The closing behaviour of the natural aortic valve

6.3. THE CLOSING BEHAVIOUR OF THE NATURAL AORTIC VALVE

ANTON A. VAN STEENHOVEN, CEES W.J. VERLAAN, PIETER C. VEENSTRA, ROBERT S. RENEMAN

1. INTRODUCTION

As discussed in earlier work (1), proper understanding of natural aortic valve closure is essential for the design of artificial triple leaflet valve prostheses. Some insight in valvular closing during deceleration of the main stream has been obtained from model studies (2, 3, 4). The present study was conducted in order to investigate this closing behaviour in animal experiments and to compare the results with those obtained from the theoretical model designed on the basis of the fluid behaviour in the analogue (5). Aortic valve movements were studied in open-chest dogs using direct high-speed cinematography. The aortic valve is schematically shown in Figure 1; it has three leaflets and behind each leaflet there is a half-spherical cavity, the sinus of Valsalva.

2. ANIMAL EXPERIMENTS

For an optically clear image of the aortic valve, perfusion of the heart with a transparent liquid is required (6). Under these circumstances the heart has to rely on the small oxygen content in a hemoglobin-free solution. Therefore, the duration of observation of the aortic valve is limited. In this technique reliable physiological recordings of the valve can only be made

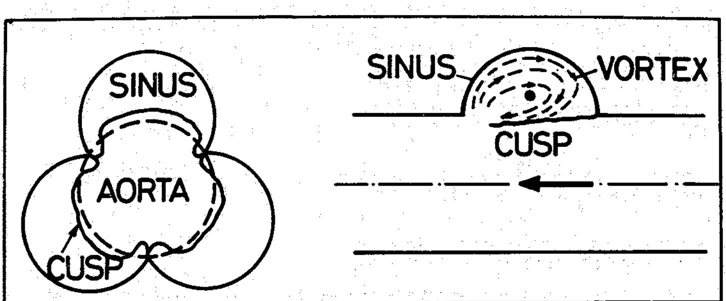

Figure 1. Diagram of the aortic valve and the sinuses of Valsalva (9).

J. Baan, A.C. Arntzenius, E.L. Yellin (eds.), Cardiac Dynamics, 477–488.

during the first six minutes following the start of perfusion. Separate coronary perfusion with blood (7) provides a much longer period of time for observation (three hours). In this technique, however, small quantities of blood enter the left ventricular chamber, causing a decrease in light transmission within the liquid and therefore a reduction in film speed. Methods applied to the intact animal (8) only give information about the valve in the closed position. For high-speed in-vivo recording of aortic valve movement only the first method can be used.

2.1. *Methods and materials*

Experiments were performed on mongrel dogs of either sex, unknown age, and ranging from 25 to 45 kg. The animals were premedicated with Hypnorm (1 ml/kg body mass i.m.). Anesthesia was induced with sodium pentobarbital (10 ml/kg body mass i.v.) and, after endotracheal intubation, was maintained with oxygen-nitrous oxide. Ventilation was kept constant during the experiment with a positive pressure respirator (Bird).

The ECG was derived from the limb leads. The chest was opened through the left fifth intercostal space and the heart was suspended in a pericardial cradle. Left atrial pressure was measured through a pulmonary vein with a polyethylene catheter connected to a pressure transducer (Ailtech). Millar catheter-tip micromanometers (PC 470) were used to measure aortic and left ventricular pressures. An electromagnetic flow probe was placed on the ascending aorta and connected to a sine-wave electromagnetic flowmeter with a carrier frequency of 600 Hz and an upper frequency response of 100 Hz, – 3 dB (Transflow 600). The determined variables were recorded on a multi-channel physiological recorder (Schwarzer) and on an electromagnetic tape recorder (Ampex PR 2230). The upper frequency response of the whole recording system was 280 Hz, – 3 dB.

For direct cinematographic recording of aortic valve movement, a thin (4 mm) flexible fiberscope (Olympus BF 4C2) was placed in front of the valve through the left carotid artery under fluoroscopic control. In water the optical system has a visual field of 45°. Light from a mercury vapour lamp (ACMI-FCB 1000) was emitted from the tip of the lens system at an intensity of 400,000 lux and a colour temperature of 5000° K. Aortic valve motion was filmed with a high-speed film camera (Hitachi-Himac) at a speed of 200 frames/sec using Kodak Video News Film 7240 (125 ASA). With special processing procedures a speed of 1000 ASA could be reached. Coupling of optical and electrical signals was achieved using a timer signal on both film and tape recorder.

