Geometry assessment of coronary artery anastomoses with construction errors by epicardial ultrasound

Thomas C. Dessing, Ricardo P.J. Budde, Rudy Meijer, Patricia F.A. Bakker, Cornelius Borst, Paul F. Grundeman*

Heart Lung Center Utrecht, University Medical Center Utrecht, Utrecht, The Netherlands

Received 5 March 2004; accepted 5 May 2004; Available online 9 June 2004

Abstract

Objective: There is concern about the quality of the distal anastomosis in off-pump coronary artery bypass grafting. We investigated the impact of specific construction errors on anastomotic geometry using epicardial ultrasound. Methods: Twelve ex vivo pressure perfused porcine and five isolated post-mortem human hearts were used to construct 35 internal mammary artery to coronary artery anastomoses, either without (n = 7) or with a standardized construction error (oversutured toe, oversutured heel, cross-over or purse string; each error, n = 7). The anastomotic geometry was visualized and measured by a 13 MHz ultrasound mini-transducer. Impression cast material was used to validate anastomotic geometry. Results: All 28 errors were visualized properly. Two unintended construction abnormalities were observed. In the porcine heart, the ratio of anastomotic orifice area and outflow corner area was 1.3 ± 0.2 (mean ± standard deviation) in the control group and reduced in the error groups: oversutured toe, 0.6 ± 0.2 (P = 0.001); oversutured heel, 0.9 ± 0.2 (P = 0.037); cross-over, 0.4 ± 0.2 (P < 0.001); purse string, 0.3 ± 0.2 (P < 0.001). None of the errors reduced the area of the inflow or outflow corner itself compared to the recipient coronary artery. In the human heart, all construction errors as well as wall plaque were visualized properly. In all anastomoses, ultrasound geometry corresponded to cast geometry. Conclusions: Ex vivo, epicardial 13 MHz ultrasound enabled accurate visualization and assessment of four different construction errors in the coronary anastomosis. All errors reduced the area of the anastomotic orifice, but not the inflow or outflow corner.

Keywords: Anastomosis; CABG; Echocardiography; Stenosis; Ultrasound

1. Introduction

Concern has been raised about the quality of the distal anastomosis in off-pump and minimally invasive direct coronary artery bypass grafting (MIDCABG) [1]. Anastomotic suturing may be hampered by suboptimal conditions, such as limited access and working space, residual motion of the target area, poor angle of view and/or torrential backflow. Due to these surgical limitations, there is a risk of technical construction errors, which is indicated by the detection of an immediate angiographic stenosis in up to 9% of patients undergoing MIDCABG operations [1]. However, little is known about the alteration of anastomotic geometry by specific construction errors [2,3].

In the 1980s, the potential value of epicardial ultrasound for the quantitative assessment of coronary artery luminal and wall dimensions has been demonstrated [4], as well as for coronary anastomosis visualization [5]. Recently, IVUS also showed to be a promising method to determine anastomosis dimensions [6]. With modern improvements in transducer size and technology [7,8], epicardial ultrasound may prove a helpful tool to assess the impact of construction errors on anastomotic geometry.

In pressure perfused porcine and human hearts, we investigated the epicardial ultrasound 2D presentation and geometry alteration of specific construction errors in coronary artery anastomoses. The constructed errors consisted of an oversutured toe, an oversutured heel, a cross-over and a purse string.
2. Materials and methods

2.1. Perfusion model-setup

On 12 ex vivo porcine hearts 25 internal mammary artery (IMA) to left anterior descending coronary artery (LAD) anastomoses were constructed and on 5 isolated post-mortem human hearts common target coronary arteries were used to construct 10 anastomoses. All conduits used for grafting were porcine IMA’s.

After construction, the IMA was cannulated to pressure perfuse (95 ± 9 mmHg) the anastomosis with saline using a Langendorff setup. The LAD proximal to the anastomosis was snared.

2.2. Surgical procedure

All anastomoses were constructed end-to-side under an operating microscope (magnification £8, wild M680, Leica AG, Heerburg, Switzerland), using a running suture technique with a prolene 7–0 or 8–0 suture. The anastomoses were constructed with the intent either to be fully patent or to contain one of the following standardized construction errors; an oversutured toe, an oversutured heel, a cross-over or a purse string. In the porcine hearts, five of each anastomosis type were constructed, and in the post-mortem human hearts, two of each type were constructed.

