Model experiments on the closing behaviour of the natural aortic valve

MODELEXPERIMENTS ON THE CLOSING BEHAVIOUR OF THE NATURAL AORTIC VALVE

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Introduction

The aim of our research project is to obtain parameters that determine the tension in the valve leaflets by means of theoretical and experimental models. As shown earlier [1], a proper understanding of natural aortic valve closure is essential for the construction of artificial triple-leaflet valve prostheses. As Bellhouse and Talbot [2] show the aortic valve starts to close during the deceleration phase of systole, thus preventing high tension within the leaflets at closure and minimizing blood trauma. For an optimal design of artificial leaflet valves, implementation of this natural closing mechanism could be of importance. In previous papers [3,4] we reported on our studies on the valve-closing behaviour after a sudden deceleration of the mainstream and we presented the first results of model-studies on the valve-closing during a gradual deceleration of the mainstream. Now, we will discuss more extensively our work on the valve closure during such a gradual mainstream-deceleration.

Experiments

To study the aortic valve closing behaviour and the role of the sinus of Valsalva, experiments are performed in a two-dimensional analogue of the aortic valve with a rectangular duct as the aorta and a half-cylindrical cavity as the sinus. A 2 µm thick foil (Makrofol KG) is used as cusp material. The model is scaled up to reality by means of the dimensionless numbers of Reynolds and Strouhal. The scaled model parameters have the following values: sinus radius $R = 0.045$ m, initial mainstream velocity $U_o = 0.075$ m/s, deceleration time $\tau_o = 10$ s, the fluid used being water. The flow pattern around the cusp and in the sinus is visualized by means of the hydrogen-bubble technique. The experimental information is recorded on film and photographs. Valve closure is studied during a linear deceleration of the mainstream. As reported earlier [4] it is observed that during such a deceleration the cusp remains nearly straight, and rotates around the attachment line. Behind the cusp a region of recirculation is clearly visible, which shows some resemblance with the phenomenon of flow separation.

We will discuss two new series of experiments performed in the two-dimensional model. First the dependance of valve closure on the deceleration time τ and the initial mainstream velocity is dealt with. The closing parameter λ is defined as the ratio of the narrowest cross-section below the valve cusp to the initial cross-section of the channel, while time t is reduced with respect of the deceleration time τ: $t = t/\tau$.

Figure 1 shows the experimentally found displacements, characterized by the parameter λ, as a function of the dimensionless time t^x, for different values of the deceleration time τ. Figure 2 shows the valve closing behaviour for different values of the initial mainstream velocity U. These experiments show that the experimentally observed λ(t) is slightly dependent on τ and U. For rather short deceleration times, $\tau < 0.3\ \tau_o$, the cusp does not remain straight any longer, but takes the shape that is typical for a sudden deceleration [4].

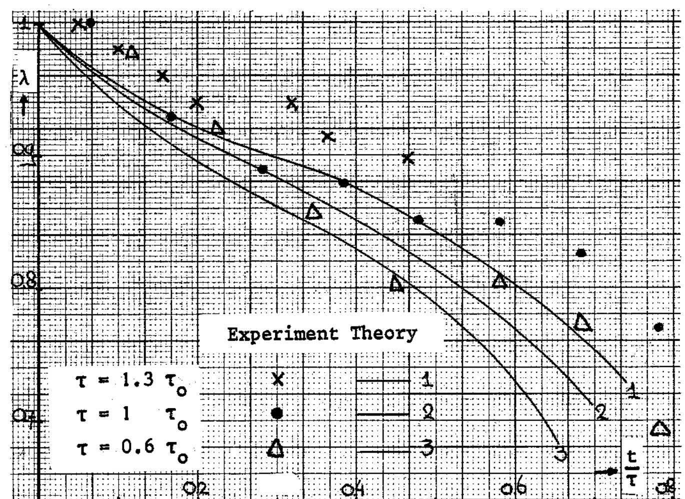

Fig. 1. The closing behaviour for different values of the deceleration time τ.

