Abstract

**Objectives:** The technical aspects of minimal invasive surgery are discussed, together with a comparison of off-pump MIDCAB with off-pump sternotomy, with special respect to outcomes of death, infarct and anastomoses. **Methods:** Technical aspects of beating heart surgery are described under the headings: Trauma; Access; Stabilisation; Ischaemia; Haemostasis; Suturing; and Circulatory support. Data from papers and meetings on minimal invasive surgery were collated to September 1998 and correlated with the unit of origin. Percentage figures were back calculated to provide an actual number from which a new data base was obtained relevant to the reporting incidence. For statistical analysis a Chi squared test with Yates correction was used. **Results:** Sixty-three centres reported 3304 cases of MIDCAB surgery (M) and 21 centres reported over 3060 cases of off-pump surgery through a sternotomy (S). There was no difference in early or late death rates between the two groups (1.6% M:2.2% S). There was a higher infarct rate with MIDCAB (2.9% M:1.45% S; $P < 0.03$). The occlusion and stenosis rates for MIDCAB were 3.9 and 6.6% whilst for sternotomy off-pump they were 4.9 and 1.4%. The stenosis difference was significant at the $P < 0.001$ level. A combined occlusion and stenosis rate showed a higher incidence with MIDCAB (10.5%), than sternotomy 6.4% ($P < 0.08$). Four major series showed comparative data before and after stabiliser usage in MIDCABs. The stenosis rate was significantly reduced with stabilisation from 9.6 to 3.7% ($P < 0.002$) as was the combined occlusion and stenosis rate from 16 to 5.0% ($P < 0.0001$). In the total series there was no significant difference in length of stay (4.6 days), incidence of atrial fibrillation (9%), or between conversion to sternotomy (MIDCAB group) or to bypass (sternotomy group) (5%) between the two groups (M and S). Grafting the right coronary artery by MIDCAB produced worse results than for the left anterior descending artery (LAD). **Conclusions:** There is an important failure rate with beating heart surgery; stabilisers reduce this risk and are essential tools in both MIDCAB and beating heart surgery and encourages the further use of minimally invasive approaches. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Minimally invasive; Meta-analysis; Coronary; Beating heart; MIDCAB

1. Introduction

First reports of minimal invasive surgery came from off-pump surgery via standard sternotomy [1–4] and from off-pump mini thoracotomy (MIDCAB) [5–8]. Since then beating heart surgery whether as minimal incision surgery or as avoiding extracorporeal circulation has become increasingly popular for coronary artery by pass grafting. The techniques required in either procedure have developed with both technological development and with the experience of the surgeons. This paper sets out to highlight many of the aspects of minimal invasive surgery which are important to integrate into the operation, and to compare off-pump MIDCAB with off-pump sternotomy, with respect to outcomes of death, infarct and anastomotic problems and to relate these outcomes with the changes in technical adjuncts.

2. Material and methods

Data from papers and meetings on minimal invasive surgery were collated form June 1995 to Sept 1998 and correlated with the unit of origin. Information was sought on patients, having either MIDCAB or off-pump surgery via a sternotomy. Data collected included – total numbers, death, peri-operative myocardial infarction, late death, length of stay, post operative arrhythmias, and analysis of graft occlusion or stenosis by either angiography or non invasive tests. Percentage figures were back calculated to provide an actual number from which a new data base was obtained relevant to the reporting incidence. Statistical
analysis was by using Chi squared test with Yates correction factor.

Technical aspects of beating heart surgery are described under the following headings. (1) Trauma; (2) Access; (3) Stabilisation; (4) Ischaemia; (5) Haemostasis during grafting; (6) Suturing; and (7) Circulatory support.

