Fragment Reconstruction of Coronary Arteries by Transesophageal Echocardiography
A Method for Visualizing Coronary Arteries With Ultrasound

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Background—If transesophageal echocardiography (TEE) is to play a role in coronary diagnostics, satisfactory image documentation of the coronary status is indispensable so that the requirements for validity and quality assurance of a medical examination can be met. Our goal was to develop a suitable and valid procedure for imaging coronary arteries with 2D TEE.

Methods and Results—After pilot trials and formulation of requirements, a new method of imaging coronary arteries was designed, supported by theoretical and mathematical principles: FRC-TEE, or fragment reconstruction of coronary arteries by means of 2D TEE. The method generates images of successive vessel fragments so that reconstruction in a summation picture is possible. The procedure orients itself to the vessel and ensures proof of identity by permanently following it on the screen. FRC-TEE was evaluated in 12 consecutive patients with an indication for TEE. One hundred percent visualization in proximal, middle, and distal segments was achieved. The total lengths visualized were $10.74 \pm 2.56$ cm for the right and $8.67 \pm 1.12$ cm for the left coronary artery. Stents and stenoses within the vessels were identified convincingly. Because of a technical problem, investigation of the left anterior descending artery was initially avoided. In a pilot trial series (n=12), $6.65 \pm 0.92$ cm of this vessel was imaged.

Conclusions—FRC-TEE is a newly developed method of visualizing coronary arteries by means of ultrasound, which permits good pictorial documentation. Initial studies have achieved promising results. Representation of the length of coronary arteries with ultrasound was considerably improved with this technique. (Circulation. 2002;105:1579-1584.)

Key Words: echocardiography • coronary disease • stents • stenosis • arteries

An angiography is the “gold standard” method for imaging coronary arteries. In recent years, however, new noninvasive methods such as electron beam tomography, magnetic resonance tomography, and ultrasound technology have become increasingly important.

The most suitable ultrasound procedure for imaging coronary arteries is 2D transesophageal echocardiography (TEE). This technique offers the best image quality because of the short distance between the transducer and the heart, together with favorable anatomy for ultrasound distribution. Because 3D representation relies on reconstructions from 2D cross sections, with inevitable interpolations, its resolution remains inferior to the 2D individual image. To date, the best published results for coronary representation have been achieved with TEE.5

If TEE is to play a role in the diagnosis of coronary disease, uncomplicated and reproducible image acquisition of the coronary status is essential. Validation of this method would also provide the necessary quality assurance of a medical imaging technique. Currently, no data have been published on this important topic. Our goal was to develop a suitable procedure for representing coronary arteries with 2D TEE that would improve on earlier results and fulfill the above requirements.

Methods

After pilot trials and determination of the necessary requirements, a method of representing the coronary arteries was developed, supported by theoretical and mathematical principles: FRC-TEE, or fragment reconstruction of coronary arteries by means of 2D TEE.

Theory for FRC-TEE

The representation of coronary arteries by means of 2D ultrasound is based on the sequential acquisition of images of fragments of the coronary circulation. When successive 2D cross sections of coronary artery fragments are assembled, a vessel can be visualized in a summation image. Successive fragments must be generated in such a way that the end of one fragment and the beginning piece of the next are identical (identity requirement). The permanent picture generated on the screen of this identical piece ensures that the fragment images stem from the same vessel. This furnishes structure proof (permanence requirement). The identical fragment piece should not change its position in the 2D section image during the permanent picture by any more than a small amount (position-true requirement).
Implementation
A point volume that fulfills the requirements for identity and permanence, despite a change in position of the section plane, is defined by the middle axis of the array when this is rotated. This volume is imaged in every conceivable picture that is produced by means of 180° rotation and guarantees the identity, permanence, and position-true requirements. The point volume "middle axis" is not just a straight line but, after the inclusion of elevation, a cylinder with a diameter the size of the elevation. Because this fluctuates with the image depth, the cylinder also has a fluctuating diameter. The requirement for true position of structures is fulfilled approximately in the cylinder because after rotation of the ultrasound array, it is viewed from another angle. The change in viewing angle corresponds to the rotation angle. During rotation of the array, the structures lying in the cylinder change position slightly. This is tolerable because the migration can be observed and the distance of the new position from the original can be, at maximum, the value of the elevation at this penetration depth. According to the findings of our group, a structure is imaged most clearly on ultrasound if it is at a depth (or at a slightly smaller depth) that corresponds to the selected focus. If the focus is set clearly behind the structures recognized as coronary arteries, then a greater elevation than in the focus can be assumed. To portray 2 coronary fragments where the distal end of the first fragment is identical to the proximal end of the second one solely by rotating the array, this common piece of fragment must be brought into the position of the central cylinder. Repositioning of the array is achieved by means of repositioning the probe.

