Reconstruction of Closing Phase Kinematics by Motion Analysis for a Prosthetic Bileaflet Valve

V. Barbaro, M. Grigioni, C. Daniele, G. Boccanera
Laboratory of Biomedical Engineering - Instituto Superiore di Sanità, Viale Regina Elena 299, 00161Rome, Italy
E-Mail: grigioni@sun.iss.it

Abstract

The occluder motion of bileaflet valves has been studied by researchers in order to understand critical kinematic features that can be associated with post-implant complications. The closing phase, in particular, was studied monodimensionally using different techniques (laser and timing gate) in order to investigate the cavitation potential of valves, but the results these techniques yield are not measurable in vivo.
Therefore we analysed the valve closing phase motion by means of High Speed Videography (HSV) on a bileaflet valve model, the 29 mm-sized Sorin Bicarbon. Testing was performed in a standard way using the pulse duplicator developed at the University of Sheffield (UK) with the valve mounted in mitral position, and the HSV system (Kodak Ektapro) running at 12000 frame per sec, synchronised on the flow waveform.
The kinematic analysis of this prosthesis started from a modelling process needed to reduce the leaflet degrees of freedom due to the pivot design. In fact, the spherical coupling between leaflet and housing yields hypocycloid trajectories for the leaflet points. Thus a trajectory table (TT) was built that can be addressed by the y coordinate of the recorded leaflet points, reducing the problem to a monodimensional one. To verify the model we used a two-orthogonal-camera set up, at 1000 frame per/sec.
Finally, from the frontal view recordings at 12000 Hz and the trajectory table (TT), the whole leaflet motion just immediately before the closure time was obtained synchronously with pressure and flow traces. Motion analysis calculations provided angular and tip velocities related to the left ventricular dp/dt values to evaluate the prosthesis function and performance.

1.Introduction

The study hereby presented is part of a research programme aimed to investigate the mechanics of mechanical valve prostheses (MVP) by means of High Speed Videography (HSV). The aim was to realize a simple HSV set up using kinematic models to evaluate the kinematics and dynamics of MVP to be transferred to in-vivo studies. At present, the closing phase of MVP, in mitral position, is the most studied portion of the heart cycle in order to characterise MVP fluidomechanical efficiency. In fact, the study of the "*maximum leaflet tip closing velocity (Max CV) - left ventricular (LV) dP/dt*" relationship in the late closing phase is regarded as a key factor in MVP cavitation potential assessment, e.g. in Kingsbury,[1] Graf,[2,3] Rau,[4] Wieting,[5] Wu.[6] To investigate this relationship different techniques were used, as in Graf,[2] and Wu,[6,7] that unidimensionally measure closing velocities. Specifically Wu[6,7] used a laser sweeping technique capable of detecting occluder velocity within the last three degrees of occluder motion close to the housing ring with good accuracy, while Graf[2] used a light barrier to obtain an averaged value of late closing velocity. HSV was used in several other studies, such as Wieting,[8] Van Steenhoven,[9] Barbaro,[10] to investigate valve occluder motion on both mechanical and tissue prostheses at different frame rates (200 to 1000 Hz). These frame rates, however, do not allow for a correct measure of kinematic quantities but only of tidal courses of valve area or trajectories of occluder focal points as in Barbaro,[10] because the late closing phase requires frame rates greater than 3000-4000 frame/s and sufficient spatial and angular resolution. In fact, these limits are attributed to HSV due to the difficulties the system has in meeting, at the same time, specifications such as sufficient resolution both in space and time (number of pixels in one frame and time interval between consecutive frames), and good recording quality at the high frame rate used. With respect to other techniques, HSV allows us to obtain the tidal course for coordinates with equally spaced samples in time, and, if it is used with a good resolution set up, it can provide useful information about MVP mechanics as well. Finally, this technique is prone to be used in-vivo, associated with other traditional imaging techniques.

We used HSV to study the Sorin Bicarbon valve (SB), for its particular pivoting mechanism that renders it difficult to apply other techniques. HSV was preliminarly used at 1000 frame/s (full frame capability) as a support to build a kinematic model for the SB 29 mm, tested in mitral position. Then, using the maximum recording speed of 12000 frame/s (12 sliced frame), a session was conducted to obtain late closing velocity.

