A three-dimensional echocardiographic comparison of a deep pericardial stitch versus an apical suction device for heart positioning during beating heart surgery

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Abstract

Background: Heart positioning during beating heart surgery produces significant haemodynamic compromise either when a deep pericardial stitch (DPS) or apical suction devices (ApSDs) are used. In this study the two techniques’ haemodynamic performance and effect on intracardiac structures were compared through transoesophageal echocardiography (TEE) obtained volume measurements and three-dimensional ventricular and mitral valve computer reconstructions.

Methods: Sequential 0° to 180° TEE images of the left heart were obtained in 10 patients undergoing beating heart surgery. Measurements with both techniques in three different positions were obtained: at baseline, the heart elevated to access its inferior surface and the heart elevated and rotated to access its lateral surface. Three-dimensional computer reconstructions of the mitral valve and the left heart were generated. Ventricular volume measurements were used to calculate stroke volume, ejection fraction and differences from baseline. An analysis of variance between each technique in all three positions was performed.

Results: Central venous, left atrial and pulmonary artery pressures were significantly increased with either technique during positioning. Both techniques significantly affected left ventricular function decreasing stroke volume and ejection fraction. In the vertical and rotated position, the ApSD produced a significant decrease from baseline both in stroke volume (DPS: 32.8% ± 18.7 vs ApSD: 55.46% ± 21.7; p = 0.02) and in ejection fraction (DPS: 19.3% ± 10.5 vs ApSD: 40.9% ± 24.6; p = 0.02). The three-dimensional reconstructions demonstrated significant distortion of the atrioventricular geometry and the mitral valve, which was more pronounced with the DPS.

Conclusion: Both techniques produce variable degrees of deformation with associated cardiac dysfunction and haemodynamic instability. Cardiac function is impeded more with an ApSD with the heart elevated and rotated.

Keywords: Beating heart surgery; Three-dimensional echo; Deep pericardial stitch; Apical suction device

1. Introduction

The performance of beating heart surgery involves extensive manipulation of the heart, which may cause transient distortion of intracardiac structures and haemodynamic instability, particularly during coronary artery grafting of the posterior and lateral cardiac surfaces. In an effort to maintain haemodynamic stability, various methods of exposure have been utilised with variable efficacy. A simple, low-cost but quite efficacious method of using a single deep pericardial retraction (DPS) suture was initially described by Bergsland et al. and by Ricci et al. [1,2]. Recently, apical suction devices (ApSDs), which position the heart so as to facilitate coronary artery exposure by applying suction on the apex of the heart, have also become commercially available. However, there is a considerable cost disparity (DPS < USD $5/patient vs ApSD = USD $650/patient) associated with each technique. Furthermore, Sepic et al., utilising an animal model, demonstrated significant differences in haemodynamic parameters between the DPS and ApSD techniques [3]. Similarly, Chang et al. demonstrated that both techniques significantly affected cardiac function during the grafting of the circumflex coronary system on a beating heart, but haemodynamic function was better preserved when an ApSD was used for positioning [4]. Therefore, we hypothesised that the two techniques must produce markedly different effects on left ventricular (LV) function.
shape, volume and filling ability as well as in mitral valve morphology, which consequently directly affects each technique’s haemodynamic performance.

The ability of transoesophageal echocardiography (TEE) to demonstrate mitral valve annulus distortion during the positioning of the heart in off-pump surgery has previously been well established [5]. Furthermore, recent developments in software technology have enabled the reconstruction of the LV and the quantification of LV volumes as well as the mapping of the mitral valve during manipulation. This novel methodology allows for more specific and accurate comparisons of cardiac function, which is not always possible when using only traditional haemodynamic measurements.

Therefore, this study’s primary aim was to utilise three-dimensional computer reconstructions of the heart and associated LV volume measurement to investigate potential performance differences between the DPS and the ApSD techniques. Secondarily we tried to qualitatively depict the shape and distortion of the mitral valve produced with each technique during heart manipulation in an effort to ascertain the mechanical causes of the haemodynamic dysfunction during beating heart surgery.