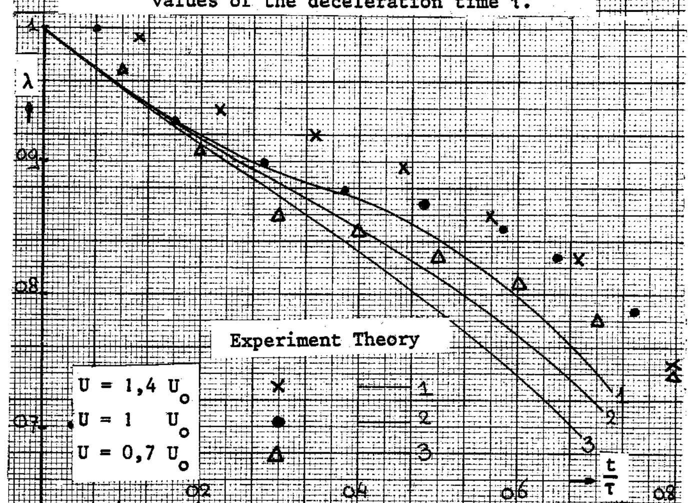

Fig. 2. The closing behaviour for different values of the initial mainstream velocity U.

Next, valve closure is investigated for different heights of the sinus cavity. This is done by filling the outer segment of the sinus with solid material. The valve-closing behaviour for different values of the sinus height is shown in figure 3. The sinus height can be reduced to less than half of its original value without a noticeable change in valve closure. If the height of the fluid cavity is reduced further, valve closure becomes more and more difficult. These experimental observations suggest that for the mechanism of valve closure in the deceleration phase of systole the presence of a cavity of a certain minimum dimension is essential, but that there is some freedom in the choice of the shape of the cavity.

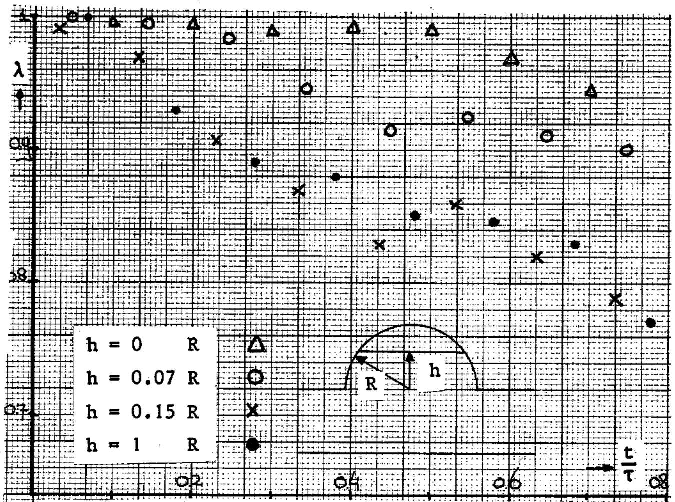

Fig. 3. The closing behaviour for different values of the sinus height h.

In both series of experiments the influence of gravity on the cusp may be neglected; in a steady state the position of the cusp was found to be independent of mainstream velocity. The experiments, however, were sometimes disturbed by a periodic motion of the free edge of the cusp.

Physical model

In order to give a description of the experimentally observed valve closure we assume that the pressure at the sinus side of the cusp is constant and equal to the pressure at the free edge. This assumption is based on the following arguments: i the path lines of the fluid in the aorta downstream the cusp are almost straight, which implies that there are no strong transverse pressure gradients; ii the observed flow velocities and the estimated fluid accelerations in the sinus are much lower that those in the mainstream.
From now on we will use the following symbols:

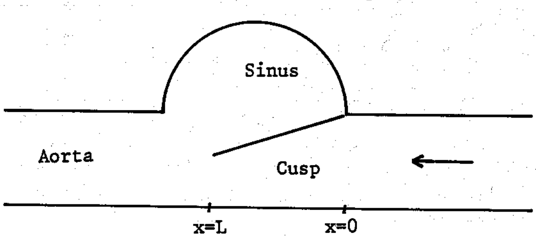

Figure 4: Schematic of the two-dimensional aortic valve model.

h_o, h_x, h_L	: aortic heights.
p_o, p_x, p_L	: aortic pressures.
u_o, u_x, u_L	: aortic fluid velocities.
L	: cusp length.
x,t	: place, time coordinate.
λ	: closing parameter defined as $\lambda = h_L/h_o$.
ρ	: fluid density.

