Effects of Off-Pump Versus On-Pump Coronary Artery Bypass Grafting on Early and Late Right Ventricular Function

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Background—Off-pump CABG (OPCABG) results in better preservation of left ventricular function in the perioperative period than conventional on-pump CABG (ONCABG); however, evidence is conflicting as to the effect of OPCABG and ONCABG on right ventricular (RV) function, possibly because of the complexity involved in measuring this.

Methods and Results—In a single-center randomized pilot study, 60 patients with normal left ventricular function undergoing CABG were randomly assigned to OPCABG or ONCABG. Patients underwent cardiac magnetic resonance imagine for assessment of RV function preoperatively, early postoperatively, and at 6 months after surgery. Fifty-one patients completed the first 2 scans, and 47 completed all 3 scans. Preoperative characteristics and RV function did not differ significantly between the 2 groups (mean SD): RV stroke volume index was 49

49

10 mL/m2 for OPCABG and 49

16 mL/m2 for ONCABG. After surgery, RV stroke volume index fell to 36

36

7 mL/m2 in the OPCABG group and 39

39

11 mL/m2 in the ONCABG group, but this did not differ significantly between the 2 groups (P=0.41). All markers of RV function recovered to preoperative levels by 6 months, with no long-term difference between the surgical techniques.

Conclusions—RV function is impaired early after surgery but recovers by 6 months. The changes were similar in both the OPCABG and ONCABG groups. (Circulation. 2008;117:2202-2210.)

Key Words: bypass ■ cardiopulmonary bypass ■ grafting ■ magnetic resonance imaging ■ right ventricle

Over the past decade, off-pump coronary artery bypass surgery (OPCABG) has been shown to reduce many aspects of postoperative morbidity, such as atrial fibrillation, respiratory complications, and length of hospital stay.1–9 Nevertheless, the majority of CABG procedures are still performed by use of cardiopulmonary bypass with antegrade cardioplegia (ONCABG).

Using cardiac magnetic resonance (CMR), we have previously demonstrated that OPCABG, compared with ONCABG, reduces left ventricular (LV) dysfunction early after surgery,3 and several groups including our own have reported a reduction in biochemical markers of myocardial injury.3,10 In contrast, although right ventricular (RV) function is a major determinant of the outcome of cardiac surgery, and RV dysfunction is associated with a high mortality,11 there has been no study using a highly reproducible technique such as CMR imaging to investigate the impact of CABG surgery and each individual technique on RV function. Studies using echocardiography and hemodynamic measurements have demonstrated early dysfunction associated with the ONCABG technique,12,13 but these techniques are poorly reproducible, and subsequent evidence has been conflicting.14–17 The 2-dimensional imaging techniques used are limited by the complex anatomic structure of the RV, with consequent difficulty in assessing its function accurately and reproducibly. Furthermore, the impact of OPCABG surgery on RV function is poorly documented.

CMR imaging is rapidly becoming established as the “gold standard” for noninvasive cardiac imaging and has the additional advantage of permitting serial measurements of both RV and LV function with a high degree of reproducibility.18,19 The aim of the present study was to investigate the impact of CABG, performed both as ONCABG and OPCABG, on RV function early (6 days) and late (6 months) after surgery. We hypothesized that OPCABG surgery would
mitigate RV dysfunction after surgery by eliminating the obligate myocardial injury from ONCABG surgery due to cardiopulmonary bypass, ischemia, and the use of cardioplegia.

Methods
In a single-center pilot study, we randomized 60 patients referred for first-time lone CABG to OPCABG and ONCABG techniques; the exact study protocol has been described in detail elsewhere. Between May 2002 and February 2003, a total of 111 patients were screened. Patients were excluded if they were >75 years old, had evidence of chronic obstructive pulmonary disease, had severe LV dysfunction (ejection fraction <20% by echocardiography), had significant renal impairment (creatinine >200 µmol/L), were enrolled in another clinical trial, or had typical contraindications to magnetic resonance. Patients were only randomized after successful completion of the first MRI scan.

Ethics
The study was approved by our local institutional research ethics committee (Oxford Research Ethics Committee No. 02/096). Each patient gave written informed consent.

Treatment and Procedures
The methods were as described previously. All surgery was performed in a single center by a single surgeon (D.P.T.) highly experienced in both OPCABG and ONCABG surgery. The aim of the surgery was to obtain complete arterial revascularization using both internal mammary arteries and the radial artery wherever possible.