2.Material and methods

The Bicarbon valve (Sorin Biomedica, Italy) uses a spherical coupling between the housing ring and the leaflets; thus free body motion should have to be considered for the leaflet rigid body. Moreover, design allowances entail a basculating motion of the leaflet, that makes leaflet closure to be different cycle by cycle, which results in a different final position inside the housing ring. This renders it difficult to evaluate the kinematic quantities (such as Max CV) by other techniques.

Then, some theoretical considerations must be made to reconstruct leaflet kinematics under sufficient hypotheses.

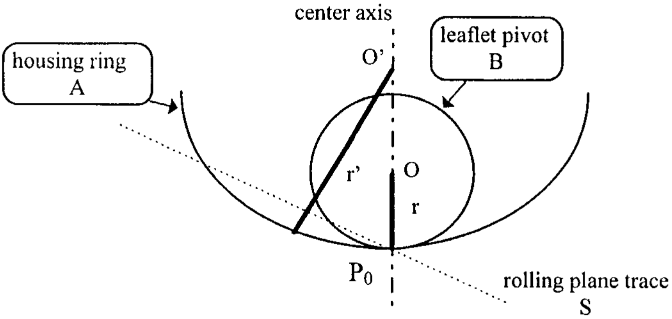

Figure 1: Rolling coupling kinematics between valve housing (A) and leaflet (B). O,O' = sphere centers; r,r' = sphere radiuses; P_0 contact point = center of instantaneous rotation; S = plane traced by the rolling sphere.

The coupling mechanism of the Bicarbon valve is reported by Vallana[11] to roll without sliding, which reduces the friction inside the coupling region. This rolling design (Figure 1) is the consequence of the two coupling regions at the lateral sides of each leaflet, where there are two spherical surfaces of different radius, one inside the housing ring (A), the other on the leaflet pivot (B). Using the manufacturer's data we drew the coupling kinematics, and predicted any possible trajectory for any point on the leaflet. However, owing to the allowances between the two spherical surfaces, a possible trajectory for each point of the leaflet can be drawn only after defining the first point of contact between the two surfaces in each coupling region before the spheres begin to roll one against the other. If we assume that the leaflet has symmetrical initial contact points on both coupling regions, the rolling travel will be planar, and draw a circumference on two parallel planes, ideally crossing (S in figure 1) the spherical regions inside the housing ring (A). Hence, any point on the leaflet, rigidly linked with the contact point, e.g. the tip (M point), follows a hypocycloidal trajectory that can be calculated. In this way, a monodimensional problem can be addressed. Thus, the kinematic model of a spherical coupling with only one degree of freedom needs the trajectories of relevant points on the leaflet, and is based on the following assumptions:

1. The two sphere centers (leaflet pivot and housing) are on the same axis (Figure 1).
2. The potential translatory movements added to the rotational leaflet action can be neglected once the leaflet pivot has its first contact with the housing sphere as a result of flow reversal.

3. The two leaflet pivots have symmetrical mechanics without lateral motion (contact points between the rolling spheres are the same on both coupling regions).
4. The HSV of any marker or point on the leaflet, by decribing a hypocycloid, reveals the complete motion of the leaflet if all the hypotheses about monodimentionality are satisfied, for which it is necessary, at least, to have stable flow conditions and to average several closure recordings.

Starting from these assumptions a Trajectory Table (TT) was built reporting the following quantities, drawn in figure 2:

1. leaflet angle degree (step less than 0.35°)
2. XY coordinates of leaflet tip (M point)
3. XY coordinates of the innermost point (D) in the gap between leaflets (B Datum)
4. radius of instantaneous rotation P_0M.

The XY coordinates of the contact point within the coupling region (P_0, center of instantaneous rotation) can always be calculated from the previous quantities.

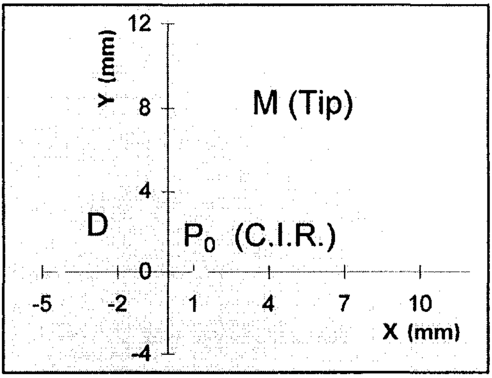

Figure 2: Planar description of the leaflet motion, M=Leaflet Tip, N = innermost point in the gap between leaflets (B-Datum), P_0 = center of istantaneous rotation.

