Assessment of the opening angle of implanted Björk-Shiley prosthetic valves

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ABSTRACT A method has been developed in which cineradiography is used for the assessment of the opening angle of implanted Björk-Shiley prosthetic valves. The method is based on the fact that the ring and the disc, which are known to be circular, appear to be elliptical on x-ray films. The spatial position of the valve can be retrieved from the characteristics of these ellipses when vectoranalysis is applied. The method's accuracy does not depend on the position of the patient with respect to the direction of the x-ray beam. The accuracy of the method was demonstrated with the use of a phantom valve. The difference between the measured and the real opening angle was \(-0.7 \pm 1.8\) degrees (mean \(\pm\) SD). Results were reproducible in patients to within \(-0.1 \pm 1.8\) degrees. In 18 patients with normally functioning valves it could be demonstrated with frame-by-frame analysis (interval between frames 20 msec) that the valves opened very rapidly up to about 60 degrees. Closing patterns varied. In one of our patients with valvular thrombosis insufficient valvular opening could be demonstrated by our method before the patient's complaints drew attention to the valvular dysfunction.


CONTROL of the performance of implanted prosthetic valves can be useful for proper patient management as well as for the study of factors governing prosthetic valve opening and closure. In the past, noninvasive diagnostic imaging techniques such as echocardiography\(^1\)\(^-\)\(^4\) or cineradiography\(^5\)\(^-\)\(^8\) have been used for this purpose. Echocardiography permits some visualization of disc motion: reflections of ultrasonic waves against the disc can be recorded. Accurate assessment of the opening angle by means of application of ultrasound, however, is not yet possible.

Radiologic methods for the assessment of prosthetic valvular opening, advocated until recently, need very specific patient positioning in order to hit the ring of the prosthesis tangentially. Due to the tilting movements of the atrioventricular groove, which can be 10 to 15 degrees during a cardiac cycle, in a majority of cases it is not possible to maintain a tangential beam direction for a full cardiac cycle. This can also happen in patients with aortic implants. A method resembling the one presented here has been described,\(^8\) but no data were presented about the accuracy of the method. Especially if films of one projection only are available (see figure 2, bottom x-ray image), estimation of the short axis and the corresponding opening angle may lead to errors.

We developed a method to assess opening and closing characteristics of Björk-Shiley disc valves for each frame of a cineradiographic run, independent of the position of the patient with respect to the direction of the x-ray beam. This method is based on the fact that projections of circular objects such as the ring and the disc of the implant are, in an arbitrary spatial position, ellipsoidal and that the spatial orientation of the valve can be retrieved from the characteristics of these projected ellipses when vectoranalysis is applied. This method will be discussed and some preliminary results that show good reproducibility and accuracy and have important clinical implications will be presented.

**Methods**

*Principle of assessment of the opening angle.* The disc of a Björk-Shiley prosthesis is supported by two struts, the positions of which can be easily identified on a projected frame of a cineradiographic film. From this information the motion axis (m) can be determined. The midpoint of this motion axis, or origin, is then determined along with the positions and the midpoints of the longest projected axes of the ring (a) and the disc (b). Lines are then drawn through the origin and the midpoints of line a, giving a', and of line b, giving b'. The lengths of a, a', b, and b' are measured as is the projected angle \(\alpha'\), included by the lines a' and b'. As is shown in the appendix the

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real opening angle ($\alpha$) can then be calculated with the equation

$$
\cos \alpha = \frac{a \cdot b \cdot \cos \alpha' \pm \sqrt{(a^2 - a'^2) (b^2 - b'^2)}}{a \cdot b}
$$

This equation gives two solutions, one of which can usually be rejected because the opening angle it represents is not realistic. In the case of two plausible solutions the equation must be solved again for another projection.

