Aortic valve mechanics

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AORTIC VALVE MECHANICS

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ABSTRACT

Model and animal experiments emphasized the relevance of presence and flexibility of aortic sinuses in valve closure. In dogs the asymmetric deformation of aortic ring and the commissure displacements during the cardiac cycle were quantified. Finite element modelling made clear that the leaflet bundles are essential for a homogeneous stress distribution.

INTRODUCTION

The aortic valve is one of the four valves controling the blood flow through the heart and is situated between the aorta and the left ventricle. In human beings its internal diameter at the outlet side is about 20 mm. In essence the valve consists of three parts: three thin (0.6 mm) leaflets, their anchorage at the valve wall (aortic ring) and distal to each leaflet a pouched extension of the valve wall(sinus of Valsalva), see figure 1. During diastole the three leaflets recline on one another, thus forming a complete closure of the aortic inlet.

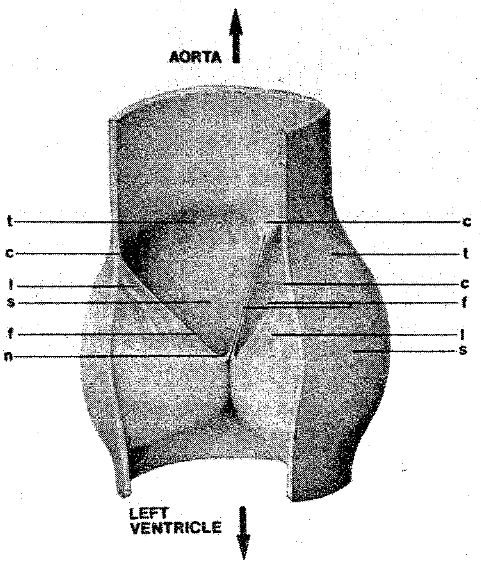

Figure 1:
Exposure of the aortic valve in the closed configuration after dissection of one leaflet and the corresponding sinus wall. (c: commissure, s: sinus wall, t: top of a sinus cavity, f: leaflet).

The typical shape of the aortic valve and the role of the various valve parts for a proper valve function have attracted scientific interest ever since Leonardo da Vinci made his first observations. Among others, significant contributions to the understanding of the fluid mechanical aspects were delivered by Bellhouse and Talbot [1], of the kinematical aspects by Thubrikar et al. [2], and of the mechanical aspects by Gould et al. [3].

Our research also focusses on the behaviour of the natural aortic valve. The main aspect of this research program concerns the determinants of the instantaneous value of the stresses in the leaflets of the natural aortic valve during the cardiac cycle. These stresses are mainly determined by the forces exerted by the blood upon the leaflets, the instantaneous three-dimensional geometry of the aortic ring and the material properties of the leaflets. These aspects are dealt with in this survey, hoping that a better insight into these aspects will lead to better specifications for the design of artificial leaflet valves. We will successively discuss our work in the area of the fluid dynamical, kinematical and mechanical analysis of natural aortic valve behaviour. In this survey we are limiting ourselves to a broad outline and do refer for more detailed information to the references cited.

FLUID DYNAMICAL ANALYSIS

To describe the interaction between the movement of the valve leaflets and the liquid flow in the aortic valve, especially while the valve is closing, model studies and in-vivo experiments have been carried out [6]. First, two-dimensional studies on the aortic valve closure were performed by means of an analogue [5,7]. As shown in figure 2 the aorta is represented by a rectangular channel and the sinus of Valsalva by a half cylinder. In between them there is a thin membrane which represents the leaflet. The experimental arrangement is made of Perspex and is thus completely transparant. The liquid flow is visualized with the use of blocks of hydrogen bubbles and the displacement of the membrane and the liquid are filmed. Especially the interaction between the contents of the cavity behind the leaflet (the sinus of Valsalva) and the aortic flow was studied when the latter is decelerating. It appears that the flow phenomena and the leaflet motion are strongly dependent on the Strouhal number, defined as $R/U\tau$, R being the sinus radius, U the maximum velocity of the mainstream and τ the deceleration time. For the aortic valve behaviour the experiments and analysis which refer