2. Material and methods

After receiving approval from our institution’s investigational review board (IRB), 10 patients undergoing triple vessel coronary revascularisation without the use of cardiopulmonary bypass were prospectively studied. All patients provided written informed consent prior to study enrolment. None had any evidence of cardiac arrhythmias, significant ventricular dysfunction or valvular abnormalities. The same surgical team performed all procedures and similar surgical techniques were used.

2.1. Anaesthetic and surgical technique

Anaesthesia was induced with propofol (1–2 mg/kg), pancuronium (0.1 mg/kg) and fentanyl (8–15 μg/kg) and was maintained by air plus oxygen and propofol (2–3 mg/kg/h). Routine monitoring was applied, consisting of five lead electrocardiograph, pressure and blood gas monitoring through a radial artery cannula, measurement of pulmonary artery pressure through a Swan-Ganz catheter, capillary pulse oximetry, capnography for end-tidal carbon dioxide levels, nasopharyngeal temperature monitoring and urine output measurement. During cardiac manipulation the mean arterial pressure was maintained above 50 mmHg through repositioning of the heart, volume loading and placing the patient in the Trendelenburg position. Normothermia was maintained through warm intravenous fluids, warm humidified air, a heating mattress and an adequate room temperature.

A standard midline sternotomy incision was used to expose the heart. Either or both of the internal thoracic arteries were harvested as a wide pedicle including the artery, vein, muscle, fascia and adipose tissue and sprayed with diluted papaverine solution (50 mg/20 ml normal saline). Subsequently, the pericardium was opened using an inverted T-shaped incision. To increase exposure and minimise haemodynamic compromise, the right pleural space was opened to create space for positioning the heart.

To perform the DPS technique a single suture was placed in the oblique sinus of the posterior pericardium below the left atrium, halfway between the level of the left inferior pulmonary vein and the inferior vena cava. A snare was placed and the suture was then used as a lever to displace the heart.

Anticoagulation was achieved with heparin (150 U/kg), which was periodically supplemented so as to maintain the activated clotting time above 250 s. Protamine was used to reverse the heparin at the end of the procedure.

2.2. Data acquisition technique

A 5 MHz multi-plane transoesophageal echocardiography probe connected to a Phillips Sonos 5500 echocardiography machine was used for all measurements and image acquisitions. Ensuring a still probe, the scan was electrically rotated through 180° with images obtained every 10° and stored on a magneto-optical disk for offline analysis. Images were centred on the mitral valve and included the left heart endocardial borders. Artefact, due to movement of the probe, was detected by comparing the 0° and 180° views, discarding sequences where this was not an equivalent mirror image. The Philips three-dimensional acquisition software, with ECG and respiration gating, was used in all three-dimensional sequences.

Subsequent to cardiac exposure and before initialising grafting, three-dimensional sequences were collected in three different positions.

The first one was a baseline measurement taken at a neutral position (position 1) prior to any manipulation.

After successful revascularisation of the left anterior descending artery (LAD), the heart was lifted to the vertical to allow access to its posterior surface. A second set of measurements at this vertical position (position 2) was then taken. Initially the heart was brought forward with the use of a DPS and the first part of the measurements in this position was taken. After a return to baseline for a period of 10 min the heart was brought anteriorly again and held using the Starfish II™ (Medtronic, Minneapolis, USA) suction device (ApSD), placed at the cardiac apex (Fig. 1A and C). The second part of the measurements was subsequently taken. Revascularisation of the inferior wall vessels was then performed. The Octopus 3™ stabiliser (Medtronic, Minneapolis, USA) was utilised in all patients for graft site stabilisation.

Finally the heart was elevated vertically and rotated to allow access to its lateral surface. A third set of images and measurements with each technique was obtained at this position (position 3) (Fig. 1B and D). All measurements were obtained after a 3-min period of stability in the new position. The sequence of image acquisition was dictated by surgical technique.

