 6 (part 1 of 2). Short- and long-term cardiac and survival outcomes

Study and country	Length of follow-up, mean ± SD or median (IQR), mo	No. (%) of participants							Overall survival rate, %	
		Angina	Late myocardial infarction	Late stroke	Graft stenosis	Graft failure	Revascularization	Death		
<b>RCAB v. C-CABG</b>										
Leyvi et al., <sup>7</sup> 2018 US	Hospital stay	NR	NR	NR	NR	NR	NR	NR	NR	NR
Su et al., <sup>8</sup> 2018 Taiwan	RCAB 52.8 (13.2–69.6)* C-CABG 33.6 (16.8–67.2)*†	NR	RCAB 7 (6) C-CABG 6 (4)	NR	NR	NR	NR	NR	NR	RCAB 67.9 C-CABG 53.9#
Lewi et al., <sup>12</sup> 2016 USA	1 mo postoperative	NR	NR	NR	NR	NR	NR	NR	NR	NR
Read et al., <sup>13</sup> 2016 US	1 mo postoperative	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ezelsoy et al., <sup>34</sup> 2015 Turkey	RCAB 87.6 ± 15.6* C-CABG(on) 68.4 ± 20.4*¶	NR	NR	NR	NR	NR	NR	NR	NR	NR
Zaouter et al., <sup>15</sup> 2015 France	Hospital stay	NR	NR	NR	NR	RCAB 2 (5) C-CABG(on) 0 (0)	NR	NR	NR	NR
Poston et al., <sup>16</sup> 2008 US	12 mo postoperative	NR	NR	RCAB 1 (1) C-CABG(off) 2 (2)¶	RCAB 1 (1) C-CABG(off) 0 (0)¶	RCAB 0 (0) C-CABG(off) 20 (20) (saphenous vein)¶	NR	NR	NR	NR
Bucerius et al., <sup>17</sup> 2002 Germany	Hospital stay	NR	NR	NR	NR	NR	NR	NR	NR	NR
<b>RCAB v. MIDCAB</b>										
Gong et al., <sup>18</sup> 2016 China	22 (range 12–60)	RCAB 4 (6) MIDCAB 4 (7)	RCAB 2 (3) MIDCAB 1 (2)	RCAB 1 (1) MIDCAB 2 (3)	NR	NR	NR	NR	NR	NR
Bachinsky et al., <sup>19</sup> 2012 US	1 mo postoperative	NR	NR	NR	NR	NR	NR	NR	NR	NR
Bucerius et al., <sup>17</sup> 2002 Germany	Hospital stay	NR	NR	NR	NR	NR	NR	NR	NR	NR

Table 6 (part 2 of 2). Short- and long-term cardiac and survival outcomes

Study and country	Length of follow-up, mean ± SD or median (IQR), mo	No. (%) of participants							Overall survival rate, %
		Angina	Late myocardial infarction	Late stroke	Graft stenosis	Graft failure	Revascularization	Death	
<b>RCAB v. PA-CAB</b>									
Wheilan et al., <sup>10</sup> 2016 US	1 mo postoperative	NR	NR	NR	NR	NR	NR	30-day RCAB 119 (1) Non-RCAB 14 152 (1)##	NR
Cavallaro et al., <sup>11</sup> 2015 US	Hospital stay	NR	NR	NR	NR	NR	NR	In hospital, 1.bypass RCAB (n = 275) 0 (0) Non-RCAB (n = 275) 3 (1) ≥2.bypasses RCAB (n = 189) 2 (1) Non-RCAB (n = 189) 1 (1)	NR

CABG = coronary artery bypass grafting; C-CABG = conventional CABG (median sternotomy); C-CABG(off pump) = C-CABG (on pump); CI = confidence interval; IQR = interquartile range; MIDCAB = minimally invasive direct coronary artery bypass; non-RCAB = nonrobotic coronary artery bypass; NR = not reported; PA-CAB = port-access coronary artery bypass; RCAB = robotic coronary artery bypass; SD = standard deviation.  
 \*Converted from years.  
 †p = 0.01.  
 ‡p ≤ 0.001.  
 §pvalue (to value for unadjusted test statistic) = 0.002.  
 ¶p not reported.  
 \*\*Within 30 days.  
 ††p = 0.01.  
 †††pvalue = 0.03.