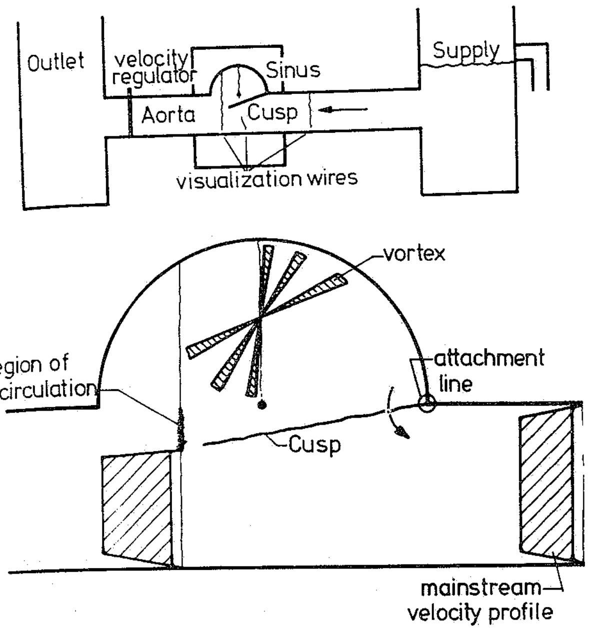

Figure 2:
Diagram of the two-dimensional analogue of the aortic valve and the visualized fluid behaviour as observed during a gradual deceleration of the main stream. From [12], with permission.

to a low Strouhal number (St<0.15) are important. In this case the leaflet remains straight and rotates slowly around its attachment. In the aorta at the rear of the leaflet a region of recirculation develops. Finally, in the sinus a trapped vortex of moderate strength can be observed. A simplified quasi one-dimensional description of the flow in the core beneath the leaflet, under the assumption of constant pressure at the sinus side of the leaflet, was found to give a qualitative picture of the initial phase of valve closure. Furthermore the influences of both the vortex and the shape of the sinus have been investigated experimentally [10]. The results indicate that the strength of the vortex does not affect the mechanism of valvular closing. The experiments also show that the geometry of the cavity is not very critical, though there is very clearly a lower limit to its depth. Finally, in a separate study [4] the stability of the valve leaflets was analysed. Just like a flag in the wind a leaflet can also carry out oscillating movements in a flow of liquid. Among other things, this appeared to be related to the difference in liquid velocity at either side of the leaflet. Hence, there is a stabilising mechanism in the aortic valve resulting from liquid flow in the sinus cavity during systole (the vortex in figure 2), which reduces the difference in velocity across the leaflet.

Next, the hemodynamics of the aortic valve were studied in open-chest dogs [12,15]. Direct cinematographic high-speed recordings of the aortic valve movement have been made after the blood had been replaced by a transparant liquid (Tyrode solution). Simultaneously, the ECG, ascending aortic volume flow (electromagnetically) and the pressures in the aorta and left ventricle were recorded. These experiments indicate that during systole the valve behaviour in relation to the aortic flow can be described as follows (figure 3). The opening of the aortic valve at the onset of systole proceeds very fast. The valve opening used to be completed within about 34 ms; the aortic flow has then reached a value of about 75% of its peak value. Under relatively physiological conditions, the shape of the valvular orifice at complete valve opening was found to be practically circular. The valve closure already starts during the acceleration phase of the aortic fluid. This early valve closure seems to be affected by the systolic aortic pressure level, the mechanism being unknown. At the onset of the deceleration phase about 8% of the closure is accomplished. The gradual closure continues during the first part of fluid deceleration; during late ejection the valve closes swiftly. At the moment of zero aortic flow, approximately 80% of the closure is completed. The remaining 20% of closure is accomplished during the back flow in the valve. The experiments suggest that complete aortic valve closure coincides with the moment of maximum back flow in the valve. Hemodynamic variables which appear to affect the closing behaviour are the systolic aortic pressure drop, which causes an expansion of the aortic root, as well as the peak aortic flow and stroke volume, which are likely to be related to the shape of the completely opened valve [16]. Comparison of the closing behaviour, as calculated from theory and as measured in in-vivo experiments under different hemodynamic conditions, shows a reasonable agreement in spite of the simplifications assumed in the model.

