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A Computer-Aided Method to Evaluate the Function of Implanted Björk–Shiley Prosthetic Heart Valves*

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Evaluation of the function of implanted prosthetic valves is important in early diagnosis of valve dysfunction. Björk–Shiley valves contain two radiopaque rings, which are projected as ellipses in cineradiography. From these ellipses the actual valve opening angle can be calculated. A computer-aided method was developed that enables measurement of ellipse characteristics reliably, independent of projection angle and valve opening. It is demonstrated that calculated and real opening angles differ less than 2° with this method. Using the same technique the tilting angle of the valve ring during the cardiac cycle is computed for evaluation of progression of valve dehiscense in case of a paravalvular leak. Application of the method to patient data is illustrated by three cases. The method is suitable for use by technicians. It can be implemented on a small microprocessor system. The method proved to be a powerful tool in the evaluation of patients with implanted Björk–Shiley valves.

INTRODUCTION

Implantation of prosthetic heart valves is occasionally followed by valve-related complications such as thrombosis, thrombo-embolism, tissue overgrowth, or valve dehiscense (*1–4*). Diagnosis of valvular dysfunction can be made by careful history taking accompanied by examinations such as auscultation, echocardiography, and cineradiography with or without cardiac catheterization (*5–7*). These methods generally have a qualitative character and permit the assessment of life threatening dysfunction only. At that stage they will be followed by emergency surgical procedures or in some cases by death.

Recently, a number of techniques have been reported to assess the opening angle of Björk–Shiley prosthetic valves quantitatively with cineradiography (*2, 8, 11*). This is made possible by the special construction of these valves: a metal valve ring and a disc, also containing a metallic ring, supported by two metal struts (*9, 10, 11*). In X-ray projections both rings are visible as ellipses. The opening angle of the valve can be calculated from these ellipses (*2, 8*).

In this paper we describe a computer-aided analysis system to determine

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opening angles and tilting of the valve ring reliably from cinefilms. The accuracy and reproducibility of the technique are discussed and clinical applications are presented.

METHODS

Mathematical analysis. Björk–Shiley prosthetic heart valves consist of a metal ring with two metal struts and a disc suspended in between. The struts of the valves, used in our department, allow opening of the disc up to a maximum of about 60°. The disc contains a radiopaque tantalum foil hoop. Both disc hoop and ring appear under X-ray projection—in general—as ellipses (Fig. 1). In the Appendix it is derived that the opening angle (α) between disc and ring can be calculated from the long (a, a') and short (b, b') axes from the projected ellipses by:

$$\cos\alpha = \frac{1}{aa'}\,(\pm\cos\phi = dd' + bb'). \qquad [1]$$

Where

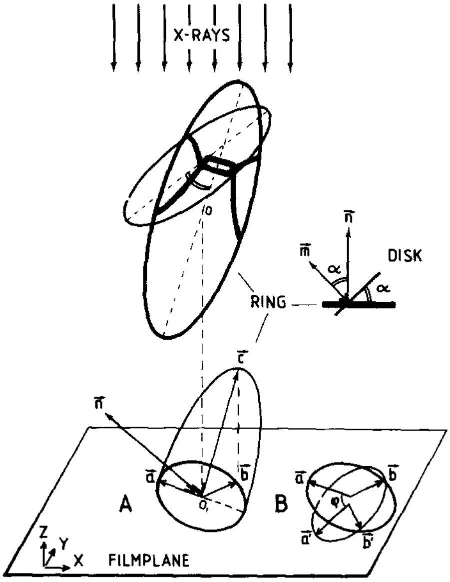

FIG. 1. Schematic representation of a Björk–Shiley prosthetic heart valve and its projection under X-ray. The radiopaque rings of valve ring and disc are projected as ellipses. The opening angle of the valve can be calculated from the normal vectors of valve ring and disc, which are projected as ellipses. In part A, the valve ring is shown with its normal vector and its projection on the film plane. In B the ellipses of ring and disc are shown with their long (a, a') and short (b, b') axes plus ϕ, the angle between these axes. From these characteristics the opening angle can be calculated. (See Appendix.)