After the animal was thus instrumented, the pulmonary veins were ligated and the blood was replaced by a transparent Tyrode solution either with

(3.3 gram per cent) or without gelatine (UCB). The liquid perfusion was done with two roller pumps, one connected to the left atrium and the other to the femoral artery. The second connection appeared to be necessary for maintaining peripheral arterial blood pressure at physiological levels. Free outflow occurred through a cannula in the pulmonary artery. After the experiment the heart was removed and the valve geometry measured. The schematical representation of the experimental setup is given in Figure 2.

Analysis of the film was performed with an analysing projector (analector, Old Delft). The cusp positions were drawn frame by frame and the valve opening area was measured with a planimeter (OTT-31). A digital computer system (B 7700) was used for comparison between the optical and electrical signals. This system also determines from five heart beats the average curves for the aortic volume flow and the valve opening area. The fluid velocity in the ascending aorta was calculated by dividing the flowmeter reading by the aortic cross-sectional area. For coupling of the aortic valve motion to the calculated flow velocity between the leaflets as an instantaneous function of time, the measured flow signal was shifted by about 8 msec according to the position of the flow probe on the ascending aorta and the electronic delay in the flowmeter system.

2.2. *Experimental results*

In general less than one minute elapsed between the start of perfusion and the beginning of filming aortic valve movements. In 13 dogs a regular heart rhythm as well as relatively normal cardiac outputs and aortic and intraventricular pressures were maintained during the filming period.

The aortic valve movements were studied under various hemodynamic circumstances. The following variables were changed: fluid viscosity, mean left atrial pressure and aortic pressure. Two extreme situations will be discussed here. Figure 3 shows an experiment performed under rather physiological conditions. In this experiment the viscosity of the perfusion liquid was similar to that of blood ($\eta = 3.10^{-3}$ Ns.m^{-2}), mean left atrial pressure ($\overline{P}_{la}$) was 13 mmHg and systolic aortic pressure (P^s_{ao}) was 90 mmHg. In Figure 4 an experiment is shown in which both the fluid viscosity ($\eta = 10^{-3}$ Ns m^{-2}) and systolic aortic pressure were low ($P^s_{ao} = 55$ mmHg), and mean left atrial pressure was high ($\overline{P}_{la} = 30$ mmHg).

From these two experiments the valve-closing behaviour was compared with the corresponding aortic flow velocity signal. Figures 5 and 6 show the average curves of these signals as derived from five heart beats. The aortic flow signal, expressed in terms of fluid velocity as a function of time is shown in the top panel and the closing behaviour of the valve in the bottom panel. The closing parameter λ^2 shown in Figures 5 and 6 is defined as the ratio of the instantaneous and the maximum area of valve opening. If the