The oversutured toe, oversutured heel and cross-over anastomoses were made by interlocking two suture bites on opposite sides of the arteriotomy in the toe area, the heel area or at the side, respectively. The purse string anastomosis was made by pulling heavily on the suture-ends before fashioning the suture.

2.3. Ultrasound equipment

As before [7], a commercially available, high frequency (up to 13 MHz in B-Mode), linear array mini-transducer (UST-5531, Aloka, Tokyo, Japan) with an image width of 10 mm (transducer dimensions: 15 × 6 × 9 mm) was used. The transducer was placed in a gel filled probe cover (Ultracover, International Medical Products, Inc., Zutphen, The Netherlands), for clear visualization of the anterior wall of the vessels. Measurements accurate to 0.1 mm were performed using the electronic calipers of the ultrasound system. In the anastomosis (Fig. 1), the size of the anastomotic orifice (1), internal diameters of the coronary artery at the toe site (3), heel site (5) and midways toe/heel site (7) were measured in both planes perpendicular to each other. The internal vessel area (A1, A3, A5, and A7) at these sections was calculated using the ellipsoid area formula \( \pi r^2 \). The areas of the IMA (A2) and the coronary artery maximally 3 mm distal to the anastomosis (A4) and maximally 3 mm proximal to the anastomosis (A6) were calculated with the circle area formula \( \pi r^2 \) using the internal diameter measured in the longitudinal image (Fig. 1). The area ratios \( A_i/A_2 \), \( A_i/(A_2 \times A_4) \), and \( A_i/(A_2 \times A_6) \) were calculated to assess whether the specific construction error induced anastomotic orifice narrowing compared to IMA and target artery dimensions. The ratios \( A_i/A_4 \), \( A_i/A_6 \) and \( A_i/\text{mean } A_2 \) were calculated to assess the impact on the outflow corner, inflow corner and the posterior wall of the coronary artery, respectively.

In the post-mortem human hearts, optimal images were obtained in both planes to visualize the geometry of the anastomosis.

2.5. Statistical analysis

Statistical analysis was only done in the porcine group. Data are presented as mean ± standard deviation (SD). One-way analysis of variance together with a post hoc comparison (Dunnnett) was used to evaluate differences in the specific area ratios between the four construction error groups (oversutured toe, oversutured heel, cross-over and purse string) and the control group. Area \( A_1 \) was normalized to the arteriotomy length, area \( A_2 \) to the IMA diameter using a ruler. All anastomoses were scanned by the same investigator (TCD) who was aware of which type of anastomosis was scanned.

In the porcine heart, the anastomosis was first delineated in longitudinal and transverse planes using B-mode imaging. Subsequently, an optimal longitudinal image (defined as anastomotic orifice and in- and outflow corner captured in one image) and transverse images in B-mode were obtained. In frozen images of the anastomosis site, measurements were performed with the electronic calipers of the ultrasound system. In the anastomosis (Fig. 1), the specific area ratios between the four construction error types were calculated to assess whether the specific construction error induced anastomotic orifice narrowing compared to IMA and target artery dimensions. The ratios \( A_i/(A_2 \times A_4) \), \( A_i/(A_2 \times A_6) \) and \( A_i/\text{mean } A_2 \) were calculated to assess the impact on the outflow corner, inflow corner and the posterior wall of the coronary artery, respectively.

In the post-mortem human hearts, optimal images were obtained in both planes to visualize the geometry of the anastomosis.

2.4. Scanning technique and measurements

Before anastomosis construction, the external diameter of the unpressurized coronary artery, the IMA and the length of the arteriotomy were measured (accurate to 0.1 mm)
and areas $A_3$ and $A_4$ to the LAD diameter before statistical comparison of the area ratios $A_i/A_2$, $A_i/A_3$ and $A_i/A_2$ was made between the different error groups and the control group. A value of $P < 0.0125$ was considered statistically significant.

2.6. Validation

A polyvinylsiloxane impression material (Kerr Co, Romulus, MI, USA) was injected into the anastomosis and coronary artery through the IMA. After the hardening process, the impression material was removed from the vessels and the obtained 3D cast of the anastomosis was used to validate ultrasound anastomotic geometry qualitatively.