of 100% for PA-CAB and 96% for RCAB; the statistical significance of this difference was not reported.<sup>9</sup>

- Time to return to normal activities: One study compared time to return to work or normal activities between RCAB and C-CABG(off).<sup>16</sup> Times were significantly shorter for patients who underwent RCAB than for those who underwent C-CABG(off) (44 d v. 93,  $p = 0.02$ ). Bachinsky and colleagues<sup>19</sup> compared time to return to work between RCAB and MIDCAB, and found that the mean time was 37 days for the RCAB group and 57 days for the MIDCAB group, a statistically significant difference ( $p = 0.01$ ).
- Quality of life: Only 1 study comparing RCAB to MIDCAB reported on quality of life 1 month after surgery.<sup>19</sup> Physical functioning was significantly better among RCAB patients. However, no differences in mental health were found.

**Resource-relevant outcomes**

- Operative time: Three studies reported on operating times for RCAB and C-CABG<sup>7,12,16</sup> (Table 7). In 2 studies, operating times were significantly longer for C-CABG(on).<sup>7,12</sup> In the third study, times were significantly longer for RCAB than for C-CABG(off).<sup>16</sup> The mean operating time in the 3 studies ranged from 162 to 348 minutes for RCAB and from 246 to 306 minutes for C-CABG. Two studies of RCAB versus MIDCAB presented conflicting results. One showed significantly longer times for patients who underwent MIDCAB (261 min v. 386 min,  $p < 0.001$ ),<sup>19</sup> whereas the other showed no significant difference between the 2 approaches (221 min v. 186 min,  $p = 0.05$ ).<sup>18</sup> The study comparing RCAB and PA-CAB showed mean operative times of 204 minutes for RCAB and 192 minutes for PA-CAB; no information on statistical significance was included.<sup>9</sup>
- Anesthesia time: Three studies of RCAB and C-CABG(on) in which anesthesia time was assessed gave conflicting results.<sup>7,12,15</sup> Two showed that RCAB was associated with significantly shorter mean anesthesia times,<sup>7,12</sup> and the third showed significantly longer anesthesia times for RCAB.<sup>15</sup> No information comparing anesthesia times for RCAB and MIDCAB, or for RCAB and PA-CAB was found.
- Length of hospital stay: Length of hospital stay was assessed in 6 studies of RCAB versus C-CABG,<sup>7,13-17</sup> of which 5 reported significantly shorter stays after RCAB than C-CABG(on) or C-CABG(off).<sup>13-17</sup> The mean or median length of hospital stay for RCAB and C-CABG ranged from 4 to 9 days and from 5 to 16 days, respectively. Three studies reported differences in length of stay between RCAB and MIDCAB: 2 studies showed significantly longer stays among patients who underwent MIDCAB,<sup>17,18</sup> whereas the other study showed no significant difference between procedures.<sup>19</sup> In the