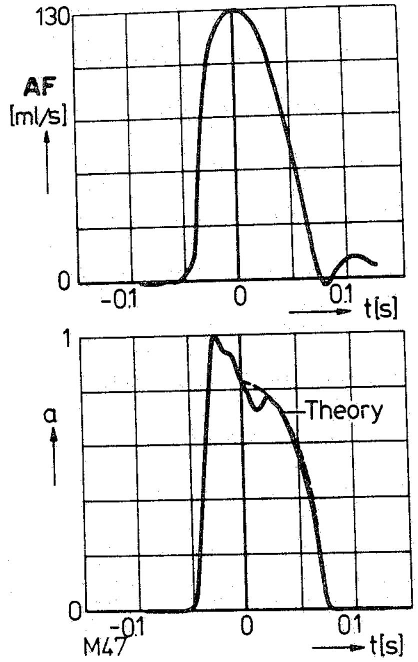

Figure 3:
The in-vivo relationship between aortic flow (q_{ao}) and the quotient of the momentary and maximum valve cross-sectional areas (a). The unbroken lines refer to the experimental results. From [15], with permission.

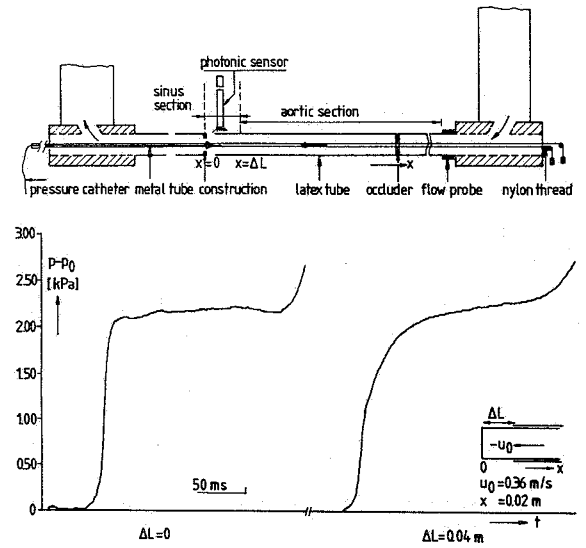

Figure 4:
Diagram of the experimental set-up to study the aortic pressure rise following valve closure and a tracing of the increase in pressure in case the compliance of the "sinus" is increased with respect to the reference situation on the left. From [25], with permission.

Finally, the importance of early valve closure in relation to the aortic pressure rise just after valve closure, was investigated in long thin-walled fluid-filled latex tubes in which the fluid is locally stopped starting from a steady flow [25]. The resulting wave-phenomena appear mathematically to be well described by the one-dimensional laws of mass and momentum. The method of characteristics is used to predict the influence of fluid viscosity and wall-viscoelasticity on the distortion of the pressure pulse while propagating upstream. Also the presence of a sinus region close to the valve was simulated. By telescoping one latex tube into another a local change in wall thickness of a factor 2 was achieved. Figure 4 shows the results in case of a compliant thin-walled sinus section of 0.04 m length adjacent to the valve and connected to a less compliant aorta. Due to the compliant sinus region the rise time of the pressure close to the valve was found to be increased. From this study it is concluded that the magnitude of the pressure rise just after valve closure is primarily determined by the back flow velocity and that the magnitude and rise-time of the pressure jump close to the valve are strongly determined by the differences in compliance between the sinus and aortic regions.