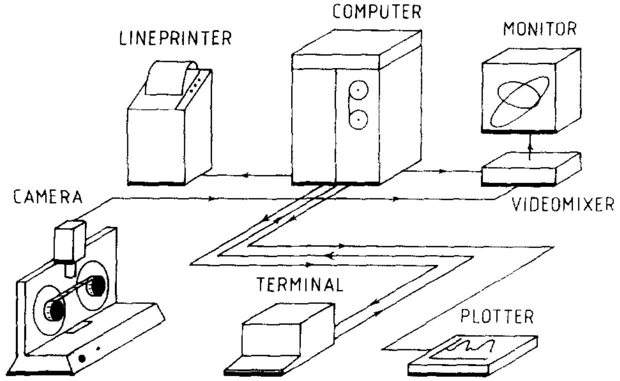

FIG. 2. Diagram showing a computer-aided valve analysis system. A cineframe of a prosthetic valve and a set of computer-generated ellipses are displayed on the same monitor. Via the terminal these ellipses can be fitted to the projections of the valve ring and disc. Lineprinter and plotting facilities are available for further evaluation.

ϕ = the angle between the two long axes of the projected ellipses and

$$d = \sqrt{a^2 - b^2}$$

and

$$d' = \sqrt{a'^2 - b'^2}.$$

The equation has two solutions for $0° < \alpha < 90°$ because both ϕ and $(180° - \phi)$ may be selected as the angle between the two long axes. In principle, two different X-ray projections are therefore required to come to the appropriate solution, which will be the one that is the same for the two projections. In most cases, however, a selection can be made easily, without using a second projection. Solutions with $\alpha > 65°$ are discarded as incompatible with the construction of the valve.

System description. In our department cineradiography (50 frames/sec) of patients with prosthetic heart valves is performed before discharge after surgery and whenever judged necessary during follow-up. Routinely, frontal, right anterior oblique, and left anterior oblique projections are used. This film is the basis for the measurements. To measure the ellipse parameters necessary for the calculation of valve opening according to Eq. [1] we have developed a computer-aided technique using an HP1000 computer (Fig. 2). Via a video-camera a cineframe is shown on a monitor. A computer program generates an initial set of ellipsoidal dot images, which are made visible on the same monitor, using a videomixer. Via the graphic cursor control of the videoterminal the program allows stepwise adaptation of position, size, and rotation of each of the two dotted ellipses displayed.

In this way, the dot images can be fitted exactly to the projections of valve ring and disc hoop, respectively (Fig. 3). After each step in the adaptation, the