Anesthesia
All patients received a standard anesthetic protocol comprising scopolamine, fentanyl, pancuronium, etomidate, and propofol, and all patients were fully heparinized (3 mg/kg) to achieve an activated clotting time >400 seconds.

Hemodynamic Parameters
Invasive blood pressure monitoring was in situ throughout the surgical procedure, and measurements were charted every 15 minutes. Mean±SD systolic blood pressure data for each patient were calculated from these recordings. Central venous pressure measurements were also recorded regularly during the procedure.

On-Pump CABG
Cardiopulmonary bypass was performed with nonpulsatile flow and at a temperature of 34°C. A membrane oxygenator and alphasat control of acid base management were used, and the mean arterial pressure was maintained at 50 to 60 mm Hg with pharmacological manipulation as necessary. Myocardial protection was obtained with 1 L of St Thomas’ cold (4°C) crystalloid cardioplegia delivered in an antegrade fashion and repeated every 30 minutes.

Off-Pump CABG
Commercially available stabilizers were used, and the coronary artery was snared proximally (but not distally) with a Silastic sling. Intracoronary artery shunts were not used.

CMR Protocol
Patients underwent 3 CMR examinations in total: a preoperative scan (within 4 weeks of scheduled surgery) and 2 postoperative scans (predischarge and then 6 months after surgery). All CMR examinations were performed with a 1.5-T magnetic resonance scanner (Sonata, Siemens Medical Solutions, Erlangen, Germany) with prospective ECG gating and with the patient in the supine position. After piloting with localizers, steady state free-precession cine images (echo time/repetition time 1.5/3.0 ms, flip angle 60°) were acquired in the horizontal and vertical long-axis planes at a slice thickness of 7 mm and temporal resolution of 24 to 45 ms. The short-axis stack was acquired parallel to the atroventricular groove in 1-cm increments (slice thickness 7 mm, interslice gap 3 mm) that covered the entire LV and RV.

Postprocessing Analysis
The method for analyzing and calculating RV volumes is standardized within our unit, and these methods, along with their reproducibility, have been published previously. The short-axis cine stack was analyzed with Argus software (version 2002B, Siemens Medical Solutions) by a single experienced cardiologist blinded to the surgical randomization and scan order. End-diastolic and end-systolic volumes were defined as the largest and smallest RV cavities, respectively. Manual tracing of endocardial borders in each successive slice position at the chosen end-diastolic and end-systolic phase was performed. The observer was allowed to be guided by the horizontal and vertical long-axis cine images. The contour tracing was assisted by windowing of both contrast and brightness and was guided by the short-axis cine pictures to ensure exclusion of epicardial fat. All volume below the level of the pulmonary valve was included, and care was taken not to include wall from the right atrium, with the first systolic movement of the wall and consistency in muscle appearance noted. Trabeculation present at the apex was excluded from the volume calculation. For each scan, the RV ejection fraction (RVEF), end-systolic volume (RVESV), and end-diastolic volume (RVEDV) were calculated with planimetry. RV cardiac output was then calculated from the stroke volume and pulse rate. All functional parameters were corrected for body surface area so that RV end-systolic volume index, RV end-diastolic volume index (RVEDVI), RV stroke volume index, and cardiac index are reported.

Power Calculation
With 25 patients per surgical group, we had in excess of 80% power to detect a difference of 0.8 SDs between the 2 surgical groups. With use of preoperative data from the present study on RVEF (SD=7), this equates to a difference of 5.6%. Thus, a retrospective power calculation suggests that the present study had sufficient power to detect a difference of 6% in RVEF at the 5% significance level.

Interobserver and Intraobserver Variability
Ten scans were selected at random; 5 preoperative and 5 postoperative studies were analyzed by the single blinded experienced operator (TJP), and the analysis was repeated after a minimum of 2 weeks had elapsed. The same studies were then analyzed by a second experienced blinded operator from the same department (T.D.K.).