KINEMATICAL ANALYSIS

The kinematics of the aortic valve ring were investigated since the stresses in the leaflets are determined among others by the instantaneous three-dimensional geometry of this skeleton of the aortic valve [18]. To that end, natural strains in the aortic ring of the dog were determined by a specially designed and developed measuring system, which is based on an electromagnetic induction technique similar to the one as described by Arts and Reneman [11]. The measuring technique basically uses two coils. One coil transmits an alternating magnetic field, which induces a voltage in the other coil. Because of the decrease of the strength of the magnetic field with increasing distance from the transmitter coil, the induced voltage is a measure for the distance between the coils. Strain is derived from the induced voltage, using electronic circuitry and assuming that the mutual orientation of the coils remains the same [14]. In open-chest dogs a coil was attached to each of the commissure and base points of the aortic ring, using a cardiopulmonary bypass technique. After termination of the bypass and stabilization of the hemodynamic variables, strains in the aortic ring were measured during the cardiac cycle at aortic pressures ranging from 4 to 20 kPa. Simultaneously, aortic pressure at the level of the commissure points and left ventricular pressure were measured. The main results with respect to the evaluation of strains in the aortic ring during the cardiac cycle are as follows. Commissure strain followed the changes in aortic pressure throughout the cardiac cycle. The average derivative of commissure strain to aortic pressure was calculated to be $1.9\times10^{-5}\pm1.2\times10^{-5}\ \mathrm{Pa}^{-1}$ (mean ± standard deviation) at an aortic pressure of 10 kPa. Strain at a given aortic pressure was systematically higher in the ventricular ejection phase than in the ventricular filling phase. The mean difference between these phases was 0.04, whereas it is likely to be independent of aortic pressure. Hence, also in the closed valve the commissure points move outward when the aortic pressure is increased. This is the result of the balance of two forces, the one exerted

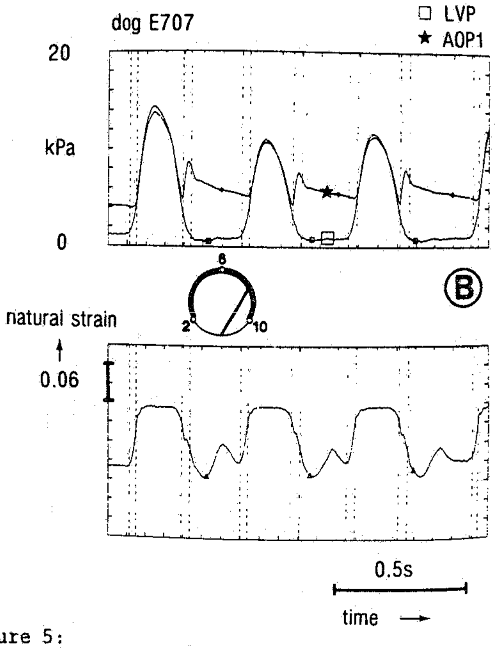

Figure 5:
Typical recording of the strain in the base plane of the aortic valve. The aortic (AOP) and left-ventricular (LVP) pressure tracings (top pannel) are also shown. Each interval along the time axis corresponds with 75 ms.

by the leaflet upon its commissure point, the other determined by the circumferential component of wall tension in the sinuses of Valsalva. All strains in the base plane of the valve were also found to vary during the cardiac cycle (e.g. the tracings in figure 5). The base plane is here defined as the plane intersecting the three base points, whereas the base circle is the circle through these points. The maximum variation during the cardiac cycle ranged from 0.03 to 0.15 and the deformation was strongly asymmetric. Base strain along a segment, adjoining the myocardium at the base circle of the valve, decreased during the ventricular ejection phase. This decrease is likely to be a result of contraction of the myocardial wall of the ventricle and the septum. Base strain along a segment, adjoining the non-contracting anterior mitral valve leaflet, increased during the ventricular ejection phase. This strain was measured along passive collageneous tissue in between the mitral and aortic valve orifice. The increase of this strain during the ejection phase may result from a combination of stretch of the collageneous tissue caused by the increased left ventricular pressure, and forces exerted upon the tissue by the myocardial wall and the mitral and aortic valve. Finally, the strain between a base and a commissure point of the aortic ring showed no specific course as a function of time.

