Intraoperative Assessment and Quantification of Coronary Artery Graft Patency Performed on or off Cardiopulmonary Bypass

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Abstract: Within the last 10 years, the incorporation of off-pump coronary artery bypass grafting (OPCAB) into many surgical practices has grown. OPCAB requires the surgeon to operate on a beating heart, and it is generally accepted that OPCAB procedures are more technically demanding. Concerns of possible incomplete revascularizations and decreased graft patency have been noted in the literature. The objective of this study was to evaluate and compare on-pump and off-pump intraoperative coronary artery bypass graft (CABG) flow parameters. Intraoperative flow studies conducted with the Butterfly (Medi-Stim Norge AS, Oslo, Norway) flow meter were analyzed retrospectively on 74 patients. Comparisons were completed between patient groups having had their revascularizations performed on or off cardiopulmonary bypass. Our study revealed significant differences in the mean flow rate through saphenous vein grafts (SVG) to the obtuse marginal artery (OM; \( p = .014 \)), to the diagonal artery (Diag; \( p = .003 \)), to the right coronary artery (RCA; \( p = .001 \)), and to the posterior descending artery (PDA; \( p = .001 \)). Total blood product use showed significantly increased use of both platelets (PLTs) and cryoprecipitate (Cryo) in the on-pump group (\( p = .027 \) and .012, respectively). No differences were found for transfusions of red blood cells (RBCs) or fresh frozen plasma (FFP). Additional findings showed a significantly decreased median length of stay (LOS) for the off-pump group. The on-pump patients had a median hospital stay of 7 days (range, 4–24 days), whereas the off-pump patients had a median stay of 6 days (range, 3–22 days; \( p = .049 \)). Although we were able to show some significance in the mean flow data supporting increased graft flow with the on-pump technique, we were not able to show an overall increase in all recorded flow characteristics to support one method over another. Keywords: graft patency, off-pump, off-pump coronary artery bypass grafting, coronary flows.

In recent years, off-pump coronary artery bypass grafting (OPCAB) surgery has become one of the most debated techniques since the introduction of angioplasty (1,2). This technique allows a coronary artery bypass graft (CABG) to be completed without the use of cardioplegia or other means to arrest a patient’s natural cardiac function. Although this technique is not new, it is still not widely accepted as a standard of practice over on-pump CABG surgery, which allows for induction of a controlled cardiac arrest (3). The reasons are debatable and vary among institutions. However, concerns of impaired technique, leading to decreased anastomotic quality and or incomplete revascularization, generally lead the list (1,3–5). Studies, both pro and con, are numerous (1). A recent study into the bulk of the literature by Sellke et al. (1) found that most studies tended to favor OPCAB in relation to less blood loss/transfusions, less renal insufficiency, and less early neurocognitive dysfunction. However, traditional on-pump CABG was favored in a number of revascularizations performed and showed significantly higher graft patency rates in a single study (1,6). Although there seems to be little consensus about which technique is more advantageous than the other, most do agree that the OPCAB procedure is more technically demanding from a surgical point of view and that there is a steep learning curve associated with it (5,7). Overall, the most recent data suggest little, if any advantage, to OPCAB over traditional on-pump CABG, warranting more research into both techniques (1,8). The aim of our study was to address any procedural advantages in relation to distal coronary artery flow rates, transfusion rates, ventilator time, and length of stay.

MATERIALS AND METHODS

Patient Population

All patients had coronary artery bypass completed at our institution between July 1, 2004 and July 1, 2005. Pa-
tients were neither selected nor deselected for on or off-pump surgery or for any other criteria. From July 2004 to October 2004, all patients requiring a CABG procedure had surgery without CPB, and from November 2004 to July 2005, all CABG patients had surgery with CPB. Transit time flow measurements (TTMFs) were taken on all patients. A total of 98 patients were considered for inclusion in the study. Of the original 98 patients, 22 were excluded from the study because of improper recording of the flow curves, yielding unreliable and inaccurate data. In addition, two patients were converted from off-bypass to on-bypass and subsequently excluded from the study. The final data analysis included in the study represents a total of 74 patients (37 patients per group). No CABG grafts were revised because of unsatisfactory flow data in the operating room (OR).