If we assume the cusp to be straight it follows from the continuity equation that:

$$u_x = \left(u_o - \frac{\partial\lambda}{\partial t}\frac{1}{2}\frac{x^2}{L}\right)\left(1 + (1-\lambda)\frac{x}{L}\right) \qquad \text{Eq.1}$$

Assuming the flow to be quasi-one-dimensional, the instationary Bernoulli equation has the form:

$$p_x + \frac{1}{2}\rho u_x^2 = p_o + \frac{1}{2}\rho u_o^2 - \rho\frac{\partial}{\partial t}\int_0^x u_x \, dx \qquad \text{Eq.2}$$

Combination of eq. 1 and 3 yields the pressure at the aortic side of the cusp as a function of position p_x, formally expressed as:

$$p_x = p_x\left(\frac{\partial^2\lambda}{\partial t^2}, \frac{\partial\lambda}{\partial t}, \lambda, u_o, \frac{\partial u_o}{\partial t}, x\right) \qquad \text{Eq.3}$$

The mean pressure at the sinusside is assumed to be equal to the pressure at the cusp edge p_L. Then the mean pressure difference across the cusp:

$$\overline{\Delta p} \equiv \frac{1}{L}\int_0^L (p_x - p_L)\,dx \qquad \text{Eq.4}$$

is taken equal to zero, resulting in a second order differential equation for $\lambda(t)$.
This equation represents the relation between the aortic fluid velocity upstream the valve and the displacement of the cusp. The predicted cusp displacements, as a function of time, corresponding to the experimental results are shown in figures 1 and 2. It is concluded that theory and experiment show an acceptable agreement for the whole range of parameters studied, especially in view of the highly simplified pressure assumptions at the sinus side of the cusp.
The theoretical model is also applied to the natural aortic valve system, under the assumption that then the cusps will form a truncated cone. The predicted curve has been compared with the experimental results from literature [2] figure 5. Again a reasonable agreement is found.

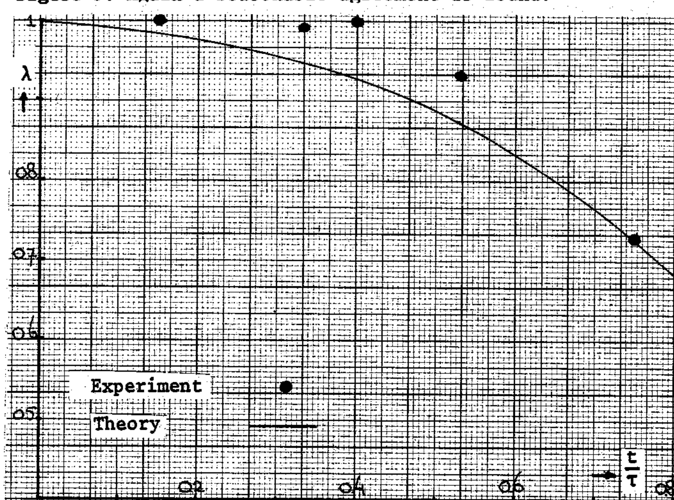

Fig. 5. The closing behaviour for the three-dimensional situation.

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References

1. J.A.E. Spaan, A.A. van Steenhoven, P.J. van der Schaar, M.E.H. van Dongen, P.T. Smulders and W.H. Leliveld: Hydrodynamical factors causing large mechanical tension peaks in leaflets of artificial triple leaflet valves. Trans.Amer.Soc.Artif.Int.Organs 21. 396-403, 1975.
2. B.J. Bellhouse and L. Talbot: The fluid mechanics of the aortic valve. J. Fluid Mech. 35, 721, 1969.
3. A.A. van Steenhoven, M.E.H. van Dongen, J.A.E. Spaan, P.J. van der Schaar, P.T. Smulders: The role of the sinus of Valsalva for the well funtioning of the aortic valve. Abstractbook Euromech. 67, 11-12, 1975.
4. A.A. van Steenhoven, M.E.H. van Dongen, J.A.E. Spaan: Two-dimensional model experiments on the closing of the aortic valve. Trans.Eur.Soc.Artif.Organs, 1976 (in press).