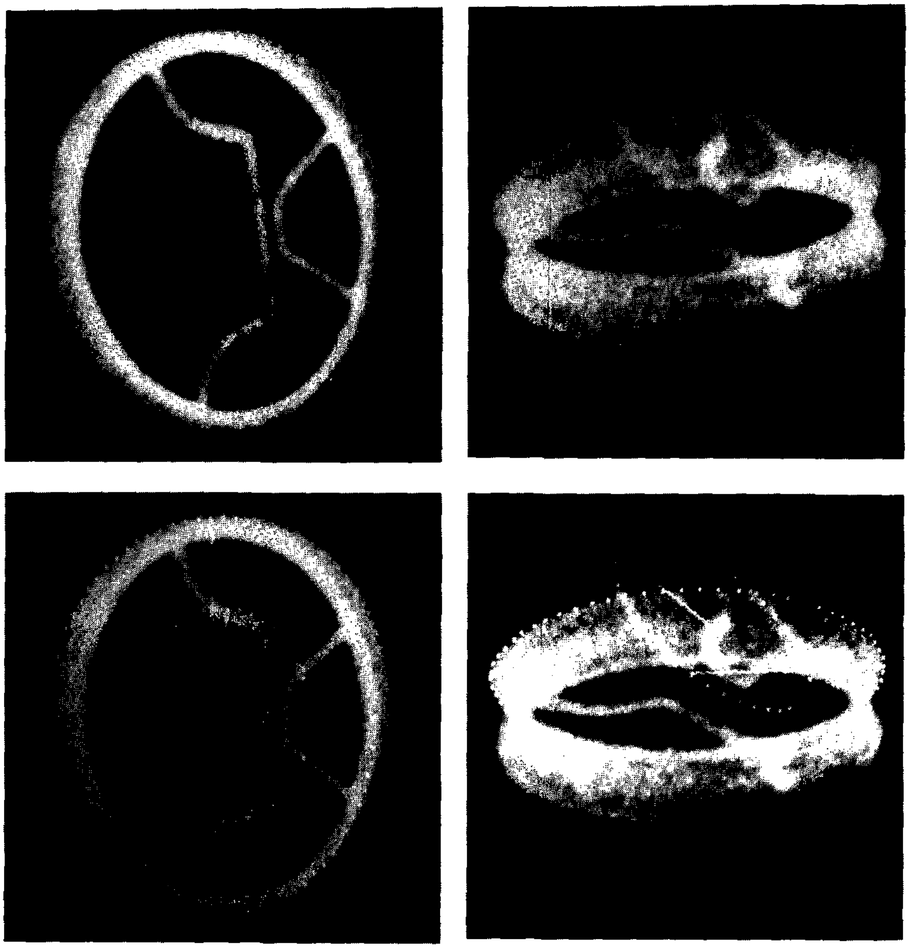

FIG. 3. In the upper row two X-ray images of Björk–Shiley valves are shown from two projections. In the lower row, ellipsoidal dot images are adapted to the projections of ring and disc hoop, taking into account the thickness and rim of the metal valve ring.

two solutions for the opening angle (Eq. [1]) are calculated and displayed. Once adaptation is satisfactory ellipse parameters are stored on disk.

In addition to the opening angle of the valve, also the tilting angle β of the valve ring during the cardiac cycle is determined. For this purpose, Eq. [1] is applied to the ellipse parameters of two ring projections in different film frames, once the ellipse parameters of one cardiac cycle have been stored in the data file. It was obvious that the smallest solution for β is the actual tilting angle of the ring between the two frames studied. This tilting angle is calculated first for all combinations of two frames within one cardiac cycle among which a maximum tilting value between two specific frame numbers is obtained.

Hardware testing. To trace and reduce errors effected by the measurement system we studied and tested the image distortion caused by the X-ray equipment, the video transmission chain, and the monitor characteristics for the film frame image as well as for the dot image.

Verification of the method. To assess the reproducibility and accuracy of the method, test measurements were performed on an isolated 21-mm Björk–Shiley valve. This valve was fixed in the center of rotation of our X-ray equipment and X-ray projections were recorded on cinefilm for 22 different projections using rotation and angulation with steps of 30°. All recordings were made for fixed opening angles of the valve of approximately 0, 15, 30, 45, and 60°, which were obtained by positioning the valve in a Perspex mould. The film frames were analyzed according to the method described. The projection of the valve was positioned in the center of the monitor screen. The size of the long axis of the test valve ring was measured to be about 80 steps on the monitor, as it mostly is in patient films.

RESULTS

Hardware testing. First, tests of the X-ray equipment using a centimeter grid showed an image distortion of less than 1% in a 10-cm radius from the center of the image intensifier. In practice there are therefore no errors to correct for in case of a valve, properly filmed in the center of the beam. This was confirmed by film frame measurements of comparable-size objects. Second, errors in the videotransmission chain for dot image and X-ray image on the monitor were investigated. Steel spheres, accurately manufactured and corresponding to different valve sizes were filmed. The images of the spheres appeared to be circular on the monitor. Measurements on the monitor showed, however, some discordance of the X-to-Y ratio when compared to the original film frame, ascribed to distortion in the camera and monitor used. The videomixer did not influence this ratio. The dot image of a computer-generated circle showed a discordance to a much greater degree. Following the procedure to be described in the next paragraph, the X-to-Y ratio of the videosystem could be equalized to 1 in the computation with an error of less than 1%.

A computer-generated dot image was matched to the film frame image of a sphere, giving parameters not having the characteristics of a circle. A correction factor was calculated for the dot image to account for this magnification in X-to-Y direction assuming the X-ray image on the monitor to be a circle. This correction factor proved to remain constant for differently sized objects.

As can be seen in Fig. 3 there is a limitation in the precision of the monitor display of the dot image. The monitor is equipped with 625 horizontal image lines. This limits the smallest variation of ellipse parameters that can be seen on the monitor and the significance of calculated results.

Also, the size of the object on the monitor does influence the accuracy of adaptation and computation. Our measurements (described below) were performed with a stepsize of one in the vertical direction, necessary to change the display from one image line on the monitor to the next, together with a calculated smaller stepsize in horizontal direction (using the correction factor), and a rotation stepsize of 1°. Third, it was found that deformation of both film frame image and dot image took place in the corners of the monitor screen. This affected both images in the same way without necessity of correction.