The Y coordinate of point D, as well as in Random Access Memory devices, is the address to the model table, and its values are obtained from HSV recording of the Y coordinate of point D on the valve.

From the series of coordinate values obtained from TT, the tidal courses of tip velocity V_M and of P_0M were calculated. To compute velocity, the sampled leaflet tip tidal courses were processed by means of polynomial fitting to avoid errors due to the differentiating algorithm applied to the raw data, as discussed in Gazzani[12]. We usually obtained correlation indexes better than 0.998, only for the late closing trajectories (less than 10 degrees), until occluder impact. Therefore tip velocity and angular velocity were obtained by using the following relationships:

Transactions on Biomedicine and Health vol 4, © 1997 WIT Press, www.witpress.com, ISSN 1743-3525

$$V_M = \sqrt{V_{MX}^2 + V_{MY}^2} \qquad (1)$$

$$V_M = \omega_0 \wedge P_0 M \qquad (2)$$

where V_{Mx}, V_{My} are the velocity components abtained from the derivative of polynomial fittings of tip M coordinates.

2.1 Experimental sessions

All the experimental sessions on SB 29 mm in mitral position were performed with the Sheffield University-developed Pulse Duplicator (PD) described by Martin,[13] set as follows: heart rate = 70 bpm, cardiac output = 4.5 l/min, mean aortic pressure = 100 mmHg, systole to cycle ratio= 35 %. A 27 mm tilting disc valve was placed in aortic position.

The HSV system was the Kodak Ektapro 1002, equipped with two cameras that simultaneously recorded two different images accomodated on a single monitor screen, thus providing two ortogonal recordings of the closing leaflet, at 1000 Hz. The HSV cameras were located, one in the front and the other on top of the PD mitral section. In this way we followed the Bicarbon leaflet motion until it disappears inside the housing ring thus verifying the theoretically predicted hypocycloid in the TT. We avoided optical distortion by using a saline solution based on NaI, which has the same refraction index of the plexiglass mounting section (n_D =1.49).

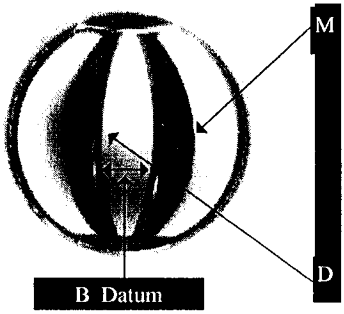

Figure 3: Sorin Bicarbon inflow view and focal points; D = innermost point whithin the gap, M = leaflet tip.

In a second session we selected a 12000 frames/s rate, and used only an intensified imager camera placed frontally at the PD atrial window. With a backlighting system we recorded the Y coordinate of the innermost point (D) at the internal leaflet edge within the gap between occluders (B Datum), as in figure 3. At this frame rate the Ektapro screen is divided into 12 parallel slices that allowed us to follow in time the D point motion for both occluders in detail. In this way, the Y coordinate was recorded at full horizontal resolution (0.04 mm/pixel). An original software controlling the PD provides a trigger to synchronise Ektapro recording with the left ventricular pressure; 16 closures were acquired and averaged.

3 Results

Results are divided into three groups: the tip (M) trajectory recorded by two cameras at 1000Hz; the tip (M) trajectories obtained from the TT addressed by the Y coordinate of point D recorded by HSV at 12000 Hz; the calculation of closing velocities.

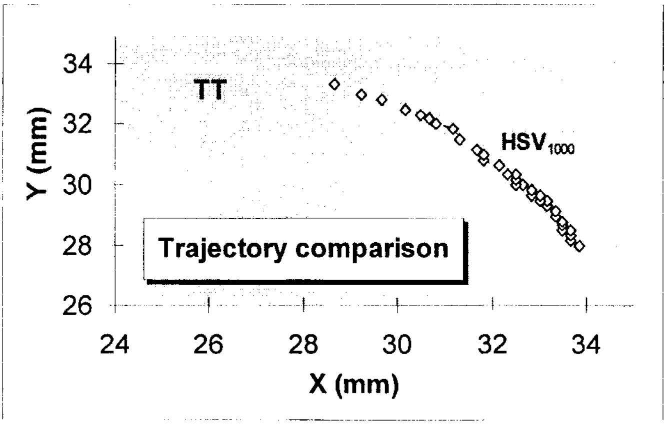

Figure 4: Comparison between theoretical hypocycloid trajectory (continuous line) and recorded data at 1000 frame/s (square dots).