Statistical Analysis
All data were analyzed with SPSS software (version 15.0, SPSS, Inc, Chicago, Ill) and based on intention to treat from the point of randomization. Continuous variables were expressed as mean±SD and compared with an unpaired t test if they followed a normal distribution. Otherwise, a Mann-Whitney test was used, and results were expressed as median and interquartile range. The χ² test was used for the comparison of dichotomous data. A between-groups comparison examining the impact of surgical technique on RV function over time was made with a repeated-measures ANOVA, with time as the within-group factor and surgical technique as the between-group factor. The same method was also used to assess the main effect of time within each group.

Because of the number of independent variables involved, we adapted a model-building strategy to assess the potential association between baseline variables and early RV function. Hence, we first performed a simple regression analysis to examine any potential association between the baseline variables (ie, age, sex, body mass index, >90% stenosis in the right coronary artery [RCA], preoperative LV ejection fraction, and preoperative RVEF) and early RV...
Table 1. Preoperative Group Characteristics

<table>
<thead>
<tr>
<th></th>
<th>OPCABG (n=30)</th>
<th>ONCABG (n=30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>61±11</td>
<td>60±9</td>
</tr>
<tr>
<td>Male, % (n)</td>
<td>83 (25)</td>
<td>90 (27)</td>
</tr>
<tr>
<td>Diabetes mellitus, % (n)</td>
<td>27 (8)</td>
<td>23 (7)</td>
</tr>
<tr>
<td>Hypertension, % (n)</td>
<td>63 (19)</td>
<td>80 (24)</td>
</tr>
<tr>
<td>Hypercholesterolemia, % (n)</td>
<td>77 (23)</td>
<td>83 (25)</td>
</tr>
<tr>
<td>Smoking, % (n)</td>
<td>27 (8)</td>
<td>17 (5)</td>
</tr>
<tr>
<td>ACE inhibitor, % (n)</td>
<td>60 (18)</td>
<td>53 (16)</td>
</tr>
<tr>
<td>β-Blocker, % (n)</td>
<td>83 (25)</td>
<td>66 (20)</td>
</tr>
<tr>
<td>Calcium blocker, % (n)</td>
<td>27 (8)</td>
<td>47 (14)</td>
</tr>
<tr>
<td>Nitrates, % (n)</td>
<td>50 (15)</td>
<td>43 (13)</td>
</tr>
<tr>
<td>Antiplatelets, % (n)</td>
<td>90 (27)</td>
<td>93 (28)</td>
</tr>
<tr>
<td>Statins, % (n)</td>
<td>83 (25)</td>
<td>87 (26)</td>
</tr>
<tr>
<td>Normal LV function, % (n)</td>
<td>60 (18)</td>
<td>60 (18)</td>
</tr>
<tr>
<td>EuroSCORE*</td>
<td>2 (1–3)</td>
<td>2 (0.75–3.25)</td>
</tr>
<tr>
<td>&gt;90% RCA stenosis</td>
<td>27 (8)</td>
<td>27 (8)</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>26±3</td>
<td>28±3</td>
</tr>
</tbody>
</table>

Values are percentage (absolute number) of each group or mean±SD. Continuous variables are reported as the mean±SD. Normal LV function was defined as ejection fraction >57% assessed by CMR imaging.

*EuroSCORE denotes the European System for Cardiac Operative Risk Evaluation and is reported as median (interquartile range).

function. Variables with \( P < 0.01 \) were then included in the multiple linear regression by a stepwise selection method to assess the "best" subset in predicting early RV function. We also used a multiple regression method to examine the interaction between grafting of the RCA and early RV function. A probability value of \( P < 0.05 \) was considered statistically significant. Bland-Altman plots were used in the assessment of interobserver and intraobserver variability.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Patients

Preoperative characteristics are listed in Table 1. Both groups were well matched with regard to age, sex, cardiovascular risk factors, and medications. Of the 60 patients recruited into the trial, 51 were included in the final analysis. No patient died, and 1 patient was converted from OPCABG to ONCABG because of severe LV impairment. Of the 9 patients who were not included in the final analysis, 2 were unable to undergo the early postoperative scan because of significant morbidity (1 ONCABG patient with a cerebrovascular accident and 1 ONCABG patient with prolonged respiratory failure). Three patients declined follow-up imaging (2 OPCABG and 1 ONCABG), and 4 patients could not be included because the early postoperative scan was affected by artifact involving the RV, either from sternal wires or wrap artifact (2 OPCABG and 2 ONCABG). Four patients who were included in the early postoperative data were excluded at 6 months because 3 patients declined further imaging (3 ONCABG), and 1 scan was considered incomplete owing to omission of the basal RV slice (1 OPCABG). Complete follow-up was therefore available for 47 patients (78%; 25 OPCABG and 22 ONCABG).