2.1. Technical adjuncts

2.1.1. Trauma

Both cardiopulmonary by pass and sternotomy provide a trauma stimulus to the patient, which can be reduced. Which of these is the more important cannot be detailed at this time, advocates of both exist. Cardiopulmonary by pass can be reduced by performing beating heart surgery with perfusion assist devices in the left or right ventricles, but it can be avoided altogether by performing beating heart surgery without any perfusion assist. Musculo-skeletal trauma is reduced pari-passu with reducing incision length, quantity of muscle divided, quantity of bone or rib divided or excised, and with the degree of abrasion of pericardial and other cavities. The reduction of both cardiopulmonary bypass and musculo-skeletal injury should achieve the optimum reduction of trauma and is the ultimate aim of minimal invasive surgery.

2.1.2. Access

MIDCAB surgery requires the dissection of a good and undamaged length of internal mammary artery and an accurate placement of the incision to access the relevant coronary artery, usually the LAD. In this operation only one graft is deployed (occasionally a jump to the diagonal as two distal anastomoses) and the whole operation is dependent on this vessel; therefore it is essential that this vessel is harvested undamaged. The incision for mini-thoracotomy is placed transversely or obliquely along the 5th interspace starting from the midclavicular line and spreading medially for 5–6 cm. This allows for a direct dissection on to the IMA and before thoracotomy thereby minimising the length and increasing the accuracy of that incision.

2.1.3. Pericardial access

Location of the site of the LAD (as medial or lateral) in respect to its position in the thorax is useful in order to be able to plan the pericardial incision right over the LAD and to ensure there is enough length of IMA harvested. Assessment is made from the chest X-ray, the angiogram and by early viewing into the pericardium. With endoscopic harvest the pericardium can easily be opened before final harvesting and before thoracotomy thereby minimising the length and increasing the accuracy of that incision.

2.1.4. Sternotomy

A full sternotomy may not be minimally invasive per se but allows for the more widespread use of multiple coronary artery grafting without bypass, which reduces patient trauma and is considered under the general heading of minimal invasive. Hemi-sternotomy has also been described [16]; this allows a more usual access to and harvest of the mammary artery. This hemi-sternotomy may be straight or tee’d with a lower inverted ‘L’ incisions or as a midway ‘C’. For circumflex grafting off bypass a full sternotomy is the incision of choice currently. To expose such posterior vessels three manoeuvres are important.

1. Placing very deep pericardial sutures on the left side of the pericardium just above the pulmonary veins and at the diaphragm. These are referred to as Lima sutures after Dr Lima from Brazil. Pulling up on even one such deep pericardial suture quickly elevates and rotates the heart into the wound such that the LAD normally hidden under the left costal margin is readily in view; the apex of the left ventricle may point upwards.

2. Mobilisation of the right side of the pleura/pericardium with division of connections between both of these and the diaphragm to allow a space into which the elevated heart may lie. This space can be further increased by separate elevation of the right sternal border with retractors and by widely opening the right pleura down to the phrenic nerve. The importance of this manoeuvre is to release the compression on to the right side of the heart which would be produced by the relatively rigid right sternal edge and right pleura/pericardium when the heart is rotated over to access the circumflex vessels.

3. Rotation of the patient to the right and in a steep Trendelenberg head down position. This increases the filling of the right ventricle which has been showed experimentally [17] and clinically [18] to be a manoeuvre that
maintains cardiac output during cardiac lifting. Its mechanism of action is still debated but undoubtedly it overcomes the partial kinking and restriction of inflow of blood to the right ventricle rather than any action to help the left ventricle. Steep downward Trendelenberg may also assist displacement of the apex out of the pericardium to allow easier access to the posterior vessels. Rotation to the right also helps by preventing the weight of the elevated heart compressing posteriorly down onto the right atrium, vena cavae and ventricular input. The effect of this manoeuvre can be demonstrated simply by seeing the effect of change in the centre of gravity of a large glass one third full of fluid: as the glass is turned to the right, the weight of the water is shifted and the centre of gravity moves laterally to the right; in the human this will take the weight of the heart away from the right atrium/cavae.