**Björk-Shiley phantom.** A phantom of a Björk-Shiley valve was manufactured from polyvinyl chloride in order to permit in vitro experiments to confirm the accuracy of results obtained with applied mathematics. The phantom was mounted on a holder to allow spatial positioning. Three series of photographs were taken with the disc opened to 31, 42, and 56 degrees and with the valve ring in 13 different three-dimensional positions. The photographs were taken with a technical camera at a distance of 90 cm. The photographs were analyzed according to the method described above and in the appendix. The real opening angle of the valve was directly measured from photographs that were taken with the motion axis perpendicular to the photographic film plane.

**Patients.** Study patients were recipients of spherical Björk-Shiley mitral tilting disc prostheses. Cineradiographic recordings were obtained for each patient in the frontal, right anterior oblique, and left anterior oblique projections. Films were obtained with patients in the recumbent position in a rotating cradle and with a focal spot of 1.2 mm and a cesium iodide 6 inch image intensifier or with a C arm in patients in a fixed position, the arm providing different beam angles, and with a 0.6 mm focal spot and a 7 inch image intensifier; for both methods the film speed was 50 frames sec$^{-1}$. Of the three runs one was selected for analysis. For this study we used the curves of the opening angles of Björk-Shiley mitral prostheses implanted in 18 patients. These patients were, at the time of observation, considered to have class I disease (NYHA) and this remained true for more than 2 years afterward. This seemed to us proof of the normal function of the prostheses at the time of observation. For contrast three curves that were obtained in another patient and that show a thrombosis-induced progressive decrease in the size of the opening angle of the mitral prosthesis during the follow-up period are presented.

**Results**

**Measurements on the Björk-Shiley phantom valve.** Results of the measurement of the opening angle of the phantom valve positioned in different spatial positions are summarized in table 1. The mean difference between the measured angle and the real opening angle for all 53 determinations was $-0.7 \pm 1.8$ degrees (mean $\pm$ SD).

**Measurements in patients**

Reproducibility. Since it is rarely possible to verify the accuracy of a method of measuring opening angle in patients because the actual angle is unknown, we were limited to an assessment of reproducibility. Three months after the first analysis 20 frames, selected at random, were analyzed for a second time. The difference between the first and the second determination was $0.1 \pm 1.8$ degrees (mean $\pm$ SD).

Normal valve function. In figure 1 frame-to-frame data during one diastole from recipients of spherical mitral disc prostheses are illustrated. The 18 patients were considered to have normally functioning prosthetic valves for the reasons mentioned above and the duration of diastole was normalized to 100% in order to enhance comparability. The opening and the definitive closure took place very rapidly, most often within three frames, which means that the valve was nearly fully open within 60 msec. In the majority of the patients the disc remained fully open throughout diastole and the curves of the motion pattern resembled square waves. In other patients a different motion pattern was observed, characterized by slow partial closing during the second half of diastole. Thus, these curves exhibit a declining pattern. The gradual downward course started about 160 msec after the beginning of diastole, a timespan that seems to correlate well with the end of the rapid filling phase of the left ventricle. In this group of patients the definitive closure is also very rapid.

### TABLE 1
Results of the measurements of the phantom valve

<table>
<thead>
<tr>
<th>Real opening angle (degrees)</th>
<th>No. of observations</th>
<th>Mean (degrees) $\pm$ SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>18</td>
<td>30.5 $\pm$ 1.6</td>
</tr>
<tr>
<td>42</td>
<td>9</td>
<td>41.5 $\pm$ 1.6</td>
</tr>
<tr>
<td>56</td>
<td>26</td>
<td>55.0 $\pm$ 2.0</td>
</tr>
</tbody>
</table>

**FIGURE 1.** Diastolic opening angles of Björk-Shiley mitral prostheses vs time in 18 patients with normally functioning valves. Every dot or square represents the result of the calculation on one single frame. The opening angle is indicated on the vertical axis and expressed in degrees. The diastole time is indicated on the horizontal axis and normalized to 100%.
however. The maximal opening angle was 61.4 ± 1.4 degrees and was reached within 126 ± 62 msec (mean ± SD).