Figure 4 shows the tip trajectory averaged from 10 closures recorded at 1000 Hz compared with the TT hypocycloid calculated from manufacturer's data; a correlation of 0.97 was reached for the visible part of leaflet tip trajectory.

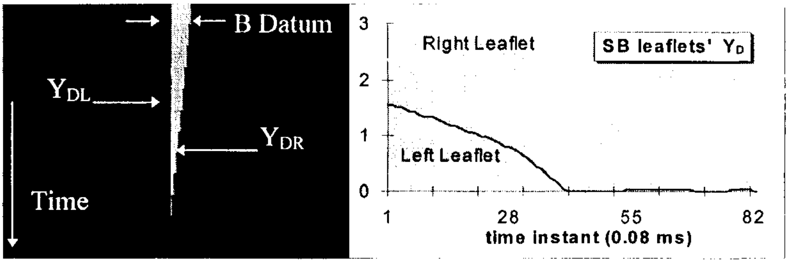

Figure 5: B Datum recording and D's Y coordinate obtained at 12000Hz; Y_{DR}= right leaflet D's Y coordinate, Y_{DL}= left leaflet D's Y coordinate.

Starting from these results, the Trajectory Table was used to follow the valve motion at 12000 Hz. During this session the first leaflet to close was generally the left one owing to the velocity profiles in the backflow at the mitral position of the PD. Figure 5a reports HSV recording of the valve B-Datum, at late closure, from which the Y coordinates of the two leaflets' D point (reported in figure 5b) were picked by IDL software programme.

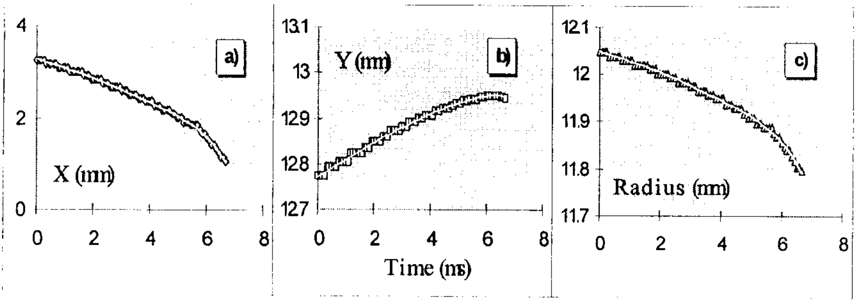

Figure 6: X (a) and Y (b) tip coordinates recorded during valve closure at 12000 Hz; Radius P_0M from TT. Discrete data in squares, polynomial fittings in white continuous line.

In figure 6 the rebouncing of the first leaflet can be clearly seen, taking into account that closure is detected when the leaflet reaches the zero velocity point (before inversion due to rebouncing).

As TT outputs, in fig. 6a and 6b, the *X* and *Y* coordinates for leaflet tip (M) are reported together with polynomial fittings (5 degrees); in figure 6c the tidal course of the non-constant radius of instantaneous rotation is drawn.

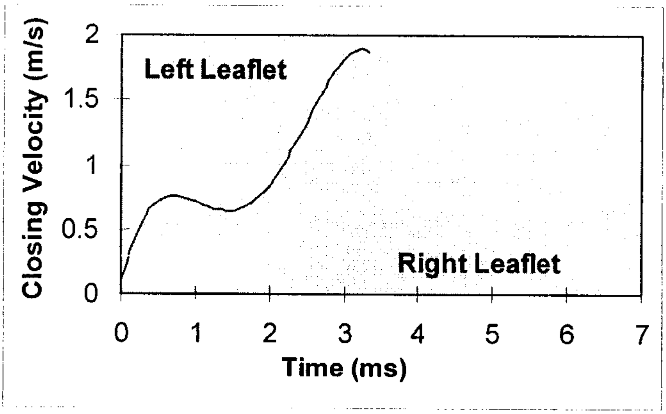

Figure 7: Example of closing velocity tidal courses of both leaflets obtained from derivative of tip coordinates.