Associated haemodynamic data were also collected by a blinded to the surgical positioning technique investigator. Each series of acquisition took approximately 3–5 min to complete. Needing to keep to a minimum the period of haemodynamic instability caused by cardiac manipulation, a full TEE exam in each position with associated colour flow
Doppler measurements and mitral valve inflow velocity profiles was not performed.

2.3. 3D echo reconstruction technique

The 4D Cardioview software (Tomtec Imaging Systems, Unterschleissheim, Germany) was used to produce customised three-dimensional image reconstructions of the mitral valve and of the LV. A single investigator carried out all reconstructions. Employing the image sequence at end systole, the mitral valve was delineated in eight cross-sectional planes and subsequently reconstructed (Figs. 2, 3 and 5). Similarly the inner borders of the left atrium and the left ventricle were delineated and reconstructed (Figs. 3 and 4). Using the volume measurement function of the software, LV volume measurements were taken at end systole and at end diastole, and an ejection fraction and stroke volume were calculated (Fig. 3).

2.4. Power calculation and statistical analysis

The null hypothesis that the mean difference in stroke volume between the two techniques would be more than 5 ml was used to calculate a minimum sample needed to detect significant differences. The criterion for significance ($\alpha$) was set at 0.05. The test is two-tailed, which means that an effect in either direction will be interpreted. With the proposed sample size of 10 pairs of cases, the study will have power of exceeding 99.9% to yield a statistically significant result.

This computation assumes that the population from which the sample will be drawn has a mean difference of 10.0 with a standard deviation of 1.0. The observed value was tested against a theoretical value (constant) of 5.0. This effect was selected as the smallest effect that would be important to detect for clinical relevance. It is also assumed that this effect size is reasonable and could be anticipated in this
Fig. 4. 3D reconstructions of the left atrium and ventricle. Observe the notable folding along the atrioventricular junction in position 2 with either technique. When the ApSD is used there is more elongation and rigidity in position 2 with additional twisting in position 3.

setting. A second goal of this study was to estimate the mean difference in the population. On average, a study of this design would enable us to report the mean difference with a precision (95.0% confidence level) of ±0.69 points. For example, an observed mean difference of 10.0 would be reported with a 95.0% confidence interval of 9.31–10.69. Sample size calculations were performed using the power analysis function of SPSS 11.0 (SPSS Inc., Chicago, USA) statistical software.

Data are expressed as mean value ± standard deviation. Normal distribution was assessed using the one sample Kolmogorov–Smirnov test. All variables were normally distributed. To assess group variability between baseline and each technique for all the various positions, one-way analysis of variance (ANOVA) was performed. Where a statistically significant difference was demonstrated, a Bonferroni analysis was performed so as to deduce which mean values were different between them. The Bonferroni technique uses t-tests to perform pair-wise comparisons between group means, adjusting for multiple comparisons. To compare each technique’s performance (in the different positions), the mean differences from baseline were calculated and compared using Student’s t-test. All tests were two-sided and p-values of 0.05 or less were statistically significant.

3. Results

Intraoperative haemodynamic measurements at different positions are presented in Table 1. All patients maintained good ventricular function throughout and no inotropic support was required to maintain haemodynamic stability. Also, none of the patients needed conversion to cardiopulmonary bypass.

Central venous pressure was significantly increased both when the heart was vertical (baseline: 10.7 ± 0.9 vs DPS: 23.2 ± 3.6 vs ApSD: 21.4 ± 4.6; p < 0.01) and when the heart was vertical and rotated (baseline: 10.7 ± 0.9 vs DPS: 23.4 ± 8.7 vs ApSD: 22.0 ± 3.8; p < 0.01). The Bonferroni analysis demonstrated that the differences were between baseline and either technique. Left atrial pressure was also considerably increased with either technique in both positions.

The use of an ApSD significantly increased systolic pulmonary artery pressure when the heart was vertical and rotated (position 3) (baseline: 28.9 ± 2.7 vs ApSD: 38.4 ± 8.3; p = 0.03) but the use of a DPS did not (mean was not significantly different from baseline). Similarly, the use of an ApSD also increased diastolic pulmonary artery pressure in position 3 (baseline: 14.9 ± 2.5 vs ApSD: 24.0 ± 5.4; p < 0.01). Diastolic pulmonary artery pressure was also significantly different when the heart was in position 2 (baseline: 14.9 ± 2.5 vs DPS: 21.6 ± 5.9 vs ApSD: 23.8 ± 8.0; p < 0.01) but the Bonferroni comparisons showed that the difference was between baseline and either technique and not between techniques.