### 2.1.5. Stabilisation

Early experience with minimally invasive cardiac surgery (MIDCAB) did not involve the use of stabilisers. Traction sutures [8] or adenosine and other pharmacological agents [19] were used to steady motion of the heart. The advent of stabilisers has made it very much easier to operate on a beating heart. There are a number of stabilisers available and these are being continuously modified. The two essential types are: (1) the suction device known as the Octopus; and (2) the Foot plate device. The suction device has a dual role in that it may steady the heart by lifting thereby reducing pressure on the ventricle and it may also be used in part to rotate or present the heart. The Foot devices are simpler to attach: they fit onto or are a part of the chest spreader and are less bulky, an advantage in small incisions. They do cause pressure on the ventricle which may adversely affect ventricular function and they have only very limited rotation/presentation function. Analysis of data shown later clearly shows a significant improvement in outcomes with the use of any stabiliser compared to no stabiliser.

### 2.1.6. Ischaemia

Both MIDCAB and off-pump surgery involve local ischaemia from temporary occlusion of the native coronary vessel. The resultant ischaemia may cause arrhythmia including ventricular fibrillation or marked bradycardia, reduced myocardial contractility, ST changes on the ECG during the operation and myocardial infarction or significant cardiac enzyme rise seen post-operatively. Measurements of cardiac enzymes especially of Troponin [20–23] all show very low levels of troponin rise in MIDCAB surgery compared to on pump surgery, with the usual levels of troponin rise being 0.3 mcg/l compared to those on by pass of about 1–2 mcg/l. Evidence taken from an early period of MIDCAB [9] showed that the ECG ST change as monitored by the anaesthetist rarely showed ST elevation above 1 mm. Predictability of ECG ST rise was shown to relate to the degree of native stenosis of the vessel being grafted [20]. Table 1 shows correlation of ST ECG change with native stenosis such that if the percentage native stenosis is 75% or less then some ECG change may be expected. In addition it has been observed by experienced off-pump surgeons that large right native coronary arteries have a nasty habit of producing arrhythmia on occlusion. Experience has shown that local ischaemia is rarely significant clinically, unless there is a mild proximal native stenosis or a large dominant right coronary artery. Methods used to combat temporary ischaemia include pharmacological slowing of the heart, pre-conditioning, and the use of intracoronary shunts. Debate concerns whether it is wise or necessary to perform a preconditioning manoeuvre prior to starting the anastomosis [24] and there is no absolute answer to this; at present this procedure is surgeon dependent. Shunting [25] is an important procedure to have available during beating heart surgery for either prevention of ischaemic problems, which may develop rapidly, or for control of bleeding through the vessel during anastomosis. As mentioned, a large right coronary, unless tightly stenosed or occluded, carries a reputation for rapid onset bradycardia with ECG change which requires prompt action in the form of external pacing, the use of inotropes and or insertion of a shunt. Excess blood loss through an open artery might in theory also be a cause of ischaemia especially if the vessel is not clamped proximally, shunting prevents ischaemia, although the placement of a shunt is cumbersome and may damage the native vessel endothelium.

### 2.1.7. Haemostasis

A stable artery allows for a steady anastomosis and reduces the risks of anastomotic stenosis or occlusion. Good haemostasis is the second vital requirement for a good anastomosis. Techniques used to obtain haemostasis include vessel occlusion and irrigation. Prior to occlusion some dissection around the target vessel will be required. Avoidance of small veins and of excess fat or muscle dissection will reduce the sometimes troublesome bleeding from these areas which are not a source of problem in conventional cardioplegia treated hearts.

### 2.1.8. Vessel occlusion

A variety of techniques are available. Suture occlusion is the commonest. Three methods exist: (1) A single suture often of silastic, which passes under the native vessel and is pulled up often in a cross manner to give soft vessel occlusion. Such a technique may be particularly valuable

<table>
<thead>
<tr>
<th>Percentage prox stenosis</th>
<th>100</th>
<th>90</th>
<th>70</th>
<th>50</th>
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</thead>
<tbody>
<tr>
<td>ST elevation (mm)</td>
<td>0.27</td>
<td>0.63</td>
<td>1.83</td>
<td>5.85</td>
</tr>
</tbody>
</table>