Surgery

The surgical characteristics have been described previously. The mean number of distal anastomoses did not differ significantly between the 2 techniques and was 2.9±0.8 for OPCABG and 2.8±0.9 for ONCABG (\( P = 0.7 \)). All grafts in the OPCABG group were arterial, as were 97% in the ONCABG group (\( P = 0.8 \)). In the ONCABG group, mean aortic cross-clamp time was 41±13 minutes, and cardiopulmonary bypass time was 57±18 minutes.

Of the 51 patients included in the final analysis, 37 (73%) had a >50% stenosis in the RCA and 16 (31%) had >90% stenosis or complete vessel occlusion. Of the 37 patients with >50% stenosis, 25 (68%) received a graft (12 OPCABG and 13 ONCABG; \( P = 0.7 \)). Among the 16 patients with the most severe RCA disease, a total of 9 received a graft (4 OPCABG and 5 ONCABG). Of the 12 patients (7 OPCABG and 5 ONCABG) who had disease that affected the RCA in whom no graft was placed, the usual reason was that the distal vessel was too small/diffusely diseased or was not dominant.

Early Functional Recovery

As shown in Table 2, no significant difference was found in the mean±SD preoperative RV functional parameters between each group. The mean±SD RV E':EF was 66±6% in the OPCABG group and 65±8% in the ONCABG group, and RV stroke volume index was 49±10 and 49±16 mL/m², respectively, which indicates well-preserved RV function in both cohorts. After surgery, RV E':EF decreased significantly in both groups (\( P < 0.05 \); Figure 1), with a relative reduction of 12% in the OPCABG group and 7% in the ONCABG group, but without significant intergroup difference (\( P = 0.46 \)). A similar pattern was also observed for RV stroke volume index (Figure 2). This effect was predominantly due to a fall in RV E':EF in both groups, with a relative reduction of 27% in the OPCABG group and 20% in the ONCABG group, which again was without significant intergroup difference (\( P = 0.75 \)). In contrast to RV E':EF, RV end-systolic volume index remained constant in both surgical cohorts at all 3 time points (Table 2).

Late Functional Recovery

The early reduction in measures of RV function recovered completely by 6 months, with normalization of all volumetric parameters in both groups (Table 2), which indicates no significant long-term change in RV function after revascularization. The RCA was grafted in 25 patients (12 OPCABG and 13 ONCABG), and neither the receipt of a graft nor the surgical technique had a significant impact on early RV function, although the numbers in this subgroup analysis were small (Table 3). In these 25 patients, the relative reduction in early RV E':EF was 14% in the OPCABG group and 6% in the ONCABG group. Of the 26 patients who did not receive a graft to the RCA, 12 (7 OPCABG and 5 ONCABG) had an angiographically significant stenosis (>50%). The reason for not grafting these RCAs was that either the vessel was too small/diffusely diseased or that it was nondominant. Nevertheless, despite the high percentage of RCA stenosis in this group, there remained no difference in any parameter of RV function between those receiving a graft and those who did
not, and again, no significant interaction was detected between surgical technique and the early parameters of RV function ($P_{0.23}$). Table 3).

Forty-four patients (20 OPCABG and 24 ONCABG) received grafts to the lateral wall (intermediate or circumflex coronary arteries). Despite the high percentage (86%) of patients who had grafts to this territory, no significant impact of OPCABG technique was found on the overall intraoperative hemodynamic response. Blood pressure measurements during lateral wall grafting were not recorded separately; however, our intraoperative policy is to maintain a mean arterial pressure 60 mm Hg either by volume or by pharmacological manipulation where necessary. Furthermore, because grafts to the lateral wall took approximately an average of 10 minutes to complete, changes in hemodynamic parameters would have had only a short-term impact on overall average intraoperative systolic blood pressure. Overall, the mean intraoperative systolic blood pressure was 108±6 mm Hg in the OPCABG group and 110±7 mm Hg in the ONCABG group ($P_{0.23}$). The mean central venous pressure was 8±2.0 mm H$_2$O in the OPCABG group and 8±2.3 mm H$_2$O in the ONCABG group ($P_{0.94}$). Only 5 patients (3 ONCABG and 2 OPCABG) required postoperative inotropic support.

