Modeling Valveless Blood Flow in the Embryonic Heart and Artificial Pumping Devices

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In humans, the heart starts its contractile activity around day 21of embryonic development. At this developmental stage, the heart is a relatively tubular thick-wall vessel. The embryonic heart growths rapidly during the fourth week of development in a process that includes elongation, looping and increasing of diameter occur. In addition, chambers of primitive atriums and ventricles are formed. For almost 100 years it was accepted that the pumping action of the heart is induced by myocardial peristaltic waves. Recently, it was suggested that the embryonic heart works as a dynamic suction pump like the valveless Liebau pumping phenomenon. Previous studies of valveless pumping were concerned with either optimization of the conducting system or exploration of the mechanisms that generate the unidirectional periodic flow. All the studies assumed a uniform cylindrical compliant tube, and in most cases a thin-walled tube was treated. In order to explore the effect of asymmetries in the tube geometry on the pumping function of the embryonic heart we developed a one-dimensional (1D) model of fluid flow through a collapsible tube with varying internal diameters and a sinus-like cave at an asymmetric longitudinal position where periodic external pressure was applied (Fig. 1). The non-dimensional governing equations (e.g., continuity, Navier-Stokes and tube law) were solved by utilizing MacCormack numerical method. In addition, we also developed an axisymmetric two-dimensional (2D) model using ADINA commercial finite-element package. The results obtained from the 1D simulation were in good agreement with those obtained from the 2D ADINA-based model (Fig. 3). The simulations revealed that unidirectional pumping is due to the suction-like process initiated by the additional volume within the local sinus-like cavity, difference in the left and right fluid resistance and inertia effects. A sensitivity analysis showed strong dependence of the unidirectional net flow on the excitation parameters and location, which was widely described in previous studies. In addition, geometric asymmetries in the tube internal diameter can also increase the unidirectional net flow. This model provides an initial understanding of geometry effect on the pumping function of the embryonic heart, but three-dimensional simulations are required to fully understand the pumping mechanism of the embryonic heart.

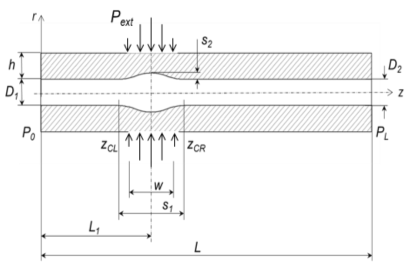

Figure 1. The model of embryonic heart.

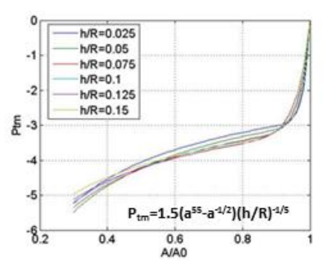

Figure 2. Similarity tube law for different *h/R* ratios.

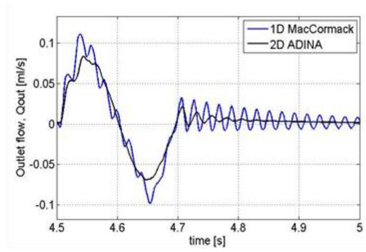

Figure 3. The outflow during one excitation cycle obtained from 1D and 2D numerical simulations.