MECHANICAL ANALYSIS

For the design of a theoretical model describing the mechanical behaviour of the leaflets of an aortic valve in its closed configuration, first the histological structure and the mechanical properties of valve tissue were investigated [13]. For both studies porcine aortic valves obtained from the slaughter house were used. Following staining with a combination of orcein for the elastin fibres and van Gieson's picrofuchsin for the collagen fibres, the sections (10 μm) were studied by light microscopy [9]. The valve leaflet appeared to have a triple-layered structure (see figure 6): a dense layer composed of mainly collagen fibres and bundles, oriented in one particular direction, at the aortic side, a grid of randomly oriented elastin fibres at the ventricular side and, in between, a loosely structured layer. The sinus walls consisted of mainly circumferentially arranged smooth muscle cells embedded in a grid of elastic tissue with no special fibre orientation. The attachment of the leaflets to the sinus walls is constituted by the aortic ring, a crownlike fibrocartilaginous structure containing large amounts of collagen fibres. A striking finding was the considerable constriction in the centre of the leaflet, in the vicinity of the aortic ring parallel to the ring. This constriction can be regarded as an (elastic) hinge enabling the leaflet to carry out movements during opening and closing of the valve without the occurence of any major flexural stresses.

The mechanical properties of the leaflets as well as the sinus and aortic walls were investigated in vitro in uniaxial tensile experiments [20]. Tissue strips, taken in different directions from the various parts, were stretched with constant strain rates and subsequently kept at a constant stretched length (see figure 7). Care was taken not to exceed the physiological strain ranges. Considerable differences were found between the stress-strain curves of the leaflet tissue on the one hand and the sinus and aortic tissues on the other. These differences can be explained qualitatively by their different histological structures. In the leaflet-tissue strips, cut in the direction of the collagen bundles (circumferential direction), a considerably higher stress was required to produce a certain strain than in the specimens taken perpendicularly to the bundles (radial direction). The tangent moduli in the circumferential direction were by more than a factor 10 higher than in the radial direction. In the sinus and aortic walls no

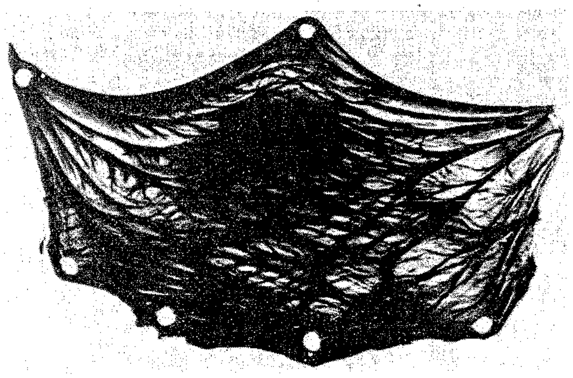

Figure 6:
A leaflet taken from a porcine aortic valve. From [9], with permission.

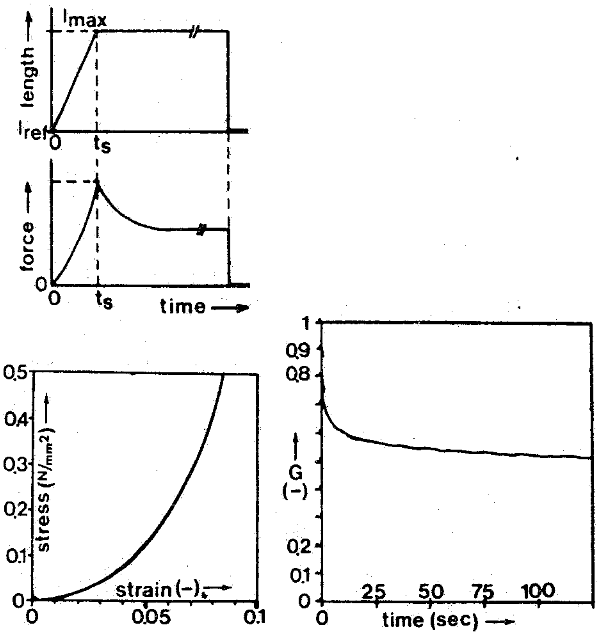

Figure 7:
Schematical representation of the experimental set-up to determine the elastic and viscous properties of fresh leaflet tissue and typical stress-strain and relaxation curves.