Test valve measurements. The film frames obtained with the fixed valve as described under "verification of the method" were analyzed, resulting in pairs of calculated valve opening angles. Selection of the correct solution of Eq. [1] was easy, since one of the solutions always approximated the original angle closely. The resulting calculated angles (means ± standard deviation) for each applied opening angle in the 22 projections are summarized in Table I.

The table shows two series of analyses of the same film performed 3 months apart. The mean differences between first and last analysis and the standard deviation of the differences were calculated for each projection and each opening angle. The Student *t* test applied to these results showed no significant difference between mean values and zero. Thus good reproducibility was demonstrated. With respect to accuracy it can be seen that with our set-up the actual opening angle can be determined within 2° for every projection and every opening angle of the valve.

Clinical and research applications. The clinical value of the method has already been demonstrated in several cases. Figure 4 shows the opening angles throughout the cardiac cycle of a Björk–Shiley mitral valve, which was implanted in a 56-year-old female.

A and B (Fig. 4) indicate measurements with an interval of 35 months. Curve A shows a rapid opening and closing of the valve as well as a maximum opening angle of 58°. Nearly 3 years later (B) the valve shows an abnormal motion pattern, indicated by a slower opening and closing velocity, a decreased maximum opening angle of 20°, and incomplete closing. The patient had severe complaints of dyspnea and at the immediately carried out operation a thrombosed valve had to be replaced.

Figure 5 shows registrations of calculated opening angles during the cardiac cycle in a 55-year-old male who developed atrial fibrillation (curve B) some

TABLE I

ASSESSMENT OF REPRODUCIBILITY OF THE CALCULATION OF THE OPENING ANGLE OF A TEST VALVE FROM CINEFILM

Opening angle applied (α) degrees	First analysis α calculated (means ± SD)	Second analysis α calculated (means ± SD)	Difference between first and second α (means ± SD)
0	0.5 ± 0.6	0.7 ± 0.4	0.2 ± 0.6
15	15.7 ± 1.0	15.4 ± 0.3	0.0 ± 1.1
30	30.4 ± 0.8	30.5 ± 0.5	−0.1 ± 0.9
45	44.3 ± 0.6	44.6 ± 0.4	0.2 ± 0.6
60	58.9 ± 0.9	59.2 ± 0.4	−0.3 ± 0.9

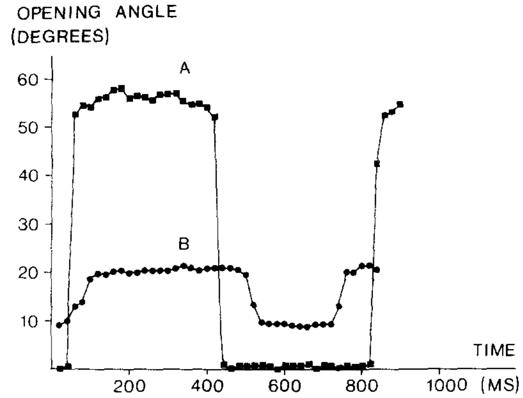

FIG. 4. The calculated opening angle of an implanted Björk–Shiley mitral valve as a function of time during a complete cardiac cycle. Zero time is set 40 msec before the opening of the valve. Indicated by A are the results derived from cineradiography, 2 weeks after implantation. A normal maximal opening angle of about 60° is reached at this time. Thirty-six months later (curve B) a diminished maximal opening angle (up to about 20°) can be demonstrated.

time after surgery. Comparison with the initial curve (A) which was recorded during sinus rhythm, shows that mitral valve opening has considerably changed at end diastole—the time at which atrial contraction occurs normally.

In Fig. 6 the calculated opening and tilting angles of a Björk–Shiley mitral valve during the cardiac cycle are presented from measurements which were obtained 5 months apart. Calculated maximum tilting angles of the valve ring being 6° on the first film (A) had increased to 27° (B). The heart rhythm had changed to atrial fibrillation (curve B). The patient was a 57-year-old male who at angiography demonstrated severe mitral incompetence in the period corresponding to measurement B. This was ascribed to valve dehiscence, which at

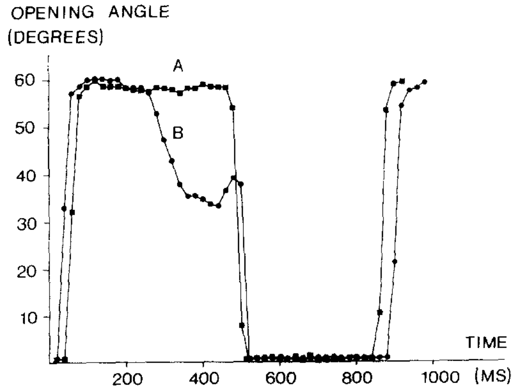

FIG. 5. A graph similar to Fig. 4 showing normal control measurements (curve A) and deviating follow-up measurements (curve B) during atrial fibrillation.