Multivariate analysis of preoperative factors likely to predict early RVEF indicated that only preoperative RVEF and LV ejection fraction predicted outcome. Body mass index, gender, age, preoperative coronary artery anatomy, pre-operative 6 days 6 months

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before Surgery</th>
<th>6 d After Surgery</th>
<th>6 Mo After Surgery</th>
<th>P Within Group</th>
<th>P Between Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVCI, L·min$^{-1}$·m$^{-2}$</td>
<td>OPCABG 3±0.7</td>
<td>2.6±0.4</td>
<td>2.9±0.6</td>
<td>0.04</td>
<td></td>
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<tr>
<td></td>
<td>ONCABG 2.9±0.9</td>
<td>2.8±0.8</td>
<td>3.2±0.8</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>RVEDVI, mL/m$^2$</td>
<td>OPCABG 74±12</td>
<td>62±9</td>
<td>72±14</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ONCABG 75±20</td>
<td>64±16</td>
<td>76±14</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>RVESVI, mL/m$^2$</td>
<td>OPCABG 25±6</td>
<td>26±6</td>
<td>26±9</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ONCABG 26±7</td>
<td>25±8</td>
<td>26±7</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>OPCABG 62±8</td>
<td>75±12</td>
<td>64±11</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ONCABG 60±12</td>
<td>73±15</td>
<td>65±17</td>
<td>&lt;0.001</td>
<td></td>
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</tbody>
</table>

RVCI indicates RV cardiac index; RVESVI, RV end-systolic volume index. Repeated-measures ANOVA analysis with time (within-group comparison) and surgical technique (between-groups comparison) for 47 patients, presented as mean±SD.

Figure 1. Mean RVEF and 95% CIs measured preoperatively, at 6 days postoperatively, and at 6 months. *Between-groups comparison for the 2 surgical techniques. †Within-group comparisons indicating a significant effect of surgery (both types) on early RV function. RVSVI indicates RV stroke volume index (mL/m$^2$).

Figure 2. Mean RV stroke volume index (RVSVI) and 95% CIs measured preoperatively, at 6 days postoperatively, and at 6 months. *Between-groups comparison for the 2 surgical techniques. †Within-group comparisons indicating a significant effect of surgery (both types) on early RV function.
Effects of CABG on RV Function

CABG is associated with a significant reduction in RV function soon after surgery, but this is completely reversed at 6 months. The early reduction in function was due to a decrease in the RVEDVI, whereas the RV end-systolic volume index remained fixed at all 3 time points. This is in direct contrast to the effect of surgery on early LV function, as shown in Figure 5. In brief, LV function was better preserved early after surgery in the OPCABG group owing to a reduction in LVESVI as opposed to an increase in the ONCABG group, but no change occurred in LVEDVI in either group.

The mechanism of the different response of the 2 ventricles to CABG is complex and remains unclear. We previously suggested that the early improvement in LV function with OPCABG was due to reduced myocardial ischemia, which facilitated early recruitment of hibernating myocardium. However, this was not reproduced in the present study results for early postoperative RV function. In view of the fact that the RV is both embryologically and morphologically distinct from the LV, it is possible that it is differently affected by myocardial ischemia. We know that the RV is perfused in a different way to the LV; being thin walled, it receives blood in both systole and diastole and furthermore is often adequately supplied from collaterals. Therefore, continued physiological coronary perfusion during OPCABG surgery may not confer the same benefit on early RV function as it does with LV function. The selective effect of surgery on RVEDVI might also be attributed to the thin wall of the RV and pericardium, because even relatively minor inflammation, effusion, or hematoma associated with surgery could significantly affect RV diastolic function and filling capacity. Moreover, RV diastolic function could be further impaired by myocardial stiffness arising from tissue edema that results from surgical handling. Previous studies that have shown early (<24 hours) RV systolic dysfunction associated with surgery have demonstrated increased pulmonary vascular resistance. These studies linked the changes to positive pressure ventilation, cardiopulmonary bypass, systemic inflammation, and increased pulmonary bed vasoconstriction by vasoactive drugs. These factors are unlikely to be

Interobserver and Intraobserver Variability

The results for intraobserver and interobserver variability (Table 5) demonstrated acceptable intraobserver variability, with a coefficient of variation for the repeated assessment of RVEF of 4%. Greater variation was present in the measurements of end-systolic and end-diastolic volume indexes (Table 5). Interobserver variability was predictably greater (coefficient of variation 12%), but this had less impact on this particular study design because all the analyses were performed by a single operator. Bland-Altman plots for intraobserver and interobserver variability (Figures 3 and 4) indicate that at least with interobserver variability, all measures of reproducibility were within the limits of agreement (2 SD of the mean difference).