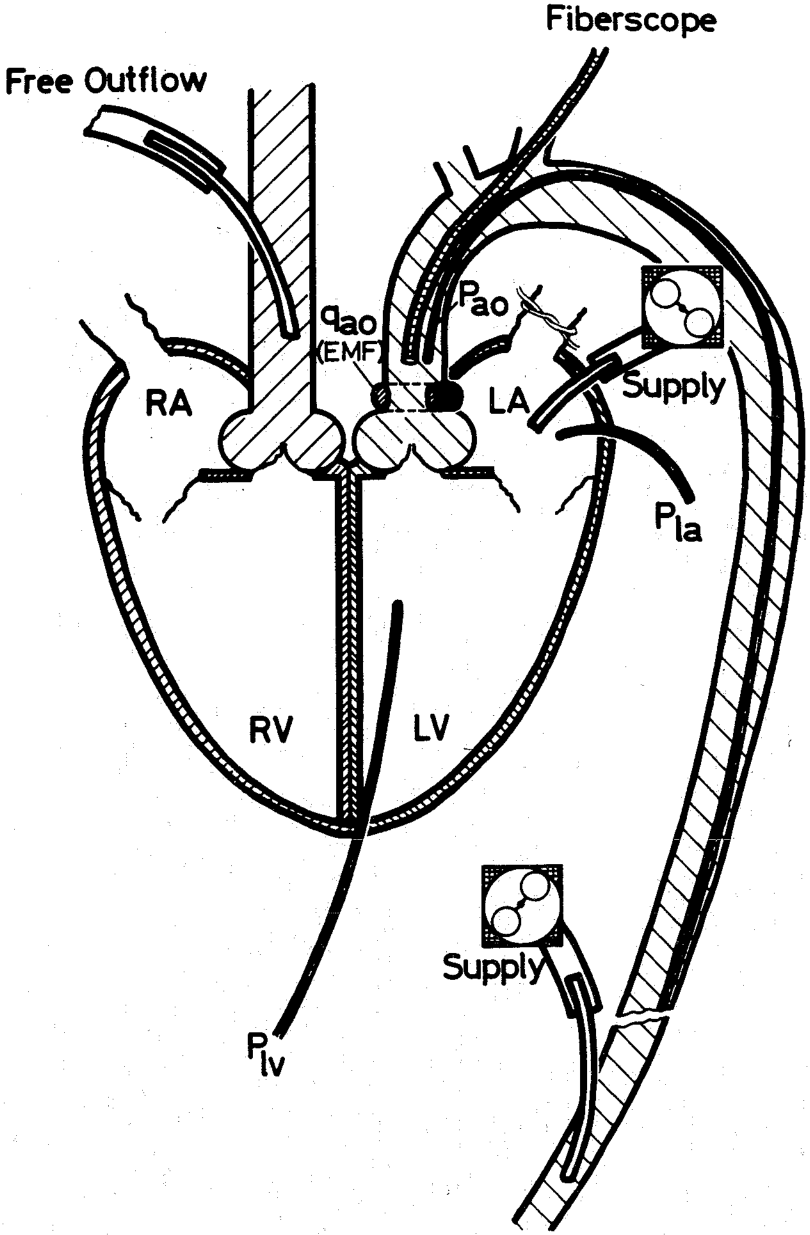

Figure 2. Diagram of the position of the measuring devices.