3. Results

3.1. Porcine hearts

External recipient vessel diameters are listed in Table 1. All anastomoses were easily visualized in both longitudinal and transverse planes. The four different construction errors presented each with a characteristic alteration of anastomotic geometry. The oversutured toe and heel were seen longitudinally as ridges reducing the length of the anastomotic orifice by $26 \pm 7\%$ (mean $\pm$ SD) and $14 \pm 10\%$, respectively (Fig. 2). The cross-over presented longitudinally as a bright echo from the suture in the middle of the anastomotic orifice resulting in two small orifices and a longitudinal diameter reduction of $22 \pm 12\%$ (Fig. 2). The purse string anastomosis showed a reduced anastomotic orifice in both scan planes (Fig. 2). In cross-section, all constructed errors showed a reduced width of the anastomotic orifice.

The area ratios $A_3/A_4$, $A_3/A_6$, and $A_4$/mean $A_3$ for the four different groups are presented in Table 1. No statistically significant differences were observed between the ratios $A_3/A_4$ and $A_3/A_6$ of the different error groups and the control group. Thus, the specific construction errors had no effect on the in- or outflow corner of the anastomoses. After normalization of areas $A_1$, $A_2$, $A_3$ and $A_4$, the area ratios $A_i/A_3$ and $A_i/A_4$ of all error groups, but for the oversutured heel, were significantly smaller than in the control group (Table 2). In each of the four constructed errors the area of the anastomotic orifice was significantly reduced relative to the graft cross-sectional area (ratio $A_i/A_2$, Table 2).

One control anastomosis showed a minor technical abnormality. A small ridge (0.7 mm) at the toe site was visible, due to an extra stitch placed at the toe area.

At the anastomotic site, small septal perforators with diameters ranging from 0.2 to 0.7 mm were easily spotted. In all anastomoses, ultrasound geometry corresponded qualitatively with cast geometry findings, including the location of septal perforators and side-branches.

3.2. Post-mortem human hearts

External recipient coronary artery diameter ranged from 1.5 to 2.5 mm (median 2.0 mm).

In one control anastomosis, the complete outline of the anastomotic site could not be visualized due to the presence of abundant plaque with severe calcification. All constructed errors were properly visualized in longitudinal and transverse images. One oversutured toe anastomosis showed an adventitial flap waving up and down in the anastomotic orifice closing it off almost completely. This was confirmed by the cast. Presence and extent of coronary pathology was well visualized and quantifiable. In all anastomoses, ultrasound geometry corresponded qualitatively with cast geometry.

4. Discussion

The principal results of this study are: (1) In the porcine hearts, all four standardized anastomosis construction errors presented with a significant reduction in anastomotic orifice area; (2) In the ex vivo porcine heart, all 25 anastomoses were visualized properly, including the anatomy of the LAD at the anastomosis site; (3) In the post-mortem human heart, all 10 but one (due to calcification) anastomoses were

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements (mm) and area ratios for the control group and the four different construction errors in the porcine hearts</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>External LAD diameter</td>
</tr>
<tr>
<td>External IMA diameter</td>
</tr>
<tr>
<td>Arteriotomy length</td>
</tr>
<tr>
<td>$A_3/A_4$</td>
</tr>
<tr>
<td>$A_3/A_6$</td>
</tr>
<tr>
<td>$A_4$/mean $A_3$, $A_5$</td>
</tr>
</tbody>
</table>

Areas $A_i$ to $A_7$, see Fig. 1. Values presented as mean $\pm$ SD. No statistically significant difference was observed between $A_3/A_4$ and $A_3/A_6$ of the different error groups and the control group. $A_1$, LAD area at toe site; $A_2$, LAD area 3 mm distal to toe site; $A_3$, LAD area at heel site; $A_4$, LAD area 3 mm proximal to heel site; $A_5$, LAD area midway heel/toe site; IMA, internal mammary artery; LAD, left anterior descending coronary artery.
visualized properly, including the complete outline of the anastomosis site and presence of plaque.

The four constructed errors did not influence the in- or outflow corner area ratios of the anastomoses (Table 1), in contrast to the anastomotic orifice ($A_1$) area ratios which were significantly reduced for all the error groups except the oversutured heel (Table 2).