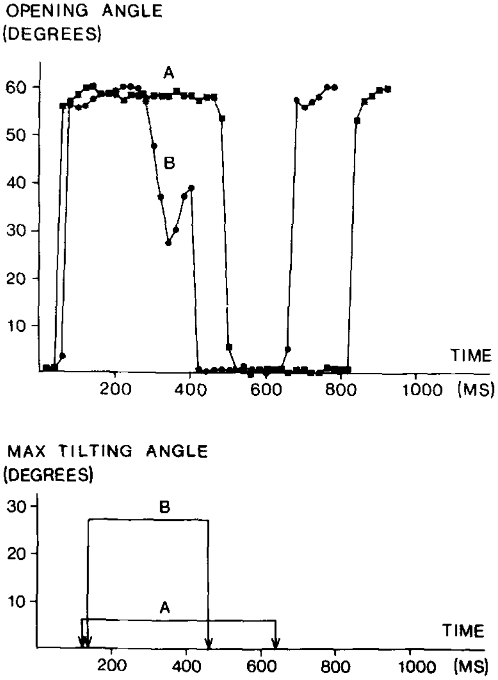

FIG. 6. In the upper panel a graph similar to Figs. 4 and 5 is shown. Curve A shows the normal postoperative prosthetic valvular opening and closing. Curve B was taken 5 months later during atrial fibrillation. In the lower panel the maximum tilting angle of the valve ring during the cardiac cycle is presented, together with the moments between which this occurred. A and B refer to the same cardiac cycle as in the upper panel.

operation turned out to be the correct diagnosis. With our method the production of graphs shown in Figs. 4, 5, and 6 requires about 30 min. This time is mainly spent on adaptation of ellipses to ring and disc-hoop projections in the different film frames.

DISCUSSION

In this paper a new, computer-aided method is presented, which enables the accurate and reliable determination of the opening and closing characteristics of implanted Björk–Shiley mitral and aortic prosthetic valves from their X-ray projections. The standard deviation of repetitive determinations of the opening angle of a small test valve from arbitrary X-ray projections is demonstrated to be less than about 1.0°. This makes a reliable assessment of small variations of the opening behavior possible.

The method involves the stepwise adaptation—by pushing knobs on a computer videoterminal—of position, size, and rotation of two ellipsoidal dot images to the ellipsoidal projections of valve ring and disc hoop. An important advantage of the method is the minimal reliance on motor skills and geometric insight of the operator, especially when compared to methods using tracking of the ellipses or the determination of axes and angles with manual methods (*2, 8, 10*). Thus inter- and intraobserver variability is influenced in a positive sense. Evaluation of differences between the used X-ray projections showed that analysis was more difficult in some projections than in others. In particular, if the disc-hoop projection is (partly) hidden by the ring projection, ellipse adaptation becomes more difficult. Also, if one or both ellipses approach circles it is difficult to establish the direction of the long axis accurately. If one or both ellipses become very narrow, the two solutions of Eq. [1] approach each other ($b \cdot b'$ small) and selection of the correct opening angle becomes difficult.

Consequently, for measurement we select that projection in which disc hoop and ring are clearly visible and appear as rather elongated ellipses. The duality of opening angle determination due to the double solution of Eq. [1] does not cause problems in practice, in particular when a favorable X-ray projection has been selected. Moreover, the availability of different X-ray projections enables comparison of the calculated results and can be used to yield the correct solution when the researcher is in doubt.

The method described is currently employed in analyzing patient data. For each cinefilm, ellipse adaptations are performed for all frames during one cardiac cycle, after selection of a favorable projection. Examples have been presented to demonstrate the usefulness of the method, both in immediate diagnosis of the adequacy of valve functioning and in studying valve behavior during normal and abnormal cardiac rhythms. The described method is the first to analyze mechanical valve behavior *in vivo* routinely.