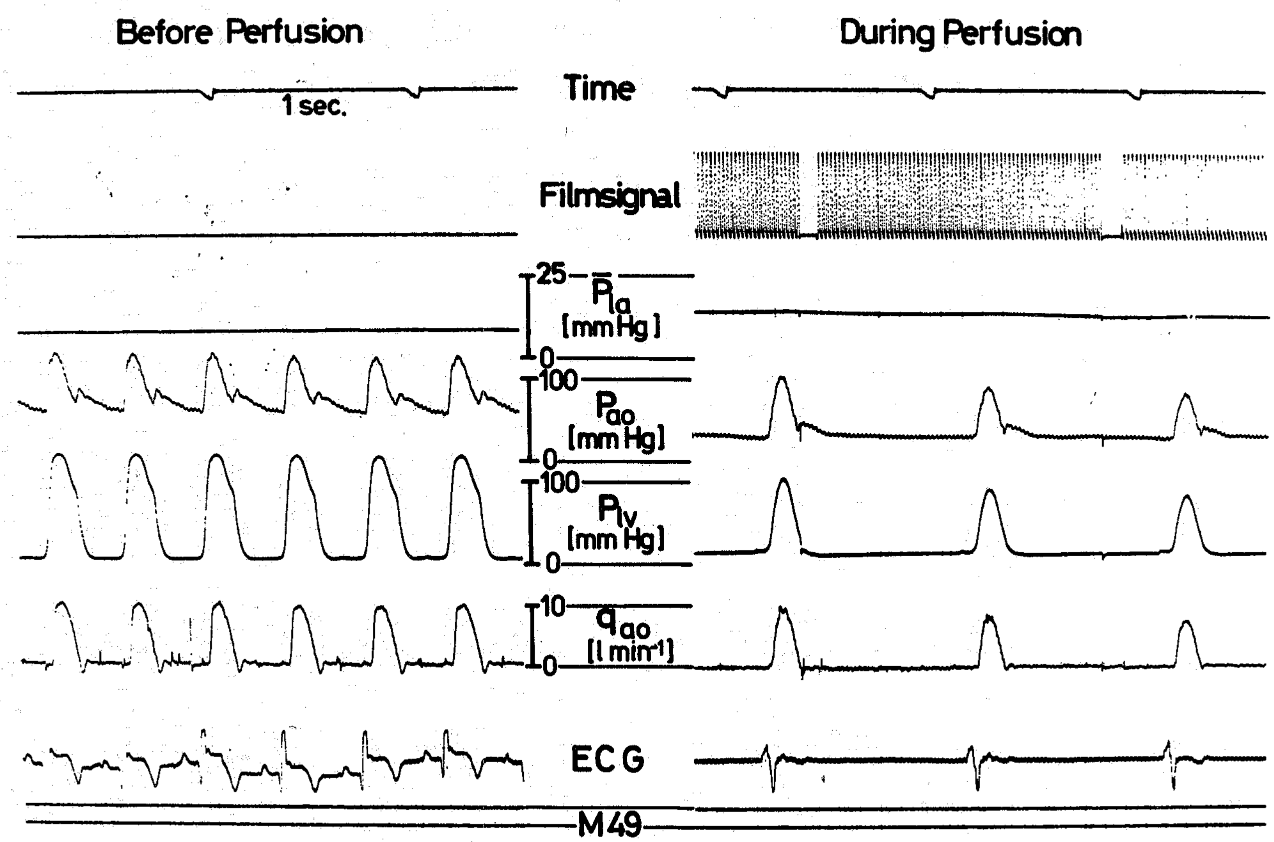

Figure 3. Recorded tracings of ECG, ascending aortic flow (q_{ao}), left ventricular pressure (P_{lv}), aortic pressure (P_{ao}), mean left atrial pressure ($\bar{P}_{la}$) and the film signal under rather normal physiological hemodynamic conditions, before and during perfusion.

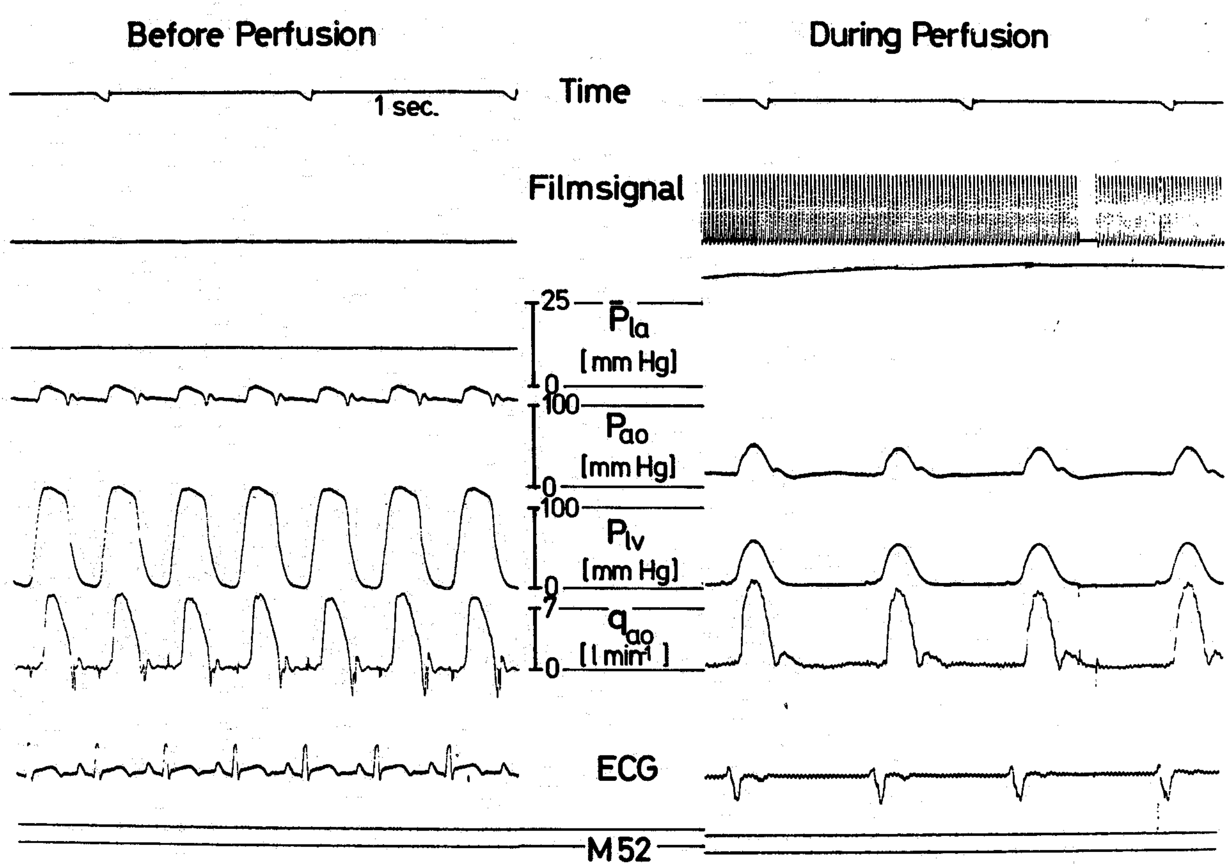

Figure 4. Recorded tracings of ECG, aortic ascending flow (a_{ao}), left ventricular pressure (P_{lv}), aortic pressure (P_{ao}), mean left atrial pressure ($\bar{P}_{la}$) and the film signal, with high left atrial pressure and low arterial pressure and viscosity, before and during perfusion.

