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Fundamental mechanics of aortic heart valve closure

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Abstract

Stresses in a prosthetic heart valve at closure are determined by its geometrical and structural characteristics, by the mechanical support environment, and by the momentum of the valve leaflets or occluder and of the blood at the instant of closure. The mass of blood to be arrested is significantly greater than that of the leaflets or occluder, and is therefore likely to dominate the closure impulse. The kinetic energy of the blood must be transduced into potential energy in the structural components (valve leaflets, aortic root and aorta). This paper presents a methodology for computation and parameterisation of the blood momentum associated with a valve in the aortic position. It is suggested that the influence of physiological parameters, such as systolic waveform and systemic impedance, on the closure characteristics can be investigated based on the fluid dynamic implications. Detailed results are presented for a single leaflet mechanical valve (Bjork-Shiley 60° Convexo-Concave). It is demonstrated that a simple analytical method can yield results that might be adequate for the purposes of valve design.

Keywords: Heart valves; Closure; Impulse; Blood momentum; Computational fluid dynamics

1. Introduction

Structural analyses of the closure characteristics of a heart valve prosthesis have tended to focus on the movement and arrest of the valve leaflets or occluder under the action of assumed fluid pressures (Black et al., 1991; Blick et al., 1995; Yuan et al., 2003). It is suggested, however, that the magnitude of the closure impulse is driven by the momentum of the blood rather than by that of the occluder. Furthermore, the actual motion of the valve during the closure phase is determined by complex interaction of fluid dynamic and structural system characteristics. Only a coupled fluid-structure analysis can address these issues adequately. The purpose of this paper is to present a simple methodology by which impulse force and moment associated with the closure of a single leaflet mechanical heart valve prosthesis might be estimated, and to compare the result with that of a coupled solid–fluid analysis in the context of the Bjork-Shiley Convexo-Concave (BSCC) 60° valve.

2. Methods

The force of impact depends on a complex interaction of fluid dynamic and structural system characteristics. It is suggested, however, that valve closure can be separated into two parts, namely a pre-impact and a post-impact phase. In the pre-impact phase the main question is how the valve occluder is entrained in the flow, and therefore how much momentum is built up before the valve reaches the closed position. The momentum of the fluid is large compared with that of the occluder. In the post-impact phase the impulse (units

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Nomenclature

c	Pressure wavespeed in aorta
F	Constant force on aortic valve associated with travelling stress wave
h	Offset of rotation axis of single disc valve occluder from tube axis
L	Rotational momentum of fluid mass surrounding valve
p	Constant pressure on each side of aortic valve associated with travelling stress wave
Q	Flow rate
R	Occluder radius
$\bar{v}$	Spatial mean velocity
$\dot{\theta}$	Rate of rotation at the instant of closure
ρ	Density of fluid

of force multiplied by time) is translated into stresses in the structural system. The benefit of the separation into two phases is that the influence of the physiological characteristics that determine the fluid momentum at closure, and thus the impulse, can largely be separated from the structural characteristics that determine the stress distribution on the valve structure at closure. In this paper, the influence of patient physiological parameters on computed closure momentum for a single leaflet valve in the aortic position is explored. In the pre-impact phase, a coupled analysis is performed to compute the motion of the occluder. At a given position the occluder is arrested instantaneously, and the subsequent history of the forces on it as the fluid is also arrested are computed. A primary thesis of this paper is that the closure impulses (force or moment integrated over time) are governed by physiological parameters and by the fundamental geometry of the valve (single disc, off-axis rotation) rather than by subtleties in the mechanics of closure.

2.1. Physiological factors

This paper focuses on the aortic valve. Reverse flow is reported as far as the femoral arteries (Evans and Martin, 1988). It would be inappropriate to include all of this momentum in the closure computations, since most will be arrested long after the primary closure impulse is dissipated. A compressive stress wave moves away from the valve at a speed, determined by the elasticity of the aorta, of 410 m/s (McDonald's Blood Flow in Arteries, 1990). It is suggested that the important physiological factors governing aortic valve closure might be (i) the flow waveform, (ii) the pressure wavespeed and (iii) systemic resistance and compliance.

In the current study, a systolic forward-flow waveform reported by Snell et al. (1965), illustrated in Fig. 1, has been assumed. Two parameters are varied, systolic duration and total flow. The justification for selection of flow as the inlet condition during the period of forward flow is twofold: firstly the alternative of prescription of pressure means that the results depend on the extent of the fluid domain, and secondly the heart will tend, over the longer term, to adjust pressure and ventricular

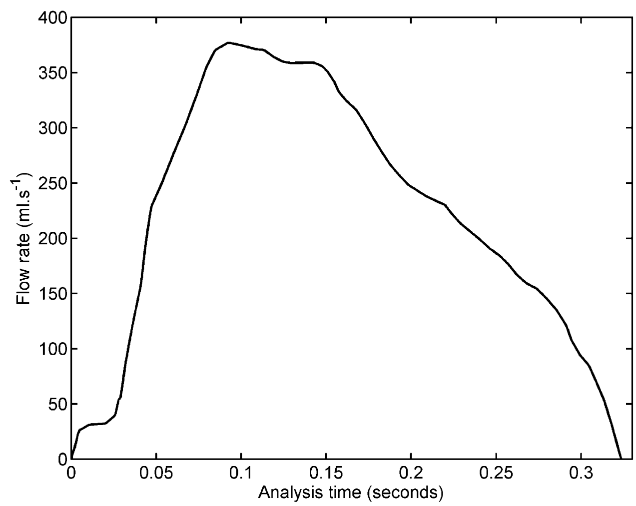

Fig. 1. Aortic flow waveform (volume flow vs. time) over systolic forward flow (based on Snell et al., 1965).

volume to achieve appropriate systolic ejection. Closure impact occurs after the end forward flow and the waveform affects the closure only indirectly. It is assumed that the rate of decline of the flow towards the end of forward flow is governed by the rate at which the ventricle is relaxing, establishing a negative spatial pressure gradient from the ventricle to the aorta. At the end of forward flow, the proximal boundary conditions are changed from prescribed flow to prescribed pressure. The pressure and temporal pressure gradient ($\mathrm{d}P/\mathrm{d}t$) computed at the inlet at the instant of zero flow are used to define the latter period of the analysis. The temporal rate of change of pressure in the ventricle ($\mathrm{d}P/\mathrm{d}t$) is assumed constant during this period (30–50 ms). A typical pressure/time waveform is illustrated in Fig. 2. A sharp rate of decline of forward flow, associated with a rapidly reversing pressure gradient, might induce fast valve closure.

The systemic resistance and compliance determine the effective back-pressure, and thus the rate at which the fluid is accelerated backwards towards the ventricle. The time constant is long (~1 s, Wieting et al., 1999) compared with the closure period (< 50 ms), and so the closure momentum is relatively insensitive to these parameters.