Explanation of the Repositioning Procedure
ϕ is the angle that describes the position of the array relative to the 0° plane attained through electronic rotation. The 0° plane is perpendicular to the axis of the probe. ϕ can assume values from 0° to 180°. For repositioning, 3 cases must be differentiated:

1. If 0° < ϕ < 90°: rotation of the probe permits presentation of the coronary fragment in the center (Figure 1A). ϕ = 0°: The fragment end lies left or right of the middle axis of the array ⇒

Figure 1. A through C, Cases of probe repositioning in FRC-TEE. A, Rotation; B, advancement or withdrawal; C, combination of rotation and advancement or withdrawal. D through F, Graphics for data calculation for repositioning in FRC-TEE. D, Calculation of repositioning distance for 0° < ϕ < 90°; E, calculation of repositioning distance for 90° < ϕ < 180°. For D and E, E₀ is "inclined" exit plane in which fragment end lies; E₀ is assumed plane perpendicular to probe to which ϕ from E₀ is referred; B is end point of coronary fragment and is in both E₀ and F₀; F₀ corresponds to plane perpendicular to probe, which contains fragment end B after movement of probe; A and C are intersection points where perpendiculars drawn from B cross middle axes of F₀ and E₀; e is segment [BC] and corresponds to distance from B to middle axis of E₀; and y is distance that has to be calculated, or distance by which probe must be advanced or withdrawn. F, Calculation of rotation angle ϕ. x indicates distance of fragment end to middle axis of array; m is its distance from intersection point of middle axis with tip of array. L indicates left; R, right.
right or left rotation; \( \phi = 180^\circ \): the fragment end lies left or right of the middle axis of the array \( \Rightarrow \) left or right rotation.

2. If \( \phi = 90^\circ \): advancement or withdrawal of the probe allows imaging of the coronary fragment in the center (Figure 1B). The fragment end lies left or right of the middle axis of the array \( \Rightarrow \) advance or withdraw.

3. If \( 0^\circ < \phi < 90^\circ \): a combination of rotation and advancement or withdrawal of the probe allows imaging of the coronary fragment in the center (Figure 1C). \( 0^\circ < \phi < 90^\circ \): The fragment end lies left or right of the middle axis of the array \( \Rightarrow \) right rotation plus advancement or left rotation plus withdrawal; \( 90^\circ < \phi < 180^\circ \): the fragment end lies left or right of the middle axis of the array \( \Rightarrow \) left rotation plus advancement or right rotation plus withdrawal.

By trigonometry, approximate distances and angles can be calculated for all 3 cases of position change. To calculate case 3, the combination is divided into 2 single movements. First, the probe is advanced or withdrawn to an extent that the fragment end that has to be positioned in the central cylinder is visualized in a plane that is perpendicular to the probe. The perpendicular planes possible for \( \phi \) are 0° and 180° planes. In this perpendicular plane, the fragment end is brought into the central cylinder solely by rotating the probe under visual control. See Figures 1D and 1E for clarification of the distance calculation. The calculation is based on the sine theorem:

For any triangle:

\[
\frac{a}{\sin \alpha} = \frac{b}{\sin \beta} = \frac{c}{\sin \gamma}
\]

For right-angle triangle:

\[
\sin \alpha = \sin 90^\circ = 1
\Rightarrow
\frac{1}{\sin \beta} = \frac{a}{b}
\Rightarrow
b = \sin \beta \times a
\]

or generalized:

\[
\frac{\text{Side opposite}}{\text{Hypotenuse}} = \sin \beta
\]

In the above case, this means:

\( \beta \) = the angle between [BA] and [BC], given by \( \phi \) or \( 180^\circ - \phi \) (dependent on rotation to 0° or 180°; see below).