pronounced differences were observed between the stress-strain curves of tissue strips taken in two perpendicular directions. These tissues appeared to be much more compliant than the leaflet tissue. Their tangent moduli were by a factor 2 to 10 smaller than the corresponding values for the radial leaflet specimens. The characteristics of the leaflet tissue clearly reflect the stiffening function of the collagen bundle structure. The high compliance of the sinus and aortic walls was consistent with their high elastin content. The insensitivity of their characteristics to direction can be explained by the random character of the fibre orientation. After applying a certain strain with a constant, high strain rate the stress in the leaflet specimens decreased by 37 to 50% of its maximum value during the constant-length phase of the experiments. In the sinus and aortic strips this decrease ranged from 25 to 37%. The long-term relaxation behaviour of the specimens showed no distinct dependence on the direction in which they were cut. More experimental data are needed to decide whether this applies to the short-term behaviour as well. The stress relaxation in the specimens was analysed using the quasi-linear viscoelastic model as proposed by Fung [19]. Prediction based upon this model indicates that on cyclic loading the viscous losses in the leaflets are relatively large as compared to the losses in the sinus and aortic walls. This may be particularly relevant for the valve in dynamic situations.

The theoretical modelling of the mechanical behaviour of the closed valve under pressure load was based upon the methods of finite elements. Nonlinear aspects- geometrical and constitutive- were included in the considerations. Here two types of elements were used, namely cable and membrane elements. The cables were used to schematise the collagen bundles whereas the membranes were used in modelling the elastin layer in the leaflets. The aorta was represented by a rigid cylinder and hence all displacements of the leaflet at the intersection of the leaflet and the aorta (the aortic ring) were suppressed, although rotation of the leaflet was still possible at this intersection. With this model the mechanical significance of the bundle structure in the leaflets of the closed valve was studied. With and without bundles the principal stress directions in the membranous parts were found to be almost coincident with the circumferential and radial directions. Without bundles maximum principal stresses occurred in the circumferential direction.

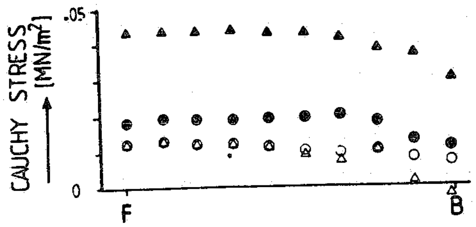

Figure 8:
The calculated stress distribution in the circumferential direction of the leaflet with (o ●) and without (Δ ▲) bundles. Solid and open symbols represent maximum and minimum stresses, respectively.

The effect of the bundle structure appeared to be twofold. The bundles transmit the pressure load on the membranous parts to the aortic wall. At the same time they cause a more homogeneous stress distribution in these parts by reducing the maximum principal stress values to the level of the minimum principal stresses (see figure 8). The values of the latter remained almost unchanged in comparison with their values in the case without bundles. Because with bundles the stresses in the principal directions became nearly the same, shear stresses in the membranes are negligibly small.

CONCLUSIONS

The three areas of basic research described up to this point, have dealt with the total functioning of the aortic valve, from leaflet movements to stress distribution in the leaflet. The immediate objects of research are the unique mechanisms which enable the valve to function so long and so well. Although a number of aspects are still subject to investigation the following preliminary conclusions can be drawn:

- early closure of the valve during systole thanks to the action of a cavity behind each leaflet;
- reduction in leaflet instability by virtue of the presence of a directional liquid flow in the sinus of Valsava;
- reduction of leaflet stresses immediately following closure as a result of the high degree of sinus compliance;
- lowering of stresses in the leaflets due to the movement of the commissures of the aortic valve ring;
- optimum absorption of stress and transmission of force in the valve, as a consequence of its specific structure and tissue composition;
- diminution of flexural stresses in the leaflets as a result of the presence of a hinging point in the leaflet.

In ongoing research we try to implement the observed stress-reducing mechanisms acting in the natural aortic valve into the design of an artificial leaflet valve prosthesis [21-24].

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