When the heart was in the vertical position (position 2) a significant difference in the cardiac index between baseline and either technique (baseline: 2.7 ± 0.8 vs DPS: 1.9 ± 0.5 vs ApSD: 2.0 ± 0.5; p = 0.01) was demonstrated. The cardiac index was derived from a thermodilution-based continuous cardiac catheter with averaged values and therefore it does not necessarily correlate with structurally calculated cardiac output from the LV reconstructions.

Calculated values from the three-dimensional reconstructions are presented in Tables 2 and 3 according to position. The two techniques had significant effects on left ventricular function. There were no differences in filling and residual volumes at both positions, neither when an ApSD nor when a DPS was used.

With the heart in the vertical position (position 2), both techniques produced a significant decrease in stroke volume

<table>
<thead>
<tr>
<th></th>
<th>Position 1 (baseline)</th>
<th>Position 2 (heart vertical)</th>
<th>Position 3 (heart vertical and rotated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DPS</td>
<td>ApSD</td>
<td>p-value</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>68.0 ± 17.6</td>
<td>82.0 ± 14.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Systolic blood pressure (mmHg)</td>
<td>115.5 ± 5.8</td>
<td>104.6 ± 21.8</td>
<td>0.34</td>
</tr>
<tr>
<td>Diastolic blood pressure (mmHg)</td>
<td>57.1 ± 10.2</td>
<td>65.2 ± 10.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Central venous pressure (cm H2O)</td>
<td>10.7 ± 0.9</td>
<td>23.2 ± 3.6</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Left atrial pressure (cm H2O)</td>
<td>12.1 ± 2.7</td>
<td>20.8 ± 7.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Mixed venous oxygen saturation (%)</td>
<td>78.1 ± 7.0</td>
<td>72.3 ± 8.3</td>
<td>0.08</td>
</tr>
<tr>
<td>Systolic pulmonary artery pressure (mmHg)</td>
<td>28.9 ± 2.7</td>
<td>32.9 ± 9.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Diastolic pulmonary artery pressure (mmHg)</td>
<td>14.9 ± 2.5</td>
<td>21.6 ± 5.9</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cardiac index (l/min/kg)</td>
<td>2.7 ± 0.8</td>
<td>1.9 ± 0.5</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SD. One-way ANOVA testing was used for all comparisons.
position 2 with both the ApSD and the DPS (baseline: 69.5 ± 13.1; p < 0.01) compared to the baseline value. The change from baseline, however, was not statistically significant when the two techniques were compared. In addition the ejection fraction was significantly reduced in position 2 when the two techniques were compared. In position 3, with the heart vertical and rotated, stroke volume was significantly decreased when an ApSD was used (baseline: 69.5 ± 13.1; vs DPS: 46.0 ± 23.6 vs ApSD: 32.0 ± 38.9; p = 0.01). The Student’s t-test demonstrated a more significant reduction with ApSD use, when the changes from baseline were compared (DPS: 32.8 ± 18.7 vs ApSD: 55.46 ± 21.7; p = 0.02).

Ejection fraction was also significantly different when the heart was in position 3 (baseline: 59.1 ± 4.5 vs DPS: 41.6 ± 12.4 vs ApSD: 21.8 ± 18.6; p < 0.01) and the Bonferroni analysis demonstrated that the difference was between baseline and each technique as well as between techniques. When the techniques were compared with regards to the difference from baseline, the ApSD was associated with a higher reduction in ejection volume compared to the DPS technique (DPS: 19.3 ± 10.5 vs ApSD: 40.9 ± 24.6; p = 0.02).