The whole reduction of the radius of instantaneous rotation for a 29 mm sized valve, from opened to closed, was about 1 mm, but only 0.3 mm in the late closing phase, thus leaflet moment of inertia decreases when approaching closure. From X and Y traces in figure 6a and 6b, tip velocities V_M were obtained as in figure 7 for both leaflets. Data in figures 5,6,7 correspond to the last 7 ms of the leaflet closing motion.

Table I. Kinematic quantities (mean ± S.D.) estimated from HSV at 12000Hz on SB 29 mm, at dP/dt = 2200 ± 0.46 mmHg/s.

	Max closing velocity (m/s)	Impact velocity (m/s)	Impact Angular velocity (rad/s)
Left Leaflet	1.58 ± 0.41	1.48 ± 0.32	0.127 ± 0.004
Right Leaflet	1.78 ± 0.64	1.78 ± 0.64	0.148 ± 0.017

In table I the main kinematic quantities are reported. These values correspond to a ventricular dP/dt calculated as discrete derivative using 5 ms spaced samples of LV pressure before closure as in Rau[5]; an averaged value was obtained from 16 cycles averaged LV waveforms.

Less variability was obtained in detecting velocity with respect to data for other bileaflet valves as in Wu.[7] SB shows also a smaller angular velocity for the first leaflet that closes, but in any case, smaller values with respect to other valves were obtained, for both leaflets. These data together with the high moment of inertia of SB (e.g. about twice as much the value estimated for StJude Medical of similar size) related to the high leaflet weight and radius of rotation (~12 mm) characterise SB kinematics. However, SB leaflet tip velocity values remained at medium level with respect to the corresponding measured closing velocities in literature for bileaflet valves, as in Graf[2] and Wu.[7] At the same dp/dt value, impact velocity for several bileaflet valve models ranges approximately between 1 - 3 m/s and, in particular for the second SB leaflet, our values are in agreement with Graf's[2] SB measurements in a study on cavitation potential.

When analysing the tidal course of SB angular quantities, cycle by cycle, also negative accelerations were found before closure. It must be taken into account that the pivot stops whithin the coupling region can be responsible for leaflet deceleration, especially in the first closing leaflet, because it can basculate at closure and occupy some of the space at the disposal of the second leaflet. Thus the latter produces an impact on the flat leaflet surface at the B Datum. This is not the case with other valves, where the leaflet impact is mainly between the leaflet edges and the housing ring stops, and this phenomenon is prone to produce cavitation, as explained in Graf.[2] In SB this is mostly the case for the first leaflet that closes, decelerating along the smoothed pivot stops.

4 Discussion and conclusion

Closing velocity data for SB were in substantial agreement with those for other mechanical valves. Maximum closing velocity values were in the order of those measured by Wu[6,7] and Graf,[2] and dp/dt (calculated as in Rau[5]) was well correlated with velocity data. Impact velocity was generally lower than maximum closing velocity due to deceleration before closure, at least for the first leaflet in the case of SB. It is to be noted that the high weight of the SB leaflet and, thus, the high mmomnet of inertia I as well, are counterbalanced by the reduction of the instantaneous rotation radius due to the travel of the rotation center towards closure, and closing velocity values were in the same range of other bileaflet valves. This analysis shows that similar dynamic behaviours can be obtained with different design choices. SB design can reduce (by a decreasing radius and moment of inertia) velocities and impact energy with respect to constant radius design such as in StJM as reported in Barbaro.[14] It must be remembered that the role played by pivot design in the bileaflet valve is relevant to several aspects of the valve mechanics, such as long-term durability and wear, and short-term events, e.g. cavitation.

The left leaflet was the first to close and this is to be attributed to the non uniformity of the backflow through the valve due to Sheffield PD geometry, because the influence of gravity was negligible in its horizontal set up. Wu[7] reported the effect of gravity on the asynchronous closure of mitral prostheses mounted in anatomical position. In any case, flow uniformity must be taken into account to characterise the propension of a valve to follow flow disturbances in relation to its kinematic properties (e.g. moment of inertia).