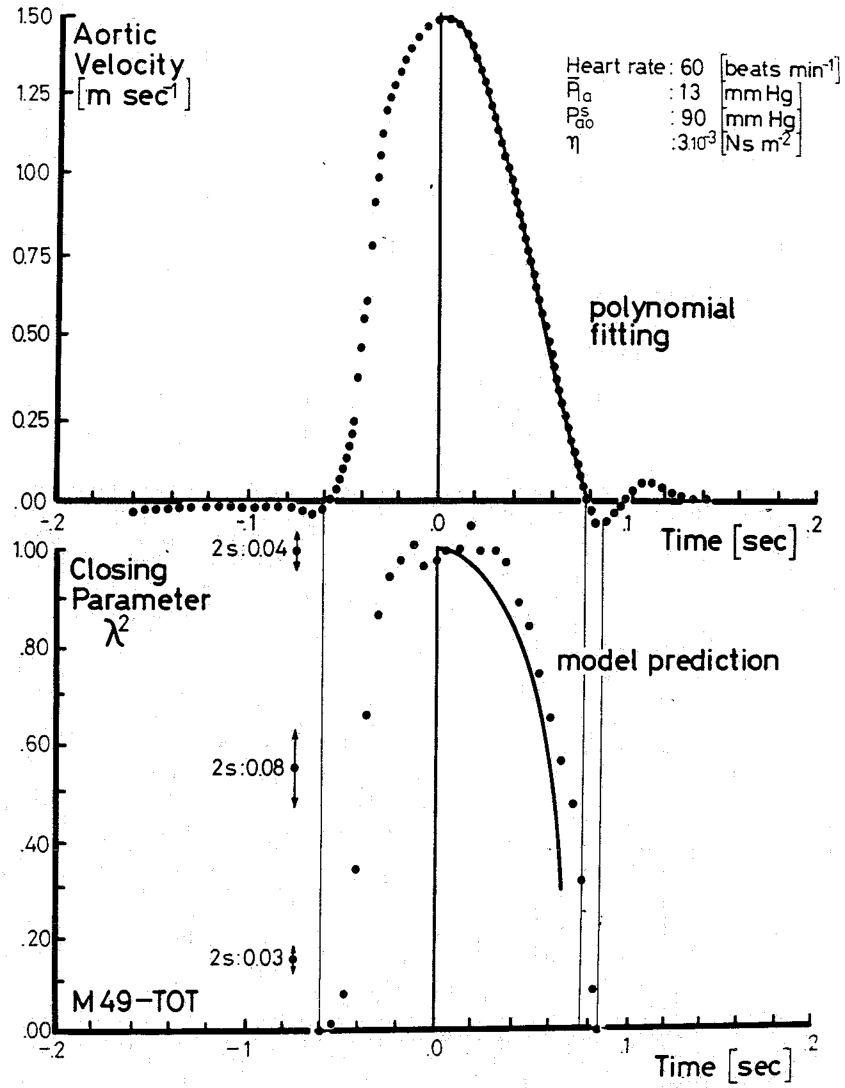

Figure 5. The relation between aortic fluid velocity (*top*) and closing behaviour of the aortic valve (*bottom*) under relatively normal physiological hemodynamic circumstances.

closing parameter equals 1, the valve is completely open and if this parameter equals zero, the valve is closed. In both graphs the dotted points represent the experimental results. The method used for describing valve movements is subject to some inaccuracy, especially when the valve is completely open. In this situation the image of the leaflet is often vague and