Discussion

Although the RV is an important predictor of outcome after CABG, it has been studied infrequently compared with the LV, and the effects of revascularization with both on-pump and off-pump techniques remain less well documented. To the best of our knowledge, this is the first study using CMR to follow change in RV function both early and late after surgery. Furthermore, we have compared the effects of ONCABG and OPCABG surgical techniques on RV function in this randomized trial. The main findings of this pilot study indicate that RV function is impaired early after CABG surgery, that this is independent of the surgical technique, and that it is followed by complete recovery at 6 months. Finally, multivariate analysis indicated that the only predictors of postoperative RV function were preoperative RV and LV function.

Table 3. RV Functional Parameters Early After Coronary Artery Bypass Surgery in Patients With and Without a Graft to the RCA

<table>
<thead>
<tr>
<th></th>
<th>RCA Grafted (n=25)</th>
<th>RCA Not Grafted (n=26)</th>
<th>Test for Interaction P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute change in RVEF, %</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPCABG</td>
<td>12</td>
<td>−9±8</td>
<td>14</td>
</tr>
<tr>
<td>ONCABG</td>
<td>13</td>
<td>−4±7</td>
<td>12</td>
</tr>
<tr>
<td>Absolute change in RSVI, mL/m²</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPCABG</td>
<td>12</td>
<td>−14±6</td>
<td>14</td>
</tr>
<tr>
<td>ONCABG</td>
<td>13</td>
<td>−8±9</td>
<td>12</td>
</tr>
</tbody>
</table>

RVEF indicates RV ejection fraction.

Table 4. Factors Predicting Early Postoperative RVEF

<table>
<thead>
<tr>
<th>Factors Predicting Early RV Estimates</th>
<th>CI</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preoperative LVEF</td>
<td>0.23</td>
<td>0.05–0.4</td>
</tr>
<tr>
<td>Preoperative RVEF</td>
<td>0.52</td>
<td>0.23–0.8</td>
</tr>
</tbody>
</table>

LVEF indicates LV ejection fraction. $R^2=0.371$; adjusted $R^2=0.344$ for the full-model coefficient. Other variables such as body mass index, age, gender, >90% stenosis of RCA, and grafting of the right or circumflex coronary arteries did not have an association with early RVEF.

and circumflex/RCA grafting did not predict RV function after surgery (Table 4).

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causative in the present findings because they mediate RV dysfunction through cavity dilation, not reduction as we demonstrated. In addition, several studies have demonstrated normalization of pulmonary vascular resistance by 48 hours after surgery,24,25 and therefore, this would be unlikely to affect RV function 6 days after surgery.

Comparative Studies
There has been confusion in the literature about the effects of surgery on RV function and conflicting reports of the various methods of assessment (Table 6). The reduction in early RV function associated with both types of surgery that we observed has also been reported previously, although not with CMR. The present findings for both RV and LV function partially reflect those of Alam et al,17 who used tissue Doppler imaging in ONCABG patients and reported a 25% reduction in RV free-wall systolic and diastolic tricuspid annular velocities up to 1 year after surgery but significant improvements in mitral annular velocities over the same time period. Their documentation of RV diastolic dysfunction early after ONCABG is consistent with our own finding of reduced RVEDVI in both groups early after surgery. However, whereas Alam et al17 found only a partial recovery of RV function at 12 months, we found complete recovery of all volumetric parameters by 6 months. This may be explained by the contribution that the interventricular septum makes toward RV function, because although Alam et al17 found only a partial recovery of RV free-wall function, they demonstrated preserved motion of the interventricular septum at all time points. Given mild impairment of free-wall function, effective contraction of the interventricular septum could preserve overall RV function, producing normal volumetric calculations, in keeping with the present findings.