*ST elevation and percentage of native proximal stenosis in 50 patients.
on the main right coronary as this vessel is often diseased and may be injured or fail to accept snuggling or clipping: further the suture does help to elevate and present that vessel. (2) Snuggling sutures: these have a width from 0 to 6.0 are used with a snagger possibly over a pledget of rubber or felt and closed down to occlude the vessel; the suture is passed singly around the artery: alternatively a double loop suture can be placed around the artery without a pledget or snagger and this is also effective. Damage to the vessel has been proposed [26,27] as the cause of proximal or distal vessel stenosis with suture occlusion; although recent experimental evidence suggests this may not be so [28], especially if the snaring is done gently. It is important to note that if the occlusion suture is used to position the artery with traction then the risk of vessel stenosis is more likely. Occlusion sutures should be placed for occlusion only and should always be gentle. (3) Clips: soft flat metal clips such as the Aclan clip are effective in occluding the native vessel. They have been shown (Grundeman, personal communication) not to cause vessel damage on the normal pig heart. Application of Aclan clips requires a degree of dissection around the vessel at the place of application otherwise they may fly off. The dissection of the artery may be extensive and continuous to the anticipated arteriotomy in both proximal and distal directions or by local para-arterial stab incisions increased by blunt scissor dissection at the placement sites. Any method of occlusion may be inadequate because of collateral flow, difficulty in accurate occluder placement or disease in the native vessel. For this reason irrigation is an added and important adjunct.

2.1.9. Irrigation and blowers

Saline may be infused from a drip or from a syringe carried out by the assistant or scrub nurse or through the use of a humidified blower. It is important in using a blower to ensure that carbon dioxide is used as the gas and not air or oxygen; carbon dioxide is very soluble in blood and will not cause gas embolisation at least not in modest quantities, whereas nitrogen as in air does. The carbon dioxide gas must be humidified as dry gas blowing over the anastomosis will cause the endothelium to dry out quickly and produce possible irreversible desiccation changes. The combined use of a blower with gentle vessel occlusion is currently the technique of choice.

Shunting has been discussed above. Early application of a shunt eliminates both ischaemia and provides an operative field clear of blood. New shunts are being developed which may be easier to place than the current models and which offer less potential endothelial damage. The Indications for shunting are – mild proximal native vessel stenosis (<75%): a large dominant right coronary being grafted in its distal main part before the bifurcation with the posterior descending vessel: elevation of the ST by 2 mm or more: and any situation in which good haemostasis cannot be obtained.

2.1.10. Suturing

During the initial phase of off-pump surgery and suturing without stabilisers, many surgeons tried new methods of suture orientation and placement to improve results or comfort. However with good stabilisation there is now no need to vary from the normal suture technique as the surgeon currently uses on anastomoses on full bypass. A single circular suture is both popular and accurate. Checking for haemostasis before removal of the stabiliser will allow easier placement of additional sutures should this be needed.

2.1.11. Circulatory support

Circulatory support may be needed for any anastomosis but is infrequent except for posterior wall vessel grafting or large rights. Good diligent anaesthesia is vital as the surgeon is concentrating on the anastomotic intricacies. Tendelenberg head down, volume filling, simple pressure agents such as methoxamine are our first choice agents. Thereafter catecholamines such as adrenaline or isoprenaline for bradycardias and renal dopamine may need to be given initially as boluses but occasionally an infusion is required.

2.1.12. Complications

These are largely dealt with in the meta-analysis. Death, arrhythmias, infarct, vessel occlusion or stenosis, harvest damage to the mammary graft and need for conversion to bypass or sternotomy have all occurred in small percentage numbers. Elevation of the heart may drop the cardiac output and a continuous cardiac output monitor is a useful adjunct where available. Trans-oesophageal echo helps to view the heart for local wall motion abnormalities. Hypotension can set up renal failure or stroke but experience in beating heart surgery has surprisingly shown that the incidence of these is less than expected and indeed these target organ problems are now quoted as indications for off-pump procedures [2,56,79,92,95,96,101].