**Table 7. Resource-related outcomes**

Study and country	Mean ± SD or median (IQR)			Readmission, no. (%) of participants
	Operating time, min	Anesthesia time, min	Length of hospital stay, d	
<b>RCAB v. C-CABG</b>				
Leyvi et al., <sup>7</sup> 2018 US	RCAB 162.0 ± 30.0* C-CABG(on) 306.0 ± 48.0*	RCAB 294.0 ± 30.0* C-CABG(on) 420.0 ± 36.0*	RCAB 4 (3–8) C-CABG(on) 5 (5–8)	NR
Su et al., <sup>8</sup> 2018 Taiwan	NR	NR	RCAB 9 (7–12) C-CABG 15 (11–26)	NR
Leyvi et al., <sup>12</sup> 2016 US	RCAB 210.6 ± 6.6* C-CABG(on) 279.6 ± 7.8*	RCAB 336.6 ± 6.0* C-CABG(on) 396.0 ± 9.0*	RCAB 6 (4–9) C-CABG(on) 7 (5–11)	<i>Within 30 d</i> RCAB 12 (9) C-CABG(on) 6 (4)
Raad et al., <sup>13</sup> 2016 US	NR	NR	RCAB 5.0 ± 3.8 C-CABG(on) 6.7 ± 3.8	<i>Within 30 d</i> RCAB 23 (16) C-CABG(on) 22 (15)
Ezelsoy et al., <sup>14</sup> 2015 Turkey	RCAB 186.9 ± NR C-CABG(on) NR	NR	RCAB 6.6 ± 1.0 C-CABG(on) 7.8 ± 2.3	NR
Zaouter et al., <sup>15</sup> 2015 France	NR	RCAB 373 ± 60 C-CABG(on) 179 ± 60	RCAB 8 (6–10) C-CABG(on) 12 (10–14)	NR
Poston et al., <sup>16</sup> 2008 US	RCAB 348 ± 72* C-CABG(off) 246 ± 54*	NR	RCAB 3.8 ± 1.5 C-CABG(off) 6.4 ± 2.2	<i>Within 30 d</i> RCAB 4 (4) C-CABG(off) 9 (9)
Bucerius et al., <sup>17</sup> 2002 Germany	NR	NR	RCAB 8.9 ± 3.2 C-CABG(on) 16.3 ± 9.0	NR
<b>RCAB v. MIDCAB</b>				
Gong et al., <sup>18</sup> 2016 China	RCAB 220.8 ± 23.1 MIDCAB 185.5 ± 49.3	NR	RCAB 7.8 ± 3.0 MIDCAB 9.2 ± 3.8	NR
Bachinsky et al., <sup>19</sup> 2012 US	RCAB 261.0 ± 36.8† MIDCAB 386.0 ± 49.4†	NR	RCAB 8.2 ± 5.4 MIDCAB 5.1 ± 2.8	NR
Bucerius et al., <sup>17</sup> 2002 Germany	NR	NR	RCAB 8.9 ± 3.2 MIDCAB 15.9 ± 6.5	NR
<b>RCAB v. PA-CAB</b>				
Jegaden et al., <sup>9</sup> 2011 France	RCAB 204 ± 42* PA-CAB 192 ± 36*	NR	RCAB 5.5 ± 1.6 PA-CAB 7.0 ± 3.0	NR
<b>RCAB v. non-RCAB</b>				
Whellan et al., <sup>10</sup> 2016 US	NR	NR	RCAB 4 (3–6) Non-RCAB 5 (4–7)	NR
Cavallaro et al., <sup>11</sup> 2015 US	NR	NR	<i>1 bypass</i> RCAB ( <i>n</i> = 275) 5.3 ± 2.8 Non-RCAB ( <i>n</i> = 275) 6.8 ± 3.9 <i>≥ 2 bypasses</i> RCAB ( <i>n</i> = 189) 6.8 ± 7.5 Non-RCAB ( <i>n</i> = 189) 6.8 ± 3.4	NR
C-CABG = conventional coronary artery bypass grafting (median sternotomy); C-CABG(off) = C-CABG (off pump); C-CABG(on) = C-CABG (on pump); IQR = interquartile range; MIDCAB = minimally invasive direct coronary artery bypass; non-RCAB = nonrobotic coronary artery bypass; NR = not reported; PA-CAB = port-access coronary artery bypass; RCAB = robotic coronary artery bypass; SD = standard deviation. *Converted from hours. †Total time in operating room.				

single study comparing RCAB and PA-CAB, the mean length of hospital stay was 5.5 days for RCAB and 7 days for PA-CAB; no information on statistical significance was provided.<sup>9</sup> One national database study showed that, overall, the length of stay for robotic procedures was significantly shorter than for nonrobotic procedures (4 d v. 5 d, *p* < 0.001).<sup>10</sup> In the other national database study, stays were shorter after robotic surgery among patients who required only 1 bypass but were no different among those who required multiple bypasses.<sup>11</sup>

- Readmission rates: In 2 studies comparing C-CABG(on) and RCAB, there were no significant differences in rates of readmission within 30 days between approaches.<sup>13,16</sup>

Readmission rates ranged from 4% to 16% in the RCAB group and 9% to 15% in the C-CABG(on) group. None of the studies on minimally invasive procedures (MIDCAB or PA-CAB) provided information on readmission rates.