The 13 MHz resolution of the mini-transducer proved sufficient to visualize the complete outline and characteristics (septal perforators, coronary pathology) of

Table 2

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Control</th>
<th>Oversutured toe</th>
<th>P-value</th>
<th>Oversutured heel</th>
<th>P-value</th>
<th>Cross-over</th>
<th>P-value</th>
<th>Purse string</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_2/A_1$</td>
<td>1.1 ± 0.2</td>
<td>0.5 ± 0.3</td>
<td>&lt;0.001</td>
<td>0.6 ± 0.1</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>0.3 ± 0.2</td>
<td>0.037</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$A_3/A_1$</td>
<td>1.3 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.001</td>
<td>0.9 ± 0.2</td>
<td>0.037</td>
<td>&lt;0.001</td>
<td>0.3 ± 0.2</td>
<td>0.037</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$A_4/A_1$</td>
<td>1.5 ± 0.4</td>
<td>0.7 ± 0.3</td>
<td>0.002</td>
<td>1.0 ± 0.2</td>
<td>0.036</td>
<td>&lt;0.001</td>
<td>0.3 ± 0.2</td>
<td>0.037</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Areas $A_1$ to $A_4$, see Fig. 1. Values presented as mean ± SD. $A_1$, anastomotic orifice area; $A_2$, IMA area; $A_3$, LAD area at toe site; $A_4$, LAD area 3 mm distal to toe site; IMA, internal mammary artery; LAD, left anterior descending coronary artery.
the anastomotic site. Based on measurements made with the electronic calipers of the ultrasound system, calculations could be made to assess the impact of the specific construction error on anastomotic geometry.

Apart from the intentional construction errors, two unintended technical abnormalities (ridge due to extra stitch and adventitial flap) were revealed. Both unintended errors mimic clinical practice too. Thus, 13 MHz epicardial ultrasound may be a valuable diagnostic tool to assess anastomotic quality prior to chest closure. The small size of the present mini-transducer allows its application in between the suction pods of a cardiac stabilizer [7,10].

Besides the use for anastomotic geometry assessment [5,8,9], epicardial ultrasound may help to localize the target artery and choose the anastomotic site based on the evaluation of its wall thickness, plaque morphology (calcifications) and lumen diameter [4,5,10]. We expect high-frequency epicardial ultrasound to become a useful intra-operative diagnostic modality that is a non-invasive, fast, simple, and relatively inexpensive method in both on- and off-pump coronary artery bypass surgery. Angiography, currently considered the gold standard, is invasive, time consuming, expensive and not always immediately available in the operating room [1]. An additional disadvantage is the uncertain significance of early abnormal findings, which could lead to unnecessary revisions. Quantitative analysis of the angiogram is possible, but time consuming and displays far less anatomical detail of the anastomosis. Epicardial ultrasound in contrast, clearly displays the anatomy and dimensions of the anastomosis and therefore can differentiate for example between gross anastomotic construction errors, adventitial flaps and thrombus or spasm, which resolves after the immediate post-operative period.

Another widely used non-invasive method to assess bypass graft function is transit time flowmetry. However, flowmetry provides no anatomical information of the anastomosis. The observed flow depends on other factors as well. A crucial limitation is that flowmetry will only detect a severely stenosed anastomosis (>75%) [11].

Next to flowmetry, ultrasound can easily be employed as a complementary quality control method to provide information about bypass graft function and anastomotic geometry, respectively. For example, epicardial ultrasound may detect an adventitial flap in the anastomotic orifice in the presence of a normal flow recording. Flowmetry, on the other hand, may detect reduced volume flow in the presence of a flawless anastomosis, indicating either a proximal anastomosis problem, graft kinking, graft spasm, or reduced distal runoff.

The limitation of this study is its laboratory setting, with pressure perfusion by saline of the bypass graft. In addition, the merits and limitations of the present transducer for detection of anastomosis construction errors in the clinical setting and in an observer blinded experimental setting remain to be established.

In conclusion, ex vivo, epicardial 13 MHz ultrasound was successful in accurately visualizing and assessing the geometry of four different construction errors in the distal coronary anastomosis. All errors reduced the anastomotic orifice area.

Acknowledgements

The authors acknowledge the technical contributions of Merel Schurink and Cees Verlaan, and the statistical advice of M. Schipper, PhD.

References