At 12000 frames/s, the results presented here give about 12 points equispaced in time for the final leaflet angular positions (less than 8 degrees) before closure. At closure impact the quantization error for the leaflet angles was less than 0.35 degrees. These data can be usefully compared with the work of Wu[6,7] that using the Laser sweeping technique reports a mean of 20 points in a similar angle range before closure. Therefore, the HSV application hereby described shows sufficient accuracy in comparison with other techniques.

It must be stated, though, that the major limiting factor in this SB kinematic representation can reside in the Trajectory Table based on simplified assumptions. However, the correlation value of 0.97 for trajectory comparison (at 1000 Hz) and the agreement with the velocity values obtained by other authors makes us confident in the validity of the method. We also feel that, once the Trajectory Table has been calculated on the basis of the pivot mechanics, the HSV application is quite simple, which allows us to imagine a successful use of this technique in vivo.

References

1. Kingsbury, C., Kafesjian, R., Guo G., Adlparvar, P., Unger, J., Quijano, R.C., Graf, T., Fisher, H., Reul, H., Rau, G. Cavitation threshold with respect to dP/dt: evaluation in 29 mm bileaflet, pyrolitic carbon heart valves, *The Interantional Journal of Artificial Organs*, 1993,16, 7, 515-520.
2. Graf, T., Reul, H., Detlefs, C., Wilmes, R., Rau, G. Causes and formation of cavitation in mechanical heart valves, *J Heart Valve Disease*, 1994, 3, Suppl.I, S49-S64.
3. Graf, T., Reul, H., Rau, G. Cavitation potential of mechanical heart valve, *Journal of artificial organs*; 1990, 13, 9: 609.
4. Rau, G., Reul, H., Eichler, M., Schreck, S., Wieting, D.W. The effect of left ventricular dP/dt on the in vitro dynamics of the Bjork-Shiley convexo-concave mitral valve, *J Heart Valve Disease*, 1995,4, Suppl I, S17-S20.
5. Wieting, D.W., Graf, T., Reul, H., Rau, G., Kafesjian, R., Stobie, R. In vitro studies to determine the cavitation threshold left ventricular dP/dt for Edwards-Duromedics mitral heart valves, *Journal of artificial organs*, 1990, 13, 9: 608.
6. Wu, Z.J., Wang, Y., Hwang, N.H.C. Occluder closing behaviour: A key factor in mechanical heart valve cavitation, *J Heart Valve Disease*, 1994, 3, Suppl.I, S25-S34.
7. Wu, Z. J., Hwang, N.H.C. Asynchronous closure and leaflet impact velocity of bileaflet mechanical heart valves, *J Heart Valve Disease*, 1995, 4, Suppl.I, S38-S49.
8. Wieting, D.W., Kafesjian, R., Stobie, R., Adiparvar, P., Ward, D., Unger, J. Hi-speed videography of Edwards duromedics heart valve dynamics and fluid dynamics, *Journal of artificial organs*; 1990, 13, 9: 608.
9. Van Steenhoven, A.A., Van Duppen, J.A.G., Cauwenberg, J.W.G., Van Renterghem, R.J. In vitro closing behaviour of Bjork-Shiley, St Jude and Hancock heart valve prostheses in relation to the in vivo recorded aortic valve closure, *J. Biomechanics*, 1982; 15, 11: 81-848.
10. Barbaro, V., Boccanera, G., Daniele, C., Grigioni, M., Palombo, A. *"In-vitro test comparison of Prostethic Heart Valve: closing phase"*. IXth Congress of ISAO, XXth Congress of ESAO, 4-8 July, Amsterdam. *The International Journal of Artificial Organs*, 1993, 16, 6, 469.
11. Vallana, F., Rinaldi, S., Galletti, P.M., Nguyen, A., Piwnica, A. Pivot design in bileaflet valves, *ASAIO Transactions*, July-September 1992, 38,3, M600-M606.
12. Gazzani, F. Comparative assessment of some algorithms for differentiating noisy biomedical data. *International Journal of Bio-Medical Computing*, 1994, 37, 57-76.
13. Martin, T. R. P., Palmer, J. A., Black, M. M. A new apparatus for the in-vitro study of aortic valve mechanics. Engineering in medicine; 1978; 7: 229-230
14. Barbaro, V., Boccanera, G., Daniele, C., Grigioni, M., Valentini, P. The relevance of pivot design in bileaflet valves. XXIInd ESAO Congress, 1995, Berlin, Germany.