The maximum tilting angle of the valve ring during the cardiac cycle is automatically calculated from the available data. These calculations can lead to diagnosis of valve dehiscence, as demonstrated in the third case.

The method is well suited for execution by technicians. During a training phase, errors in every part of the routine procedure can easily be traced and corrected. As the method is suitable for implementation on a microprocessor system, it can be made more generally available. Care must be taken to perform the described tests to assure accurate functioning of the system. In particular, we emphasize the importance of determination of an exact correction factor for the monitor display. The procedure described to obtain the correction factor elegantly obviates the separate determination of different correction factors for the separate hardware elements used. The system should be checked at regular intervals.

In conclusion, we have presented a method for evaluation of prosthetic valve behavior which is accurate and reliable; it is simple to operate and may be implemented on a microprocessor-controlled system to yield an elegant setup which has already been shown to be a powerful clinical tool.

APPENDIX

In this appendix we will indicate a vector **r** by **r**, its length by r and its components by (r_x, r_y, r_z).

Let $\mathbf{n} = (n_x, n_y, n_z)$ and $\mathbf{m} = (m_x, m_y, m_z)$ be two vectors, arising from the same origin, with a relative angle α.

The vectorial product $(\mathbf{n} \Lambda \mathbf{m})$ of $\mathbf{n}$ and $\mathbf{m}$ is a *vector* perpendicular to both $\mathbf{n}$ and $\mathbf{m}$ and with length $n \cdot m \cdot \sin \alpha$.

$$\mathbf{n} \Lambda \mathbf{m} = (n_y m_z - n_z m_y, n_z m_x - n_x m_z, n_x m_y - n_y m_x).$$

The scalar product $(\mathbf{n} \cdot \mathbf{m})$ of $\mathbf{n}$ and $\mathbf{m}$ is a *scalar* defined by

$$(\mathbf{n} \cdot \mathbf{m}) = n_x m_x + n_y m_y + n_z m_z = n \cdot m \cdot \cos \alpha.$$

If $\mathbf{n}$ and $\mathbf{m}$ represent the normal vectors of valve ring and disk respectively, the opening angle (α) of the valve will be

$$\cos \alpha = \frac{(\mathbf{n} \cdot \mathbf{m})}{n \cdot m}. \qquad [A1]$$

In Fig. 1 the projection of the valve ring onto the film plane is represented. $\mathbf{a}$ and $\mathbf{b}$ indicate the long and short axis of the projected ellipse; $\mathbf{c} \perp \mathbf{a}$ and $c = a$ (circle). Let ϕ be the angle between $\mathbf{a}$ and the positive x axis.

Then

$$\mathbf{a} = (-a \cos \phi, a \sin \phi, 0) \quad \text{and} \quad (d = \sqrt{a^2 - b^2}).$$

$$\mathbf{c} = (b \sin \phi, b \cos \phi, d)$$

The (normalized) normal vector $\mathbf{n}$ is given by

$$\mathbf{n} = \frac{\mathbf{c} \Lambda \cdot \mathbf{a}}{a \cdot c} \qquad [A2]$$

$$\mathbf{n} = \frac{1}{a} (-d \sin \phi, -d \cos \phi, b)$$

An identical derivation yields the normal vector $\mathbf{m}$ of the disc. If we indicate the disc parameters by accents and choose the positive x axis parallel to $\mathbf{a}'$, the long axis of the disc projection ($\phi' = 0$) we obtain

$$\mathbf{m} = \frac{1}{a'} (0, -d', b'). \qquad [A3]$$

Combining [A1], [A2], and [A3] yields

$$\cos \alpha = \frac{1}{aa'} (dd' \cos \phi + bb')$$

where ϕ is the angle between $\mathbf{a}$ and $\mathbf{a}'$.

Because in the projection ϕ and (180° − ϕ) are indistinguishable, i.e., both may be the angle between $\mathbf{a}$ and $\mathbf{a}'$, and $\cos (180° - \phi) = -\cos \phi$, the actual equation to solve is

$$\cos \alpha = \frac{1}{aa'} (\pm\, dd' \cos \phi + b \cdot b').$$

One of the two solutions found will thus be the actual valve opening angle. Selection of the proper solution must be based on additional information (see Methods).

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