Valve dysfunction. Figure 2 shows three curves of the diastolic opening angle of a mitral spherical disc prosthesis implanted in a 55-year-old man. Figure 2, curve A represents diastolic valvular motion 14 days after implantation. The maximal opening angle was about 60 degrees; compared with the other curves shown in figure 2, this result can be considered normal. One year later, at a routine follow-up visit to a referring hospital, the cardiologist observed a change in quality of the systolic murmur that had been present since the operation in this patient. Because of this a cineradiograph was made and the motion of the disc and the ring was judged normal on visual inspection.

Three months later the patient was admitted to the same hospital because of serious dyspnea. Dysfunction of the prosthesis was suspected and the patient was referred to our hospital. When the patient arrived he had intractable pulmonary edema and an x-ray examination revealed that his prosthetic valve opened to only about 20 degrees (figure 2, curve C). The patient immediately underwent surgery for replacement of a severely thrombosed valve. Although the operation was technically successful the patient’s heart could not be weaned from cardiopulmonary bypass and he died. When, after the patient’s death, we received the cine-radiographs made 3 months before (at a time when the patient did not yet have any complaints), we agreed with the referring cardiologist that valvular motion “looked” normal by analysis with the method described above, however, it could be demonstrated that the valve was opening only about 40 degrees (figure 2, curve B), which was, compared with the other results shown in figure 1, definitely abnormal.

Discussion

The method described here in which cineradiography is used to assess the real opening angle of implanted Björk-Shiley prosthetic valves can be considered reliable and accurate. In phantom studies the opening angle, calculated with this method from photographs taken with the phantom valve in arbitrary spatial positions, deviated from the real opening angle by only −0.7 ± 1.8 degrees. Reproducibility of the determinations of the opening angle of valves implanted in patients was within 0.1 ± 1.8 degrees. The calculations can be applied irrespective of the patient’s position relative to the direction of the x-ray beam. It is

![FIGURE 2](image-url)

**FIGURE 2.** Diastolic opening angle of a Björk-Shiley prosthesis vs time in a 55-year-old man. Curve A was determined postoperatively; curve B, 1 year and 3 months later; and curve C, 3 months after curve B. Each curve is accompanied by a picture of a representative frame at maximal opening. Further clinical data in text.

![FIGURE 3](image-url)

**FIGURE 3.** Schematic drawing of a Björk-Shiley prosthesis and its projection on the film. For original: m = motion axis; 0 = midpoint of m; C = center of gravity of ring; a = midline of ring; b = midline of disc. For projection on filmplane: m' = motion axis; 0' = midpoint of m'; C' = center of gravity ring; a' = midline of ring; b' = midline of disc; l = major axis of projection of ring.
possible to perform frame-to-frame analysis (interval between frames 20 msec) to enable accurate physiologic studies. The method can be applied to valves in the mitral and in the aortic position. Although in this study we worked with spherical disc valves only, analysis of the newer convexoconcave valves, which have discs that shift during opening and closing, is also possible with this method because the position of the motion axis relative to the disc marker is assessed again for every frame.

The results, as shown in figure 1, suggest that the maximal opening angle can always be found 80 to 140 msec after the beginning of diastole. Assessing the opening angle during this period seems a practical solution to reduce analysis time, but the results only apply to normally functioning valves. The characteristics of abnormally functioning valves are largely unknown. We therefore preferred to analyze a full cycle. Furthermore, the analysis of full cycles can allow more insight into the factors regulating valvular motion. A system that includes a microprocessor is under development in order to allow rapid analysis of consecutive frames during one full cycle.