In contrast, studies that used transesophageal echocardiography found no change in RVEF after surgery, regardless of the operative technique used14,15 (Table 6). However, transesophageal echocardiography calculates 3-dimensional volumes from 2-dimensional measurements,26,27 a technique that is inherently limited by standardizing the imaging plane and the landmarks required for serial measurements. Furthermore, this technique makes several geometric assumptions about the RV that underestimate its complexity. Studies that used thermodilution catheters placed in the pulmonary artery to assess RV function also produced inconsistent results between the different surgical techniques (Table 6).15,16,24

Effect of OPCABG Surgery and RCA Disease on Early RV Function
In our pilot study, we found that both surgical techniques produced equivalent results in terms of RV function with or without grafting to the RCA. This contrasts with the findings of Durand et al,16 who, using thermodilution catheters to calculate ejection fraction, reported a significant fall in RVEF associated with the ONCABG technique compared with OPCABG in patients with a significant stenosis of the RCA.16 However, there are several reasons to possibly explain these discrepant findings. First, the study by Durand et al16 was not randomized, and the operations were performed by different

Table 5. Results for Interobserver and Intraobserver Variability for RV Analysis

<table>
<thead>
<tr>
<th></th>
<th>Intraobserver Variability</th>
<th>Interobserver Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (95% Limits of Agreement)</td>
<td>CV</td>
</tr>
<tr>
<td>RV ejection fraction</td>
<td>-0.18 (-5.2 to 4.8)</td>
<td>3.9</td>
</tr>
<tr>
<td>RVEDVI</td>
<td>0.88 (-13.4 to 15.2)</td>
<td>9.3</td>
</tr>
<tr>
<td>RVESVI</td>
<td>0.85 (-3.75 to 5.5)</td>
<td>8.8</td>
</tr>
</tbody>
</table>

CV indicates coefficient of variation; RVESVI, RV end-systolic volume index.

Figure 3. Bland-Altman plot20 indicating intraobserver variability for analysis of RV function with CMR. Bias is indicated by the solid black line; limits of agreement are indicated by dashed lines.

Figure 4. Bland-Altman plot20 indicating interobserver variability for analysis of RV function with CMR. Bias is indicated by the solid black line, limits of agreement are indicated by dashed lines.
surgeons, potentially causing both selection and treatment bias. Furthermore, thermodilution catheters derive the ejection fraction on the basis of flow rather than volume, and although potentially useful for serial measurements in an individual patient, there are no data on reproducibility. Furthermore, in contrast to the present study, Durand et al examined only patients with >90% RCA stenosis who all had grafts placed in the RCA territory.

Conclusions
The findings of the present study are important because they are the first to confidently document sequential postoperative changes in RV function with CMR, now accepted as the “gold standard” for noninvasive cardiac imaging. Furthermore, we measured the effect of OPCABG and ONCABG surgery on RV function in a randomized trial. This pilot study found that RV function was significantly impaired early after surgery. This was irrespective of the surgical technique used, but it recovered completely by 6 months. This effect was produced by changes in RVEDVI, the precise mechanism for which remains unclear but which may relate to pericardial fluid, inflammation, or hematoma altering the filling conditions of the RV. In addition, relaxation of the RV free wall could be impaired as a result of myocardial edema. We suggest that the RV is significantly impaired as a result of the general trauma of surgery, but this is not compounded by use of an aortic cross clamp or cardiopulmonary bypass.

Study Limitations
RV reproducibility is lower than published for the LV; however, MRI still far exceeds any other modality for the accurate assessment of RV function. Grothues et al reported interstudy variability for serial assessment of RV stroke volume index in a similar cohort to that in the present study at 4%, whereas Hudsmith et al reported interstudy variability for RVEF as 11%. The present results for intraobserver variability compare favorably with the literature, with the coefficient of variation for intraobserver reproducibility being 4% and that for interobserver variability being 12%.