**Study Design**

This study consisted of data gathered prospectively and reviewed retrospectively at Gundersen Lutheran Heart Institute, LaCrosse, WI. Intraoperative flow studies were analyzed, and results were compared between two patient groups. Group A had surgical revascularizations performed without cardiopulmonary bypass (CPB), and group B had their surgical revascularizations performed with CPB. After Institutional Review Board approval and in accordance with all Health Insurance Portability and Accountability Act (HIPAA) guidelines, flow data was recorded on the Butterfly flow meter (Medi-Stim Norge AS, Oslo, Norway) and collected into an Excel format. Data collected included patient demographics (height, weight, body surface area [BSA], sex, age), OR time, pump time, length of stay (LOS), ventilator time (VT), and number of grafts. Flow data consisted of mean flow, pulsatility index (PI index) (maximum flow – minimum flow/mean flow), and the percentage of diastolic filling (total diastolic flow/total diastolic flow + total systolic flow). Each of the above flow characteristics were recorded individually for grafts: left interior mammary artery (LIMA)–left anterior descending (LAD), saphenous vein graft (SVG)–obtuse marginal (OM), SVG–diagonal (DIAG), SVG–circumflex (CX), SVG–right coronary artery (RCA), and SVG–posterior descending artery (PDA). These were compared. Sequential or T grafts and radial artery grafts were excluded from the study. All additional data were gleaned from patient’s medical records retrospectively. Comparisons between the on-pump and off-pump study arms were completed by obtaining the means and SDs of the data points. Statistical analysis was performed using the Student t test for all data points, with the exception of the LOS and the VT data. The LOS and VT data were compared by obtaining the median and range values and applying the Wilcoxon rank sum test. Statistical significance was accepted at a ‘p’ value equal to, or less than, 0.05.

**Conduit Harvest Technique**

If the patient had LAD disease, the LIMA was harvested with a pedicle using electro-cautery and direct vision. The artery was flushed with papaverine solution to protect from vasospasm. SVGs were harvested endoscopically and flushed extensively with heparinized saline after removal.

**OPCAB Technique**

After induction of anesthesia, a median sternotomy was performed, and the heart was exposed. A deep pericardial stitch was placed to elevate the heart for better exposure, and patients were placed in a Trendelenburg orientation. Patients were systemically heparinized to a target activating clotting time (ACT) of 300 seconds, and their temperature was maintained between 36°C and 37°C using a Bair Hugger (Arizant, Eden Prairie, MN) warming device placed over the lower extremities and around the head. A suction device (Octopus IV; Medtronic, Brooklyn Park, MN) was placed to further increase exposure and to minimize cardiac activity at the site of the distal anastomosis. After suitable positioning was accomplished, a silastic suture was placed to occlude the artery to be bypassed for 1.5 minutes of pre-ischemic conditioning. After ischemic conditioning, the suture was released, and flow was restored for 1.5 minutes. The distal anastomosis was performed with the silastic suture in place in an end to side fashion. Proximal anastomoses were performed using a side-biter clamp on the proximal aorta.