A number of studies was performed in our department in patients with symptomatic prosthetic valve dysfunction in which this method confirmed the clinical diagnosis. An important question is, however, whether asymptomatic prosthetic valve dysfunction can be discovered in this way. From our case history (figure 2) two important conclusions can be drawn. First, it appeared that minor deviations from normal cannot always be appreciated by merely looking at an x-ray film. By comparing the film with the previous film projected simultaneously slight differences could be suspected, but the decreased opening, which certainly must be ascribed to the growing thrombus, could definitely be demonstrated by measuring and calculating the real opening angle. Second, it is important to state that the decrease in valvular opening existed before the patient had any complaints that would draw the attention to valvular dysfunction. Contrary to the common belief that prosthetic valve dysfunction occurs suddenly, it is shown in this case that insidious onset of dysfunction can occur and can be discovered early.

A recent publication summarizing the literature on this subject suggests that "in most cases a period averaging 10 months is required for pannus of organized thrombus to build up enough to cause malfunction of the valve." We demonstrated that valvular thrombosis can develop insidiously and that its consequences, namely impaired valvular opening, can be discovered at an early stage by the described method. Detection of prosthetic valve dysfunction at an early stage makes early and timely intervention possible.

References

Appendix

To calculate the opening angle of the artificial valve some basic principles of vector calculus were used. In figure 3 a schematic drawing of a Björk-Shiley prosthesis is presented. The two struts supporting the disc can always be easily identified in the individual film frames. The motion axis (m) of the disc can thus be determined. Also in figure 3, the valve contours and their x-ray projections on the film plane are shown. Given a parallel x-ray beam, ring and disc are nearly always distorted to ellipses with major axes that equal their true diameters multiplied by the enlargement factor. The motion axis of the disc is represented by the segment m; the centroid of the ring is C. The opening angle of the valve α is the angle between the two midlines a and b, which are drawn through the midpoint of the motion axis and the centroids of the ring and disc.

To compute the opening angle of the valve the following procedure is used:
(1) The motion axis m' from the projection of the struts is defined. The middle of the motion axis is called O'.
(2) The major axis (l) of the projection of the valvular ring is determined. In any projection the length of l equals the diameter (a) of the ring. The midpoint of this axis defines the centroid C' of the ellipse projected.
(3) A line is drawn through O' and C'. The length of the midline a', being the projection of a, is measured.
(4) Steps 2 and 3 are repeated for the projection of the disc. Again, the length of the major axis, equalling b, can be measured. The midline b' is the projection of b.
(5) The angle between a' and b' (called α') is measured with a protractor.

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Computation of opening angle. A coordinate system is defined, its origin being 0, with the x axis along $a'$, the y axis along the motion axis, and the z axis through 0 perpendicular to the x-y plane.

The vector representation of $a'$ relative to this xyz system is

$$
\vec{a'} = (a', 0, 0) \quad \text{and also} \quad \vec{b'} = (b' \cos \alpha', b' \sin \alpha', 0)
$$

As $a'$ and $b'$ are projections of $a$ and $b$, respectively,

$$
\vec{a} = (a', 0, z_1) \quad \text{and} \quad \vec{b} = (b' \cos \alpha', b' \sin \alpha', z_2)
$$

The length of $\vec{a}$ equals the diameter $a$ of the ring so that

$$
|\vec{a}| = \sqrt{\vec{a} \cdot \vec{a}} = \sqrt{a'^2 + z_1^2} = \sqrt{a^2}
$$

$$
z_1 = \pm \sqrt{(a^2 - a'^2)} \quad \text{and also} \quad \vec{a} = (a', 0, \pm \sqrt{(a^2 - a'^2)})
$$

$$
\vec{b} = (b' \cos \alpha', b' \sin \alpha', \pm \sqrt{(b'^2 - b'^2)})
$$

Calculated the dot product of $\vec{a}$ and $\vec{b}$ the opening angle can be found by

$$
\cos \alpha = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}||\vec{b}|} = \frac{a' b' \cos \alpha' \pm \sqrt{(a'^2 - a'^2)(b'^2 - b'^2)}}{a b}
$$

$a'$, $b'$, $\alpha'$, $a$, and $b$ can easily be measured from the projections, as indicated before.

This procedure actually gives two opening angles, due to the unambiguity of the "backprojection." One of these can usually be disregarded.
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