## DISCUSSION

Cao and colleagues<sup>1</sup> referred to contemporary data for C-CABG<sup>20,21</sup> and concluded that perioperative outcomes, including MI, atrial fibrillation, stroke, renal failure and reoperation for bleeding, were comparable to those for RCAB. The findings from the present review of



comparative nonrandomized studies showed that there were no differences in rates of conversion to C-CABG between RCAB and other surgical techniques. Rates of postoperative complications were significantly lower with RCAB than with C-CABG(off). Robotic coronary artery bypass was comparable if not superior to other surgical techniques regarding the need for blood transfusion or reoperation for bleeding. Patients who underwent RCAB had significantly shorter ICU stays and experienced significantly less pain in the initial days following surgery than those who had C-CABG. Furthermore, RCAB was similar to other bypass techniques with respect to long-term outcomes — including angina, late MI, late stroke, graft stenosis or failure, and the need for revascularization — and in rates of mortality and overall survival. However, as in the review by Cao and colleagues,<sup>1</sup> the majority of studies included in the present review involved relatively young patients (in their 60s) with left ventricular ejection fraction within the normal range (50%–70%), and the number of grafts was relatively low, especially in the RCAB group. These characteristics may have affected the overall surgical outcomes.

The follow-up period in the studies included in our review ranged from the length of the hospital stay to 5 years. This variation, together with the fact that only 1 study reported on overall long-term survival for RCAB versus C-CABG, RCAB versus MIDCAB, and RACB versus PA-CAB, makes it difficult to assess long-term survival. Mortality rates (with a follow-up duration of 5 yr) were similar to that reported in a noncomparative study on MIDCAB off pump in which patients were followed for up to 8 years (4%).<sup>22</sup>

Su and colleagues<sup>8</sup> reported that there was a tendency to use RCAB to treat simple cases, since it is more time consuming and technically demanding. Moreover, the techniques and instruments for RCAB are still evolving, and surgical teams are still learning and building their experience. The learning curve associated with RCAB has been well documented, and it takes around 100 operations before adverse outcomes are minimized.<sup>23,24</sup> Although every surgeon moves through the learning curve in an individualized fashion, most surgeons experience a greater rate of adverse events over the course of their initial experience with any new surgical technique or modality, including RCAB.

Anesthesia time is variable among centres, likely owing to differences in centre practice of RCAB anesthesia. The use of a double-lumen endotracheal tube rather than a single-lumen tube may change times. As well, the placement of a thoracic epidural catheter changes anesthesia time compared to a single-dose paravertebral block, an intraoperative block or no block.

Resource-related outcomes may depend on several factors, including patients' characteristics, surgeons' experience,<sup>23,24</sup> presurgical planning,<sup>25–27</sup> clinical pathways of each

institution, and how outcomes such as operating time, anastomosis time and cardiopulmonary bypass time are measured.<sup>1</sup> For example, since there is no sternotomy with RCAB, patients may return to the ICU from the operating room already extubated; if still intubated, they are extubated shortly after completion of surgery. This leads to an expedited ICU course. As well, the lack of sternotomy decreases blood transfusion rates and eliminates the need to restrict mobility for sternal precautions.

### Limitations

Several limitations may have affected the findings of this review. First, we did not identify any randomized clinical trials, and all included studies were comparative nonrandomized studies. Thus, confounders are likely to exist. Second, the overall quality of evidence comparing RCAB to other surgical approaches was low, which limited our ability to make strong conclusions regarding the comparison between RCAB and other CABG surgical techniques. Third, although meta-analyses can increase power and precision, they cannot eliminate any biases that exist in pooled studies. Furthermore, in the case of 30-day mortality and complications (e.g., wound infection and renal failure), sample size and number of events were still insufficient to provide pooled results with narrow confidence intervals. Fourth, variation across studies (heterogeneity) was inevitably present. To decrease its presence, we pooled only outcomes measured at similar follow-up intervals, and we did not pool studies that used different surgical techniques (e.g., studies evaluating MIDCAB were not pooled together with studies evaluating C-CABG). Also, results of meta-analyses were used only when the *P* statistic was less than 50%. In addition, as our search was conducted in English, studies that were published only in other languages were not included in this review. Last, the generalizability of the findings of this review to all patients with coronary artery disease is limited, as patients included were relatively young and had favourable baseline characteristics.

### CONCLUSION

The findings from this review indicate that RCAB appears promising and may offer benefits to patients. However, in the absence of randomized controlled trials or well-conducted observational studies, they should be interpreted with caution.

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