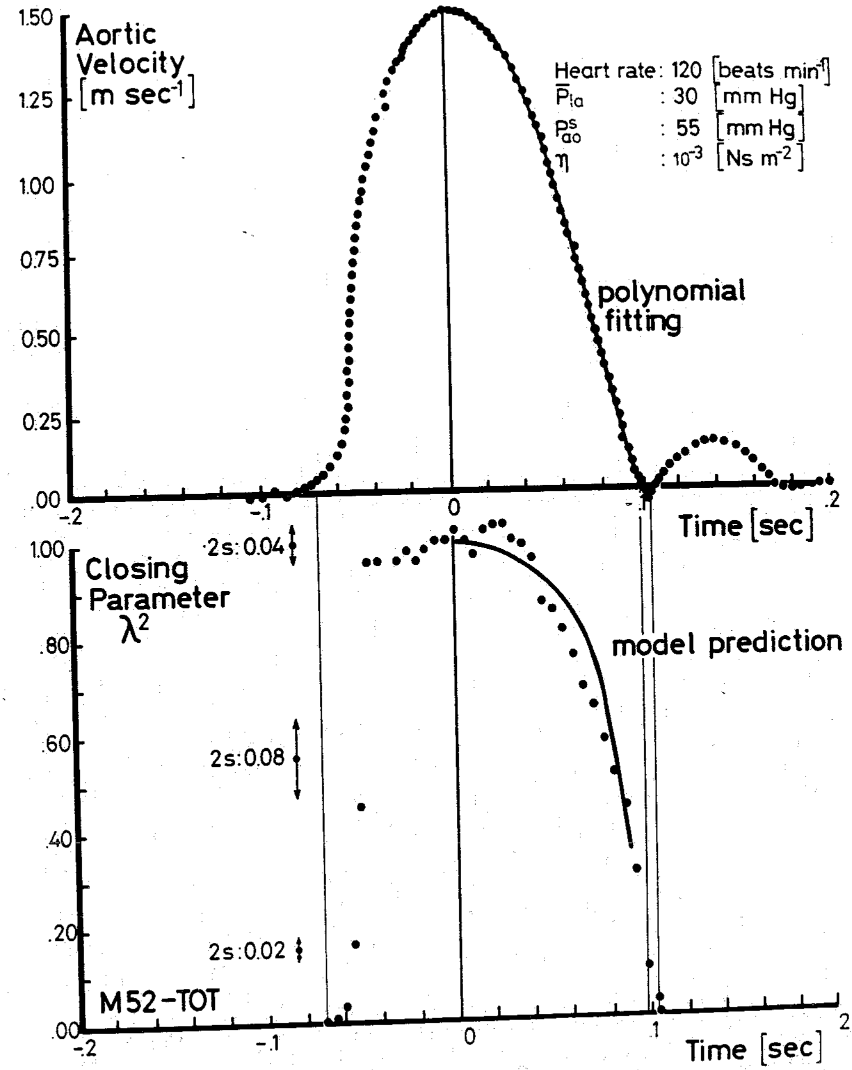

Figure 6. The relation between aortic fluid velocity (*top*) and closing behaviour of the aortic valve (*bottom*) at relatively high left atrial pressure (P_{la}) and low systolic arterial pressure (P^s_{ao}) and viscosity (η).

sometimes only parts of the leaflets can be seen. The missing parts then have to be geometrically reconstructed. Because of this procedure the closing behaviour was averaged over five heart beats, which is probably allowed since mainly random errors are involved. The 95% reliability intervals for some of the mean values of the closing parameter during the deceleration phase of systolic aortic flow are also shown in the graphs of

Figures 5 and 6. From these graphs it can be concluded that, under the different hemodynamic circumstances mentioned, the aortic valve starts to close during the deceleration phase of systolic aortic flow and that at least 80% of the closure is completed before aortic flow becomes zero. These and other experiments indicate that the moment of maximum backflow in the valve coincides with the moment of complete closure of the aortic valve.

3. MODEL STUDIES

The mechanism of the onset of valve closure during deceleration of the main flow is not yet fully understood. Bellhouse and Talbot (9) suggested that the trapped vortex within the sinus interacts with the decelerating flow field and thus pushes the leaflets into the aorta. However, their description of this interaction is not entirely satisfactory. Their theoretical model predicts pressure differences across the cusps which seem to be quite large considering the small mass of the leaflets.

Recent experimental studies (2, 3, 4) in a two-dimensional analogue of the aortic valve (Figure 7) have shown that during deceleration of the main stream:

1. The shape of the cusp does not change very much; it rotates around its attachment line.
2. The main stream velocity profile beneath the cusp remains nearly flat.
3. A region of recirculation is clearly visible behind the cusp. The flow pattern shows some resemblance with the phenomenon of boundary layer separation.
4. A vortex is present in the sinus during the stationary phase. The maximum velocity in the sinus seems to be much lower than that in the aorta.

These observations are illustrated in Figure 8.