\( a = e \)

\( b = y \), the sought distance.

For exit plane \( E_y \), a distinction must be made between the following:

1. If \( 0^\circ < \phi < 90^\circ \): rotation to 0°; \( y = e \times \sin \phi \) (Figure 1D).

2. If \( 90^\circ < \phi < 180^\circ \): rotation to 180°; \( y = e \times \sin (180^\circ - \phi) \) (Figure 1E).

This distinction is necessary to see the new plane from the same side as the original, inclined plane. Rotation by \( > 90^\circ \) would visualize the fragment end as a mirror image on the other side of the middle axis.

The rotation angle around which the probe must be turned to image the fragment end in the central cylinder is also calculated by the sine theorem; here, both segments \( x \) and \( m \) are introduced. See Figure 1F for clarification of the angle calculation. Rotation angle \( \delta \) can be calculated from \( \sin \delta = x/m \).

In case 2, where the plane is parallel to the axis of the probe, the required distance to move is that from the fragment end to the middle axis of the array. For case 1, calculation of the rotation angle is identical to that in the second step of case 3, because the plane is also perpendicular to the axis of the probe. By repeating this method, which permits imaging of 2 successive coronary fragments through rotation of the array alone, a coronary artery can be completely imaged.

**Practical Application**

In a first practical application, the capabilities of FRC-TEE were evaluated. The study group comprised 12 patients (9 men, 3 women; body mass index range 22.6 to 33.1, 55 to 73 years of age) who were hospitalized in our clinic. All patients underwent clinically indicated angiography (5 patients with no coronary artery disease, 4 with 1-vessel disease, 2 with 2-vessel disease, and 1 with 3-vessel disease). TEE was clinically indicated in all subjects, with the investigation being extended for purposes of the study. Informed consent was obtained from all patients. The study was based on the rules of good clinical practice.

**FRC-TEE**

The examinations were performed with an HP Sonos 5500 with a multiplane probe (Omniplane II) in fundamental mode (standard system, commercially available at Philips Medical Systems). The probe consists of a 64-element phased array transducer that allows fusion imaging at 4 to 7 MHz and that has color, pulsed-wave, and continuous-wave Doppler capabilities. The transducer array, encased within the tip of the endoscope, can be rotated through a 180° arc. The standard conditions for a conventional TEE examination were met. The studies were performed in quiet conditions, with the patient in a comfortable position. Patients were requested to perform controlled, shallow breathing and avoid any movement. Both the examiner and assistant were blinded to the individual’s coronary status. The assistant provided instructions for the necessary movements of the probe in accordance with the procedure algorithm. The right coronary artery (RCA) and left circumflex artery (LCx) were then investigated (no designated order). The examination of left anterior descending artery (LAD) with FRC-TEE was not performed because of technical reasons (see Discussion).

**Fragment Reconstruction**

Only a rectangular format was allowed for the cutting. The side edges were given by making vertical cuts at the proximal and distal ends of the fragment. The height of the image was kept constant except in cases in which the preceding or subsequent image showed a part of the coronary tree better (eg, side branch). After they were processed, the images were assembled next to one another or slightly overlapping each other, with orientation by the vessel and its surrounding structures.

**Interpretation and Evaluation of the Data**

The results of FRC-TEE were checked by optical comparison against the results of angiography of a plausibility control. Lengths and diameter values of the reconstructed vessels were measured and the diameter values compared with those obtained by angiography. To determine the lengths, an assumed centerline between the 2 vessel walls was measured. The ostium served as the proximal point, and the point at which the curves of both vessel walls were still identifiable served as the distal measuring point. All measurements were performed from endothelium to endothelium. The diameter was measured within 3 cm of the ostium. Stents were checked for patency with both procedures. In the case of vessel stenoses, the prestenotic diameter and minimum diameter within the stenosis were measured. Each measurement was performed twice and the mean determined. The measurements were carried out with USIP software (Research Division, Klinikum Schwalmtadt).