**Bypass Technique**

After induction of anesthesia, a median sternotomy was performed, and the heart was exposed. Arterial and venous cannulations were performed through the atria/avae and the aorta. Additional cannulae were placed for left ventricular venting and both antegrade and retrograde cardioplegia. The cardiopulmonary bypass circuitry consisted of an uncoated tubing pack, a Biomedicus centrifugal pump, and an Affinity oxygenator (Medtronic), and a hard-shell reservoir, Vision cardioplegia sets, and a hemoconcentrator (Gish Biomedical, Rancho Santa Margarita, CA). Instrumentation included the Terumo CDI 500 (Terumo Cardiovascular, Ann Arbor, MI) blood gas analyzer and the Medtronic HMS System (Medtronic). Pump prime consisted of 1500 mL Normosol R, 100 mL 25% albumin, 25g mannitol, 1 mg/kg dexamethasone, and 10,000 units heparin and either 200 mL aprotonin (Bayer HealthCare Pharmaceuticals, Wayne, NJ) or 10 g amicar. Full bypass was established after a heparinized ACT of at least 480 seconds. All patients received both retrograde and antegrade, cold, 4:1 blood cardioplegia and aortic cross-clamping. Patient temperature was allowed to drift during CPB. After cardioplegic arrest, the distal anastomoses were performed in an end-to-side fashion. Addi-
ditional cardioplegia was routinely given every 10–20 minutes. After rewarming, a warm blood hot shot was given that included 100 mg lidocaine, 2 g MgSO₄, and 500 mg CaCl₂. The aortic cross-clamp was removed. Proximal anastomoses were performed using a side-biter clamp on the proximal aorta. All shed blood was returned to the pump or cell saver.

Transit Time Flow Measurement
TTFM uses ultrasound technology to measure flow through a vessel lumen. TTFM data were recorded immediately after the last proximal anastomosis (off-pump) or immediately after coming off bypass, and after adequate hemodynamics were attained (systolic blood pressure >100 mmHg). All data were recorded before any heparin reversal had occurred. Probe size was chosen (2–4) according to graft diameter. The probe was placed on the graft, and flow measurements were recorded after flow curve stabilization. This process was repeated for each bypass graft. The data were saved on the hard drive of the Butterfly flow meter.

RESULTS
The patient demographics for our study group are listed in Table 1. There were no significant differences between the two groups across any of the demographic data.

Table 2 shows the operative data points included in the study. The mean bypass time for the on-pump patients was 93.5 ± 18.9 minutes, for a mean number of 3.5 ± 0.8 bypass grafts. The mean number of bypass grafts for the off-pump group was 3.4 ± 0.8. The median VT was the same in both groups at 7 hours. The total OR time was not significant, although there were shorter OR times (196.1 ± 38.5 minutes) for the on-pump group as opposed to 217.7 ± 57.9 minutes for the off-pump group (p = .063). There were no significant differences in number of grafts, OR time, or VT. Significant differences were found in the LOS data. The on-pump patients had a median hospital stay of 7 days (range, 4–24 days), whereas the off-pump patients had a median stay of 6 days (range, 3–22 days), with a p value of .049.

Total blood product use (Figure 1) showed no significant differences in the transfusion rates of packed red blood cells (2.5 ± 2.7 units on-pump and 1.7 ± 1.6 units off-pump) or fresh frozen plasma (0.3 ± 1.3 units on-pump and 0.0 ± 0.0 units off-pump). However, significance was achieved in the transfusion rates of PLTs and Cryo. PLTs were transfused at a mean rate of 0.6 ± 1.3 units in the on-pump group and significantly less, 0.1 ± 0.3 units (p = .027), in the off-pump group. Cryo was transfused at a mean rate of 1.0 ± 2.2 units in the on-pump group and 0.0 ± 0.0 units in the off-pump group (p = .012).

Our intraoperative flow data included three indicators of coronary artery bypass patency: mean flow, PI index, and percent diastolic filling. The mean flow data revealed significance in four of the five CABG grafts recorded (Figure 2). Significant differences were found in the SVG to OM, Diag, RCA, and PDA. All values were significantly higher in the on-pump group. The greatest differences in the means were found in the RCA (44.1 ± 20.9 mL/min on-pump and 18.2 ± 10.2 mL/min off-pump) and PDA (53.5 ± 24.6 mL/min on-pump and 21.5 ± 12.6 mL/min off-pump) grafts, both with p values of .001. Significance was not achieved in the mean flow differences between the two groups for the LIMA–LAD grafts.

The PI index data (Figure 3) showed no significant differences between the groups across any of the CABG grafts. However, there was a trend toward significance in the SVG to PDA, suggesting a higher PI index in the off-pump group (3.4 ± 3.2 on-pump and 5.3 ± 2.5 off-pump; p = .086).