Table 6. Comparisons Between Studies

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>Study Design</th>
<th>Surgical Method</th>
<th>Assessment Method</th>
<th>Timing of Postoperative Assessment</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pegg et al 2008</td>
<td>Prospective randomized trial</td>
<td>OPCABG=30; ONCABG=30</td>
<td>Cardiac MRI</td>
<td>6 d and 6 mo</td>
<td>Early reduction in RVSVI, no difference between OPCABG and ONCABG</td>
</tr>
<tr>
<td>Michaux et al 2006</td>
<td>Prospective randomized trial</td>
<td>OPCABG=25; ONCABG=25</td>
<td>2D TOE</td>
<td>Sternal closure</td>
<td>No change in early RVEF in either OPCABG or ONCABG</td>
</tr>
<tr>
<td>De Simone et al 2005</td>
<td>Prospective observational study</td>
<td>ONCABG=25</td>
<td>2D transesophageal acquisition with 3D reconstruction, PA thermodilution catheter</td>
<td>2 h</td>
<td>No change in early RVEF</td>
</tr>
<tr>
<td>Alam et al 2003</td>
<td>Prospective observational study</td>
<td>ONCABG=34; OPCABG=1</td>
<td>Tissue Doppler TTE (TDI)</td>
<td>1, 3, and 12 mo</td>
<td>28% Reduction in tricuspid valve systolic velocity at 1 mo</td>
</tr>
<tr>
<td>Durand et al 2006</td>
<td>Prospective observational study</td>
<td>OPCABG=14; ONCABG=15</td>
<td>PA thermodilution catheter</td>
<td>1, 3, 6, and 18 h</td>
<td>20% Reduction in RVEF in ONCABG group; no change in RVEF in OPCABG</td>
</tr>
<tr>
<td>Kwak et al 2004</td>
<td>Prospective observational study</td>
<td>OPCABG=30</td>
<td>PA thermodilution catheter</td>
<td>Sternal closure</td>
<td>10% Reduction in RVSVI, but no change in RVEF</td>
</tr>
</tbody>
</table>

RVESVI indicates RV end-systolic volume index; PA, pulmonary artery; TTE, transthoracic echocardiography; and TDI, tissue Doppler imaging.
The latter has less of an impact on the present results, because all analyses were performed by a single operator.

We performed delayed-enhancement CMR imaging in the present study to look for irreversible injury, which we reported for the LV. However, RV delayed-enhancement CMR images in the immediate postoperative scan were often complicated by significant artifact from sternal wires, which obscured the RV free wall. Furthermore, the thin wall of the RV and surviving pericardial fat also made the quantification of any new mass of delayed hyperenhancement unreliable, and therefore, it is not reported in the present study. This protocol assesses RV function at 6 days after surgery because earlier assessment with CMR is limited by postoperative discomfort and breath-holding capacity. Thus, we cannot exclude the possibility that there may be differences in RV function between the techniques immediately after surgery that have resolved by 6 days. The addition of preoperative and postoperative data on pulmonary vascular resistance or pulmonary artery pressures may have provided additional information about the immediate postoperative stage, but the available techniques are not reproducible, and physiological changes are too short-lived to help explain the present findings. Finally, the present study only assessed patients with normal preexisting RV function, and whether similar results would be obtained in those with impaired RV function is unknown.

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Disclosures

None.

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**CLINICAL PERSPECTIVE**

Although right ventricular (RV) function is an important determinant of outcome after cardiac surgery, it has been studied infrequently compared with left ventricular function. Those studies of RV function conducted with cardiopulmonary bypass have traditionally attributed postoperative RV dysfunction to a combination of cardiopulmonary bypass and deflation of the lungs allied to myocardial injury associated with a period of obligate ischemia and cardioplegic arrest. Controversy exists in general about the postulated benefits of off-pump coronary artery bypass grafting, and specifically, no robust investigation has been conducted into the impact of this technique on RV function. In the present study of patients with normal RV function preoperatively, 30 patients were randomized to off-pump coronary artery bypass grafting and 30 to conventional on-pump coronary artery bypass grafting. RV function was assessed with cardiac magnetic resonance imaging preoperatively, at 6 days after surgery, and finally at 6 months after surgery. No difference was observed in RV function between on-pump and off-pump coronary artery bypass grafting, which suggests that cardiopulmonary bypass and cardioplegic arrest are not the major determinants of RV function. Rather, diastolic dysfunction and impaired RV filling related to fluid status and heart rate, as well as myocardial contusion and collection of pericardial fluid, may play a role.
Effects of Off-Pump Versus On-Pump Coronary Artery Bypass Grafting on Early and Late Right Ventricular Function
Tammy J. Pegg, Joseph B. Selvanayagam, Theodoros D. Karamitsos, Ranjit J. Arnold, Jane M. Francis, Stefan Neubauer and David P. Taggart

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