**Data Analysis and Statistics**

To make comparisons with previous studies, the LCx and RCA were divided into proximal, middle, and distal segments, defined as the first 2.5 cm, between 2.6 and 5 cm, and >5 cm from the ostium of the artery, respectively. For each segment, the percentage representation was calculated. The absolute lengths and their means were measured. The diameters determined by FRC-TEE and angiography and the respective mean percent differences were calculated with the formula
TABLE 1. Lengths Visualized With FRC-TEE

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>LM</th>
<th>LCx</th>
<th>RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.56</td>
<td>6.55</td>
<td>13.16</td>
</tr>
<tr>
<td>2</td>
<td>1.27</td>
<td>8.23</td>
<td>13.84</td>
</tr>
<tr>
<td>3</td>
<td>1.61</td>
<td>7.24</td>
<td>11.75</td>
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<tr>
<td>4</td>
<td>2.28</td>
<td>8.60</td>
<td>9.78</td>
</tr>
<tr>
<td>5</td>
<td>2.09</td>
<td>6.14</td>
<td>10.08</td>
</tr>
<tr>
<td>6</td>
<td>0.21</td>
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<td>6.73</td>
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<td>8</td>
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<td>9</td>
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<td>8.89</td>
<td>15.21</td>
</tr>
<tr>
<td>12</td>
<td>1.84</td>
<td>7.19</td>
<td>8.60</td>
</tr>
</tbody>
</table>

Mean±SD (95% CI):
- TEE–Angiography:
  - LM: 1.41±0.59 (1.04–1.79)
  - LCx: 7.26±0.89 (6.69–7.82)
  - RCA: 10.74±2.56 (9.11–12.36)

All measurements were from the ostium and are in centimeters. Total (right and left [LM+LCx]) coronary artery (n=24): 9.35±1.98 (8.30–10.41) cm.

Results

All investigations with FRC-TEE were performed without complications and provided evaluable results. Examinations took on average 24 minutes (range 17 to 32 minutes), with the subsequent reconstruction requiring 24 minutes (range 17 to 32 minutes), with the FRC-TEE procedure that we have developed has several advantages over 2D coronary visualization. The continuous representation and generation of adjoining fragments ensures the identity of vessel fragments in partial images (“continuous” means at least once per heart cycle). The fact that the end of the previous image and the beginning point of the next image are identical permits juxtaposition of the images to a summation image. The number or the lengths of the fragments can be defined individually to obtain optimal image quality of the vessels. Because several images are available for each fragment in the image loops, each one can be exchanged or the image quality optimized by selection. Through reconstruction, the status of the vessel is documented in one image and can be evaluated reproducibly within a short time. The orientation on the vessel allows it to be followed independently of other structures.

FRC-TEE provides convincing results. With this new technique, the length of coronary arteries that can be imaged can be increased considerably compared with previous studies (Figures 2 and 3). Even though the present study had a relatively small number of cases (n=12), the significant difference from earlier studies is unlikely to be attributed to this alone. The division of vessels into proximal, middle, and distal segments or their length is dated, because 100% representation is possible in all segments. The shorter visualization of the left coronary artery (left main plus LCx) is caused in part by the vessel being shorter.

Visualization of the LAD raises a technical problem. In our pilot test series in which 12 patients underwent 1- or 2-image documentation, representation of the vessel could be extended to 6.65±0.92 cm, which was longer than earlier results. For visualization of the LAD, it is necessary to retroflex the probe considerably, which is in keeping with a previous finding by Tardif et al. The middle and distal vessel parts of the LAD (the portion beyond an imaginary line drawn from the apex of the heart to the pulmonary valve) run in a plane that declines relative to a horizontal plane from the proximal to the distal end. Imaging of this part requires increasing retroflexion, which results in an increasing coupling loss of the transducer head. Visualization becomes almost impossible, because at best, very short vessel pieces can be seen. Because of the necessary coupling, it is a general limitation of the TEE procedure that no planes can be generated that decline relative to a horizontal plane in the direction of the expansion of sound. Technical solutions to resolve this problem are currently under investigation. Because this problem limits the possibilities of our procedure, for now, examination of the LAD was avoided so as not to give a distorted idea of the capabilities of our technique.