**Table 1.** Patient demographics.

<table>
<thead>
<tr>
<th></th>
<th>On-Pump (n = 37)</th>
<th>Off-Pump (n = 37)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent male</td>
<td>67.6</td>
<td>56.8</td>
<td>.34</td>
</tr>
<tr>
<td>Percent female</td>
<td>32.4</td>
<td>43.2</td>
<td>.34</td>
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<tr>
<td>Age</td>
<td>64 ± 12.2</td>
<td>68 ± 11.4</td>
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<tr>
<td>Height</td>
<td>168.1 ± 14.6</td>
<td>170 ± 10.1</td>
<td>.52</td>
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<tr>
<td>Weight</td>
<td>91.8 ± 21.0</td>
<td>85.4 ± 20</td>
<td>.19</td>
</tr>
<tr>
<td>BSA</td>
<td>2.0 ± .02</td>
<td>1.9 ± 0.2</td>
<td>.14</td>
</tr>
</tbody>
</table>
The percent diastolic filling data (Figure 4) seemed to mirror the PI index data in that there were no significant values found across any of the data points. Of interest again was the SVG–PDA graft that showed trends toward significance, with a p value of .067, and mean percent diastolic filling of 53.9% ± 6.2% on-pump and 45.9% ± 15.4% off-pump, suggesting possible increased diastolic filling in the on-pump group.

DISCUSSION

CABG has been a standard of care for patients with coronary artery obstruction for >35 years (9). As technology advances, new procedures have been advocated, and many, such as angioplasty and coronary stenting, have had a large impact on patient outcomes. Such is the case with the OPCAB procedure, where cardiac surgeons have revisited a previously abandoned technique that allows for bypass grafting to be done without the use of the heart-lung machine (10). Proponents of this technique have shown better patient outcomes compared with traditional on-pump CABG procedures. Studies citing decreased LOS, decreased blood product use, decreased ventilator time, and an overall decreased cost all attributing to the use of the OPCAB technique are easily found in the current medical literature (11–13). However, there seems to be as much conflicting evidence that supports traditional CABG and shows no significant advantage to procedures performed off-pump (14,15). There does, however, seem to be a consensus that the OPCAB procedure is more technically demanding from a surgical point of view and that the learning curve is quite steep (3,6,11). We need to consider the possible decrease in graft quality, which may be attributed to a surgical procedure performed off-bypass. Early graft failure can have a huge impact on patient outcomes, including mortality and morbidity (16). In addition, decreased graft flow rates have been correlated with future graft occlusion (17,18). Studies have also shown that, in 50% of patients who die after early graft occlusion, the occlusion is caused in part by gross technical problems such as stenotic anastomotic sites (19,20). Early graft failure, although rare, can be a disastrous complication leading to increased angina, infarction, arrhythmias, and mortality. Angiographic studies of CABG patents have shown early graft failure of the internal mammary arteries to be ~5%, and 11% for saphenous vein grafts (3,21,22). Because of the technically demanding nature of the OPCAB procedure, where the anastomosis is often performed in a vertical orientation, and to the lack of a bloodless, inactive operative field, the possibility exists for more operative error, leading to decreased graft patency and increased early graft failure.

TTFM has been shown to be an effective and extremely accurate way of accessing coronary artery graft flow rates (23,24). TTFM has many advantages over traditional Doppler ultrasound technology. First, TTFM measures an infinite number of flow vectors within a vessel; this allows...
for accurate measurements independent of vessel diameter, shape, or probe angle. In addition, TTFM is not affected by hematocrit, low flows, or temperature (25). TTFM is based on the principle that the time required for ultrasound to pass through the blood upstream is slightly longer than downstream, and the difference in transit time is proportional to the volume of blood flow in milliliters per minute (24). Our experience with TTFM has shown it to be both easy to use and extremely practical in situations of questionable graft patency.