Qualitatively assessing the atrial and ventricular volumetric reconstructions demonstrated various degrees of deformation along the atrioventricular junction with both techniques. However, the use of the apical suction device appears to produce elongation of the heart in the vertical (position 2) with additional twisting when the heart is vertical and rotated (position 3) (Fig. 4).

Similarly, qualitatively comparing the reconstructed images of the mitral valve in end systole demonstrates a loss of the normal valve’s saddle shape with the formation of a distinct fold when the heart is vertical (position 2) and an additional fold when the heart is in the vertical and rotated position (position 3). Both distortions are less severe when an ApSD is utilised to position the heart (Fig. 5).

4. Discussion

This study quantifies the volumetric changes within the left ventricle and graphically demonstrates both the distortions in left heart geometry and in the mitral valve during positioning for beating heart surgery. Two techniques of exposing the posterior and lateral walls to allow access for grafting were compared: one utilising a simple low cost single pericardial stitch while the other used one of the recently available apical suction devices. It established that during positioning, haemodynamic function is impaired through two distinct mechanisms depending on the technique utilised. The use of an ApSD alters the left ventricle’s ability to

Fig. 5. 3D representation of the mitral valve, with the anterior leaflet furthest away. Note the saddle shape of the normal mitral valve. Notice the folding of the leaflets in position 2 when a DPS is used, which increases in extent in position 3. Distortion is less severe with the ApSD.
adequately eject blood by impeding longitudinal contraction and the movement of the mitral ring towards the apex while the DPS produces more of a direct compression and volume reduction effect. The detrimental effect was more pronounced when the heart was elevated and rotated using an ApSD.

A number of previous studies have demonstrated that significant cardiac dysfunction is produced when the heart is positioned to expose its inferior and lateral surfaces during beating heart surgery; and have compared various techniques of manipulation attempting to establish an optimal method [3,4,6,7]. However, all studies conducted so far have utilised conventional intraoperative haemodynamic measurements of cardiac function obtained through radial artery and Swan-Ganz pulmonary artery catheters. These methods of assessing haemodynamic function are limited both in their reliability and in their ability to demonstrate the effect on intracardiac structures. In contrast, we utilised ultrasonographic measurements and three-dimensional ventricular reconstructions to compare the effect of the DPS and the ApSD techniques both in cardiac structure and in function. Volume measurements from three-dimensional imaging have previously been validated by a number of researchers and this technique allows for a more precise and accurate evaluation of haemodynamic performance [8—13]. This approach has not previously been applied to compare cardiac performance during beating heart surgery.

Based on intraoperative haemodynamic measurements both techniques produced significant increases in central venous and in atrial pressures. This is not an unexpected finding as the displacement of the heart from its anatomical position causes the atria to become located below the corresponding ventricles and thus the blood must now flow upwards into the ventricular cavities [14]. Thus atrial filling pressures become increased to a greater extent than the corresponding ventricular end diastolic pressures and atrial size can often increase by up to 50% [14]. In addition, anaesthetic management routinely administers high volume of fluid to maintain preload during cardiac manipulation. However, the use of an ApSD to elevate and rotate the heart (position 3) also significantly increased both systolic and diastolic pulmonary artery pressures which also seems to indicate an effect on left ventricular filling and emptying.

When the heart was elevated (position 2) so as to graft the posterior descending artery, both techniques produced equally significant haemodynamic instability adversely, reducing both stroke volume and ejection fraction. The three-dimensional reconstructions demonstrated considerable angulation and distortion at the left atrioventricular junction, which we believe reduces left ventricular compliance and contractility and is mainly responsible for the haemodynamic dysfunction. Similarly, when the heart is vertical and rotated (position 3) so as to graft branches of the circumflex artery, stroke volume and ejection fraction were adversely reduced with both techniques. The left ventricle reconstructions in this position show not only significant angulation at the atrioventricular junction but also additional rotation and twisting, which further reduce contractility and cardiac function. This effect was more pronounced with the use of the ApSD, which produced a significant decrease in stroke volume and in ejection fraction both compared to baseline and to the DPS technique. It is likely that due to its underlying pulling mechanism the ApSD impedes ventricular longitudinal contraction and the unrestricted movement of the mitral ring towards the apex [14]. This represents approximately a 15—20% reduction in ejection volume [14]. The additional twisting of the myocardium in position 3 exacerbates this effect because lateral wall contraction produces a wider radial displacement than the septal or posterior—inferior walls contributing more to overall stroke volume [14]. In contrast, the underlying mechanism of the DPS is more direct compression than pulling, and thus its effect on the ability of the ventricle to contract freely is not as pronounced.