The pathological abnormalities within the vessels examined were all detected and visualized satisfactorily (Figure 3). The results demonstrated a good correlation between FRC-TEE and angiography. However, the small number of de novo and stented lesions (n=9) does not justify a conclusion about sensitivity and clinical impact of the method. Meaningful statistical parameters must be determined by a separate study with a larger number of cases.
In general, a healthy vascular status simplifies the representation of the vessels. Deposits within the vessels make the examination more difficult and limit the number of suitable pictures available per fragment. Pathological changes result in a deterioration of image quality because of increased sound reflection and generation of acoustic shadow. Nevertheless, as mentioned above, pathological abnormalities identified by FRC-TEE, especially concerning the degree of occlusion, correspond well to the results of angiography (see Results).

With FRC-TEE, it was also possible to demonstrate diffuse, circumscribed areas of increased echogenicity in vessel walls that corresponded to calcifications in the wall but which had no correlate with angiography. Whether this finding means that beginning coronary artery disease can be diagnosed with FRC-TEE requires further evaluation. Our representation technique offers an important advantage over 3D images. FRC-TEE visualizes all vessel fragments in their actual lengths, thereby permitting coronary evaluation in a single image. In 3D images, only those vessel sections that run perpendicular to the viewing direction can be evaluated along their full length. This advantage in representation by FRC-TEE is obtained at the cost of deficient dynamics. This can be compensated for, because each section can be analyzed separately in the relevant image loops for this criterion, both live during the investigation and in retrospect.

The precision required for manipulation of the probe could be interpreted as a potential limitation of this method. However, a certain “tolerance area” exists for the need for repositioning as a consequence of heart dynamics. The movement of the heart itself compensates for the inexact manipulation. Thus, if a movement is smaller or larger than the actual requirements, the particular vessel piece is not visualized at exactly the same time point but merely shifted to an earlier or later time point in the heart cycle.

At present, the reconstruction of images involves a degree of subjectivity. The assembling of 2 fragments next to each other can be a source of error. To avoid loss of information, the fragment border is placed just prior to the distal end of the visible vessel piece. The generated image, with slightly

<table>
<thead>
<tr>
<th>Coronary Segment</th>
<th>Mean±SD (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM</td>
<td>4.0±2.8% (2.8–5.3)</td>
</tr>
<tr>
<td>LCx</td>
<td>3.9±2.6% (2.8–5.1)</td>
</tr>
<tr>
<td>RCA</td>
<td>4.8±2.8% (3.5–6.2)</td>
</tr>
<tr>
<td>Total</td>
<td>4.2±2.7% (3.5–4.9)</td>
</tr>
</tbody>
</table>
overlapping fragments, simplifies a correct reconstruction. Furthermore, information from structures surrounding the vessel can help to reveal an incorrect assembly. The time required for the FRC-TEE procedure was slightly longer than a routine examination. All patients tolerated the examination without complication. We also attribute this to the fact that the necessary probe movements, which partly trigger the patient’s discomfort, were performed gently in small steps. With refinement of the FRC-TEE procedure, we anticipate that the examination time will be reduced. In the next stage, it will be possible to reconstruct the vessels during the examination with special software support. The software can be incorporated into every commercially available ultrasound system. Therefore, it will be no longer necessary to pay attention to a repeated visualization of each fragment in several loops to guarantee a successful reconstruction afterward. Without the need for reconstruction after the examination, considerable time will also be saved. Automation will reduce the number of personnel and further improve the precision of the method.

The intention of this article was to provide a detailed description of the FRC-TEE procedure and to obtain a first practical proof and analysis of its capabilities. Preliminary clinical evaluation provided convincing results, although the power of the procedure needs to be proven in larger studies.

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References
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