3. Results

In taking a look at the all the published data at the end September 1998 on a mini meta-analysis base 63 centres [8–106] reported 3304 cases of MIDCAB surgery (M) and 21 centres [2,4,16,18,23,25,41,42,49,52,73,76–78,83,85,87,92,93,96,103] reported over 3060 cases of off-pump surgery through a sternotomy (S). Several centres reported on both MIDCAB and sternotomy. Death was reported in 66% of MIDCAB and 90% of off-pump sternotomy reports. Myocardial infarction was less well reported with some 30% reports mentioning this. There was no difference in early or late death rates between the two groups (1.6% M:2.2% S). There was a higher infarct rate with MIDCAB which did not quite achieve statistical significance (2.9% M:1.45% S: P < 0.03) see Table 2a,b.

Graft patency and vessel stenosis were extracted and back calculated to give exact numbers and proportions compared
to angiography. Sixty percent of reports mentioned occlusion rates in MIDCAB after investigation by angiography or non-invasive means such as Doppler, and 35% commented on stenoses. Forty-three out of 63 centres reported with angiography and this accounted for reports in nearly 50% of cases. The use of angiography in sternotomy off-pump series was small with only 432 cases out of 3060 being analysed (19%).

The results are summarised in the Tables 2–5 and illustrated in Figs. 1–3. The occlusion rates did not vary between those detected by angiography alone and those in which either angiography or non-invasive means were used (Table 3). The occlusion rate for MIDCAB was 3.9% and for sternotomy off-pump was 4.9%. Stenoses were reported from angiography at the anastomosis site or in the native LAD vessel whether proximal or distal, or in the LIMA graft. The incidence of stenosis in MIDCAB was 6.6% and for sternotomy was 1.4%. This difference was significant at the \( P < 0.001 \) level (Table 4). A combination total for occlusion or stenosis showed a high incidence in the MIDCAB group (10.5%), which was significantly higher than the sternotomy group 6.4% at angiography (\( P < 0.08 \)).

The role of stabilisation in the high MIDCAB occlusion/stenoses incidence was found to be critical. Four major series showed comparative data for the period before stabilisers were used against that after their introduction [44,60,70,74]. This data is summarised in Table 5.

The introduction of stabilisers cut the combined occlusion and stenosis rate by half in each series and represents a significant change. Although occlusion rates per se in these series were not significantly reduced (54.4–3.6%), the reduction was sufficient to effect a highly significant combined occlusion and stenosis rate. Stenosis rate in these four comparative MIDCAB reports showed a high incidence (9.6%) which was significantly reduced with stabilisation to 3.7% (\( P < 0.002 \)). The combined occlusion and stenosis rate was very high at 16% and was reduced significantly to 5.0% (\( P < 0.0001 \)).

Stabilisation did not produce any change in the incidence of early or late death, of myocardial infarction or of conversion to sternotomy (constant at 5%) in these series.

In the total series there was no significant difference in length of stay (4.6 days), incidence of atrial fibrillation (9%), or between conversion to sternotomy (MIDCAB group) or to bypass (sternotomy group) (5%). Grafting the right coronary artery by MIDCAB did produce worse results than for the LAD, whether alone or as a combined operation (Fig. 3).

4. Discussion

The meta analysis is an attempt to summarise our knowledge of minimal invasive off-pump surgery at this time. There may be errors of omission in this analysis; however the results do show a relative uniformity. Comparison of occlusion rates with angiography and other non-invasive techniques seem very similar to each other, suggesting that there may be little difference between Doppler analysis and angiography in detecting occlusions (not stenoses). MIDCAB carried a non-significant higher occlusion rate than off-pump sternotomy but this became identical (3.6%) once stabilisers were introduced.