Another possible mechanism for the observed reduction in stroke volume and ejection fraction during positioning is distortion of the mitral valve, which induces mitral regurgitation. Recent studies have demonstrated that manipulation of the heart during off-pump cardiac surgery results in deformation of the mitral annulus [5]. The mitral annulus has previously been described with three-dimensional reconstruction, by a number of different techniques including the use of radio-opaque markers, sonomicrometry array localisation, transformation of two-dimensional annular points and manual tracing and reconstruction [15—18]. However, these techniques are limited in their ability to demonstrate folding and distortion of the mitral valve. Applying a novel reconstruction technique from ultrasonographic images, three-dimensional models of the mitral valve, which more accurately portray the distortions experienced, were constructed.

Positioning of the heart modifies the geometry of the mitral valve in various ways. When the heart is manipulated to allow access to its inferior and lateral surfaces, variable degrees of folding of the mitral valve as illustrated in Fig. 5 are observed. When an ApSD is used the anterior mitral leaflet, which hangs off the cardiac skeleton between the left and right trigones, seems to be better preserved in all positions, with folding occurring across the posterior leaflet. On the contrary, more significant distortion is produced when a DPS is used with both mitral leaflets affected by multiple folds. In our series of patients in sinus rhythm and with normal ventricular function and enough reserve to cope with these changes, the haemodynamic consequences of this were reduced, but this may be more relevant if mitral valve disease is present.

In our study the use of a DPS produced a slightly more favourable outcome compared to the more sophisticated ApSD technique. In contrast to our findings, Sepic et al., utilising an animal model, demonstrated better haemodynamic function when an ApSD was used [3]. But the translation of these results to human physiology is difficult as the position of the heart differs between species; in the swine the long axis of the heart is longitudinal and parallel to the long axis of the body whereas in the human it is at approximately a 45° angle. Similarly, Chang et al. evaluated the two techniques during the grafting of the obtuse marginal branch on a beating heart, and demonstrated preserved haemodynamic function when an ApSD was used for positioning [4]. However, both of these studies relied exclusively on traditional intraoperative haemodynamic measurements, which are not always reliable and may...
contain significant variation. This study utilised a more sophisticated methodology of assessing cardiac function through TEE volume measurements and ventricle reconstruction. In addition, in both previous studies measurements were obtained from different sequential patients increasing the chance of inter-group variance, while in this study, measurements with both techniques were performed in all patients.

There are a number of limitations with this study. First, this study evaluated only two of the most widely utilised methods of exposure. A wide variability in practice exists among surgeons and various methods have been put forward as more efficacious. Utilising the described analytic method as a possible standard of evaluation alternative techniques should be assessed. Secondly, measurements and volumetric models were constructed only for the left ventricle and thus only the left heart’s function was assessed. This probably did not alter our results given that all our patients had good right ventricular function but might limit their applicability in the setting of global cardiac dysfunction. Thirdly, the study involved a relatively small number of patients but power calculations demonstrated that the sample was adequate for interpretation of the data. Finally, none of the patients had any degree of preoperative valve disease and therefore the effects of each technique might be different in high-risk patients with preoperative mitral regurgitation and impaired left ventricular function.

In summary, we have graphically described the shape of the mitral valve and of the left ventricle during beating heart surgery and have shown that the utilisation of either a deep pericardial stitch or of an apical suction device produces variable degrees of deformation with associated cardiac dysfunction and haemodynamic instability. The use of an apical suction device seems to impair cardiac function to a greater degree, particularly when the heart was elevated and rotated to access the circumflex system.

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References