On the basis of these experimental results a simplified theoretical model was designed (4) in which the pressure on the sinus side of the leaflet is assumed to be constant and equal to the pressure underneath the free edge

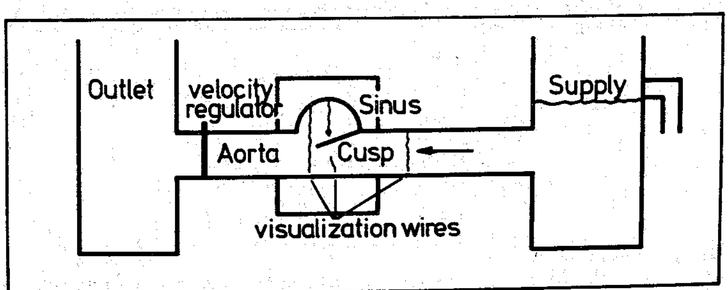

Figure 7. Diagram of two-dimensional analogue of the aortic valve.

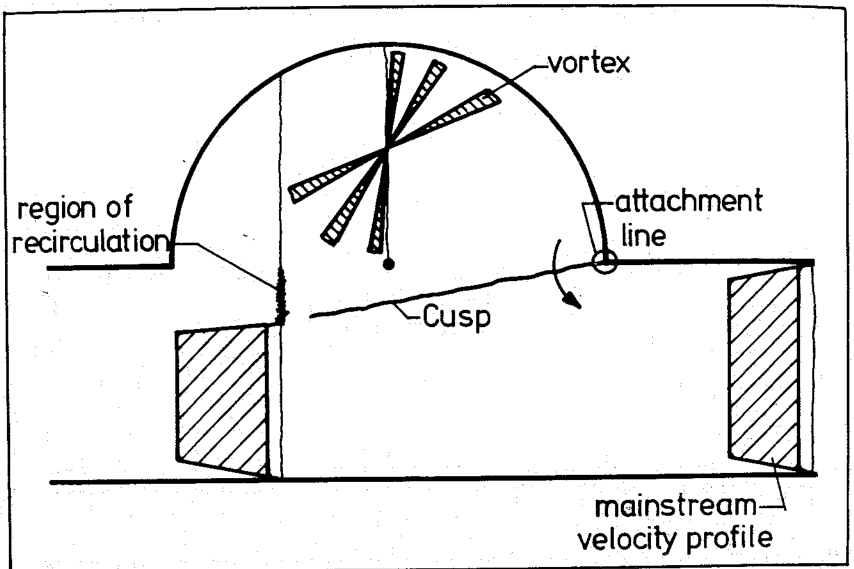

Figure 8. Diagram of the visualized fluid behaviour during deceleration of the main stream, as observed in model studies.

of the cusp. Two additional assumptions were made: the leaflet is straight and the mean pressure difference across the leaflet, because of its negligible mass, is equal to zero. From this model an equation is obtained which directly relates the aortic fluid velocity within the valve to the displacement of the leaflet.

3.1. *Application of model findings to animal experiments*

For comparison of the theoretical model with the animal experiments, the model has to be extended to the three-dimensional situation. For this purpose the cusps are assumed to be shaped as a truncated cone and the aorta to be a rigid tube. Using the same assumptions as in the two-dimensional model, after onset of deceleration ($t=0$) the following relation is found between the closing parameter (λ^2) as a function of time (t), the measured aortic velocity (u_0) and the cusp length (L):

$$\frac{d^2\lambda}{dt^2}+\frac{16}{3}\frac{u_0}{L}\frac{d\lambda}{dt}-(1-\lambda)\left(4\frac{u_0^2}{L^2}+\frac{8}{3}\frac{1}{L}\frac{du_0}{dt}\right)=\frac{2}{L}\frac{du_0}{dt}$$

for $|(1-\lambda)|\ll 1$, with initial conditions:

$$t=0:\frac{d\lambda}{dt}=0,\ \lambda=1.$$

To be able to compare the results of this theoretical model with the experimentally observed closing behaviour, shown as the points in the bottom panels of Figures 5 and 6, a polynomial curve was fitted to the experimental flow velocity signal. This curve is shown as a solid line in the top panel. Then the equation was solved numerically for this time-dependent velocity. The closing behaviour thus obtained agrees fairly well with the results of the animal experiments as evidenced by the similarity of the theoretical lines and experimental data points in Figures 5 and 6 (bottom).