The four groups which reported before and after the intro-

Table 3
Patency and stenosis in MIDCAB surgery

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Inc (%)</th>
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<tr>
<td>( (a) ) By invasive/non invasive ((3304 \text{ patients}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occlusion early</td>
<td>86/2208</td>
<td>3.9</td>
</tr>
<tr>
<td>Stenosis early</td>
<td>17/1698</td>
<td>6.9</td>
</tr>
<tr>
<td>Total anastomotic problems</td>
<td>137/1343</td>
<td>10.2</td>
</tr>
</tbody>
</table>

| \( (b) \) By angiography \((1727 \text{ patients})\) |         |         |
| Occlusion early   | 50/1281 | 3.9     |
| Stenosis early    | 64/977  | 6.6     |
| Total anastomotic problems | 114/1281 | 10.5 |

Table 4
Patency and stenosis

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (a) ) In off-pump sternotomy surgery by invasive/non-invasive techniques ((3060 \text{ patients}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occlusion early</td>
<td>21/436</td>
<td>4.9</td>
</tr>
<tr>
<td>Stenosis early</td>
<td>4/239</td>
<td>1.6</td>
</tr>
<tr>
<td>Total anastomotic problems</td>
<td>13/239</td>
<td>5.4</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>( (b) ) In MIDCAB compared to off-pump sternotomy surgery by angiography | OP (%)</th>
<th>MID (%)</th>
<th>( P )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusion early</td>
<td>4.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Stenosis early</td>
<td>1.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Total anastomotic problems</td>
<td>6.4</td>
<td>10.5</td>
</tr>
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</table>
duction of stabilisers [44,70,74] have shown a real and important improvement in results. Some of these reports did show a rather high incidence of failures (16%), so the resulting change was highly significant. Not all reports of MIDCAB done without stabilisation were bad, however overall the results were sufficient to support the view that stabilisation is a critically important step in beating heart surgery. Indeed the evidence strongly supports the view that stabilisers should always be used in MIDCAB surgery and additionally and logically that stabilisers should also always be used in off-pump sternotomy beating heart surgery. LAD occlusion rates with stabilisation (3.6%) compare favourably to those recorded by conventional surgery (4.9%) [89]. The fate of the LIMA graft is as likely to be affected by the same features as a conventional LIMA graft, that is inflammatory reaction, string sign, mal-placement, unrecognised harvest damage and competitive flow as well as any question of technical anastomotic accuracy. With a stabili-
either side of the anastomosis. These lessons should be carried forward into all applications of coronary artery grafting and into future developments. Angiography has acquired the gold standard of vessel analysis following surgery.

It is uncertain in such a large series how accurate each of the recorded results is, in particular no definition was set for myocardial infarction — that merely being volunteered by the reporting group. It is possible that less attention was paid to recording infarction in the sternotomy group because of its more standard appearance and this could explain the apparent lower incidence of myocardial infarction with sternotomy off-pump than in MIDCAB.

The poorer performance of the RIMA to the right may be explained by the different characteristics of the right coronary artery, its position for anastomosis and the higher poor target vessel finding. The meta-analysis did not show any differences between the two groups in respect to the length of stay, which was short at 4.5 days, suggesting earlier mobilisation, however, the role of observer bias in this specialised group cannot be ignored. The incidence of atrial fibrillation was small (9%) compared to often quoted figures (i.e. 15–30%) and this may reflect a lesser exposure or irritation of the atrium or pericardium in the MIDCAB group.

5. Conclusion

The techniques currently employed in beating heart surgery have been described.

A meta-analysis of MIDCAB and sternotomy off-pump surgery shows a higher early stenosis and total anastomotic problem rate with MIDCAB than sternotomy off-pump but this rate is equalised after the introduction of stabilisers. Stabilisers are essential tools in MIDCAB and beating heart surgery. There was an unexplained low and lower rate of myocardial infarction in sternotomy off-pump compared to MIDCAB. The overall success of both MIDCAB and sternotomy off-pump surgery with stabilisers encourages the further use of these minimally invasive approaches.

References


Mishra YK, Mehta Y, Juneja R, Kaswliwal R, Mittal S, Trehan N.