The most compelling finding of our study shows significant decreases in mean graft flow rate in the off-pump group compared with the on-pump group for all SVG anastomosis. Mean flow rate alone, however, is not a good predictor of graft patency, because it has been shown to be unaffected in grafts <75% stenosed (26). In addition, mean flow can be affected by distal native coronary artery size and stenosis (27). Thus, this significance becomes less impressive when the data from the PI index and percent diastolic filling (neither group showed any significant values) are incorporated. To get a true understanding of the overall flow characteristics of a vessel, we must take into account all of these parameters. Unfortunately, there is no standardized scoring system that would assign a value or rank to each of these parameters, yielding a definable overall flow value. There are many studies documenting that the optimal PI index is <5 (27,28). Our PI index data, although not significant, was, with the exception of the off-pump SVG–PDA data, within the normal accepted values. Some studies suggested that percent diastolic filling is the most important indicator of graft patency (29). Because the majority of coronary flow takes place during diastole, and at a lower pressure than the mean flow, percent diastolic filling is a more precise measurement of coronary flow. However, normal values vary between different regions of the heart, which must be taken into account when accessing coronary patency.

A thorough review of the literature produced three studies specifically comparing graft patency using TTFM between patients having CABG done on-pump and off-pump (30–32). The studies were similar in methodology but varied in number of participants (from 60 to 896). Overall conclusions from the two smaller studies found no significant differences in graft patency rates between off-pump and traditional on-pump CABG. Significant differences were found between the two groups in number of revascularizations performed. Additional findings included significantly increased flows in men compared with women (30,32).

The results of our mean flow data become more interesting when they are compared with an analogous study by Schmitz et al. (31). Similar results were found in the mean flow data of this study, showing increased flows in all of the grafts performed on-pump, including the LIMA and RIMA. Schmitz et al. (31) suggested two explanations. First, because of the induced global ischemia and subsequent acidosis produced when cardioplegia is used to arrest the heart, the coronary arteries are in a state of vasodilation during and after on-pump surgery. A second explanation, which has been widely observed by our group, is that the use of vasoconstrictors during off-pump surgery is higher to maintain acceptable hemodynamic values (31). In our on-pump study group, blood cardioplegia was administered routinely every 10–20 minutes; thus, myocardial ischemia and subsequent vasodilatation leading to increased graft flows are unlikely.

In an additional study by Louagie et al. (33), two groups of 89 patients were evaluated using dual-beam Doppler flow technology. Results again showed a trend toward increased mean flows in the on-pump group (64.9 ± 37.3 on-pump vs. 58.6 ± 35.0 off-pump; p = .063); however, statistical significance was not achieved. Of interest was the resistance data showing significantly decreased resistance in the on-pump group (p = .020). Louagie et al. (33) suggested that this finding, in conjunction with the mean flow results, is explained by the hemodilution associated with the on-pump procedure (33). In our study, however, the use of TTFM was independent of hematocrit, and our increased mean flow results cannot be explained by this factor. It should be noted that, although there are several studies showing increased mean coronary flow rates with the use of the on-pump technique, no studies were able to correlate improved patient outcomes with increased mean flow (33).

Flow and patency studies comparing on- and off-pump procedures have also been completed using intraoperative angiography by Lingaa et al. (5). Results from this study showed a trend toward higher graft flows in the on-pump group; however, statistical significance was not reached.

The supplemental findings of our study, decreased blood product use (PLTs, Cryo) and decreased LOS, seem to mirror the majority of previously published data and were effective in correlating our institutions results with the results of others.

There are many limitations to a study conducted to directly assess coronary flow that cannot be predictable, including varying coronary anatomy, the extent of proximal, native artery stenosis, and the extent of distal artery runoff. In addition, the retrospective nature of our study leaves open the possibility for procedural biases. However, this was minimized because of the fact that patients were selected or deselected for a procedure only by the frame of time in which their operation took place.

In summary, the literature contains studies with sound methodology and intriguing conclusions. Our study was able to confirm previous findings of increased mean flow rates in SVG conduits performed on-pump. Although there is no direct consensus on the explanation of this
phenomenon, it seems to be a reproducible result. In addition, we were able to show that off-pump bypass procedures are associated with a decreased use of blood products (PLTs, Cryo), and it significantly decreased the overall LOS.

REFERENCES