4. DISCUSSION

In spite of the improvement of the experimental setup by using two roller pumps to maintain peripheral arterial blood pressure at approximately physiological levels, the hemodynamic variables during perfusion changed as compared to the control situation. Variation in these variables depends among other factors on the inflow rate in both the left atrium and the femoral artery. Therefore, aortic valve closing behaviour could be studied under various hemodynamic circumstances. Occasionally during perfusion mean left atrial pressure was found to be high compared with diastolic left ventricular pressure. It is likely that these high pressure readings result from either a too high inflow rate or an unfavourable position of the pressure catheter in relation to the inflow cannula.

The results of the animal experiments indicate that aortic valve closure already starts during the deceleration phase of systolic aortic flow and that approximately 80% of the closure is completed before aortic flow becomes zero. The moment of onset of closure of the valvular leaflets, however, is difficult to determine because the changes in valvular opening during the first part of the closing curve may be due to constriction of the aortic wall, closing of the leaflets or both. Further investigations are required to distinguish between these two phenomena. Complete aortic valve closure probably coincides with the moment of maximum backflow in the valve. This is supported by the findings in model studies which show a close relationship between the time derivatives of the closing parameter and the mainstream velocity. Moreover, the present findings are in agreement with the qualitative behaviour of valve closure as observed in model experiments reported by Bellhouse and Talbot (9).

The similarity between the closing behaviour under different hemodynamic conditions as observed in the experiment and as predicted by the theoretical model suggests that the latter describes the natural valve closure fairly well. These findings, however, should be interpreted with some caution because of the simplified model assumptions.

SUMMARY

In open-chest dogs cinematographic high-speed recordings of aortic valve movement were made using a thin flexible fiberscope. Simultaneously ECG, ascending aortic flow and the pressures in aorta, left ventricle and left atrium (LA) were recorded. Replacement of blood by a transparent liquid (Tyrode solution) was done with two roller pumps, one connected to the LA and the other to the femoral artery. Free outflow occurred through a cannula in the pulmonary artery.

Comparison of the film frames with the aortic flow signals revealed that aortic valve closure starts during the deceleration phase of systolic aortic flow and at least 80% of the closure is completed before aortic flow becomes zero. Moreover, the results of a theoretical model of closure, based upon the presence of a region of recirculation behind the moving cusps as observed in model studies, agree fairly well with the experimental results.

ACKNOWLEDGEMENTS

We are greatly indebted to Th.J.A.G. van Duppen, J. Jacobs and the Audio-Visual Centre of the Eindhoven University for their technical assistance and to Drs. N.A.L. Touwen for his aid in the computer work. We wish to thank Dr. M.E.H. van Dongen for his hydrodynamic advice and A.M.P. Barts, A.J. Manders and H.G. Sonnemans for their help in preparing the manuscript.

REFERENCES

1. Spaan JAE, Steenhoven AA van, Schaar PJ van der, Dongen MEH van, Smulders PT, Leliveld WH: Hydrodynamical factors causing large mechanical tension peaks in leaflets of artificial triple leaflet valves. *Trans Am Soc Artif Int Organs* 21:396–403, 1975.
2. Steenhoven AA van, Dongen MEH van, Spaan JAE: Two-dimensional model experiments on the closing of the aortic valve. *Trans Eur Soc Artif Organs* 3:127-131, 1978.
3. Steenhoven AA van, Dongen MEH van, Vaessen ECJ, Wasser AAM: Model experiments on the closing behaviour of the natural aortic valve. *Biomed Technik* 22:135–136, 1977.
4. Steenhoven AA van, Dongen MEH van: Model studies on the closing behaviour of the aortic valve. *J Fluid Mech* 90(1):21-32, 1979.
5. Steenhoven AA van, Schaar PJ van der, Veenstra PC, Reneman RS: The closing behaviour of the natural aortic valve: abstract. *Fed Proc* 37:217, 1978.
6. Hider CF, Taylor DEM, Wade JD: Action of the mitral and aortic valves in vivo studied by endoscopic cine photography. *Quart J Exper Physiol* 51:372–379, 1966.
7. Padula RT, Cowan GSM, Camishion RC: Photographic analysis of the active and passive components of cardiac valvular action. *J Thorac Cardiovasc Surg* 56:790–798, 1968.
8. Dee P, Crosby I: Fibre optic studies of the aortic valve in dogs. *Brit Heart J* 39:459–461, 1977.
9. Bellhouse BJ, Talbot L: The fluid mechanics of the aortic valve. *J Fluid Mech* 35:721–735, 1969.