Chapter 6

Dynamic Role of the Cardiac Jelly

Before looping, when the embryonic heart is still a straight tube, the cardiac jelly occupies the bulk of the heart tube walls. Despite its preeminence in the tube composition, there is still no understanding on its role, if any, in pumping.

Using the latest findings in impedance pumping in the heart[25], a multilayer impedance pump (MIP) which design has been inspired from the embryonic heart structure features a gelatin layer similar to the cardiac jelly has been developed. The gelatin layer in the MIP amplifies elastic waves and requires only small amplitude of excitation. However the presence of this layer reduces the fluid domain by almost 50%. Is the addition of the gelatin layer in an impedance pump (IP) a benefit to the pumping performances? By extension, would the embryonic heart with the added thick gelatinous cardiac jelly layer be an optimized valveless IP?

To explore the role of the cardiac jelly role, two models of IP with and without an added thick gelatinous layer will be compared. Finite elements based simulations are carried out for the two IP models and exit flow rates are compared. The Multilayer gelatin-coated impedance pump produces a higher flow and has a higher efficiency compared to a Single Layer IP (SLIP). The results agree with a second model of MIP with a thicker and stiffer gelatin layer. Conclusions are drawn on nature’s optimal pump design of the embryonic heart.

6.1 Properties of the cardiac jelly

Cardiac jelly is a gelatinous acellular material lying between the endothelial lining and the myocardial layer of the heart at early stages of heart development when the heart is if tubular shape. It has been first characterized by Davis[18] in 1924 who gave it its name of *cardiac jelly*.

Cardiac jelly is a relatively homogenous network of collagen fibrils and fine filaments. The structural part of the jelly is ensured by the elastin and collagen scaffold, whereas its gel like appearance is controlled by glycosaminoglycan, a protein involved in the degree of hydration of the jelly. The cardiac jelly is populated by several types of proteins that participate in paracrine cell-cell communication, and proteins that promote cell migration and tissular remodelling.[14,17,57]

Little is known on the different roles of the cardiac jelly. As an extracellular matrix, it serves as a substratum for the diffusion of growth factors derived from the myocardium to the endocardium.[17,24] During the heart development, the cardiac jelly plays a central role in heart valve development and septation of the heart.[57]

The cardiac jelly may have a mechanical role in the formation of the heart tube and later in pumping. Davis[18] was first to emphasize its significance in giving mechanical cohesion to the two layers of the heart. During the fusion of the endocardial tubes that form the tubular heart, the cardiac jelly may increase the adhesiveness between the two tubules by a physical effect.[18,30] Barry[9] in 1948 used a simple geometrical reasoning to justify the presence of the cardiac jelly for pumping before valve formation. He assumed a peristaltic beat along the length of the tube similar to the one of figure 1. For such a thin-walled tube, using a tube of large radius will result in a large stroke. However, if one considers a myocardial shortening of 20% upon contraction, this thin-walled tube will not be closed upon contraction, and the peristaltic motion will result in barely any flow. Barry showed that this dilemma can be solved by using a thick-walled tube made out of an incompressible material that would transmit the force of contraction (figure 23). In addition, he calculated that in order to achieve full closure of the heart tube, this layer should have a thickness equivalent to 45% of the external radius of the tube at rest.

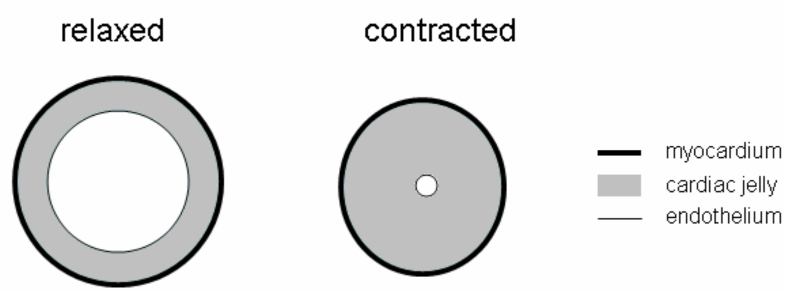

Figure 23. Simplified model of embryonic heart tube. Cross sections in relaxed and contracted states. A slight reduction of the external diameter leads to full closure of the tube thanks to the thick incompressible internal layer.

These results rely on the hypothesis that a peristaltic wave motion drives blood through the heart. However, the recent imaging techniques have helped to show that the embryonic heart may act as an IP instead.[25] In an IP, wave propagation and reflection are at the core of the pumping mechanism, and the gelatin is an especially adequate material for elastic wave propagation. The thickness of the gelatin layer ensures the amplifying of the elastic waves, while its softness ensures minimal damping and stronger wave interactions.

We propose to investigate on the gelatin as a requisite for optimal pumping in an IP. Because of its unique gel like constitution, we will focus on the elastic properties of the cardiac jelly in pumping and their contribution to achieve significant flow.

6.2 Numerical simulations

6.2.1 Models

We compared two IPs using finite elements numerical simulations. The first pump model was the MIP as introduced in chapter 2 (see table 2 for geometry and material properties). The second pump model was the classic SLIP model, being a simple fluid-filled elastic tube. The SLIP was the exact MIP geometry with the gelatin-like layer removed (figure 24). The two models were excited at the same frequency (f=10 Hz). The same boundary conditions as defined in chapter 2 were applied to each pump. To ensure numerical validity, the classic IP has been modeled with as many elements (9,250 fluid elements and 1,250 solid elements) as the MIP for which validation tests have been conducted (section 3.1). The same 1,000 time steps per pinching cycle were used to march throughout the transient simulations, and simulations are carried on until periodicity in the exit flow is achieved.

6.2.2 Exit flow rate variation in time

In the single layer and in the multilayer pump models, the exit flow (16) history plots shows a transient phase where the flow is building up before reaching a steady state of periodic oscillations and constant mean value (figure 25). When averaged over a period of time, the gelatin-coated pump produces a net forward flow of 84.28cc/s whereas the classic pump produces only 7.77 cc/s.

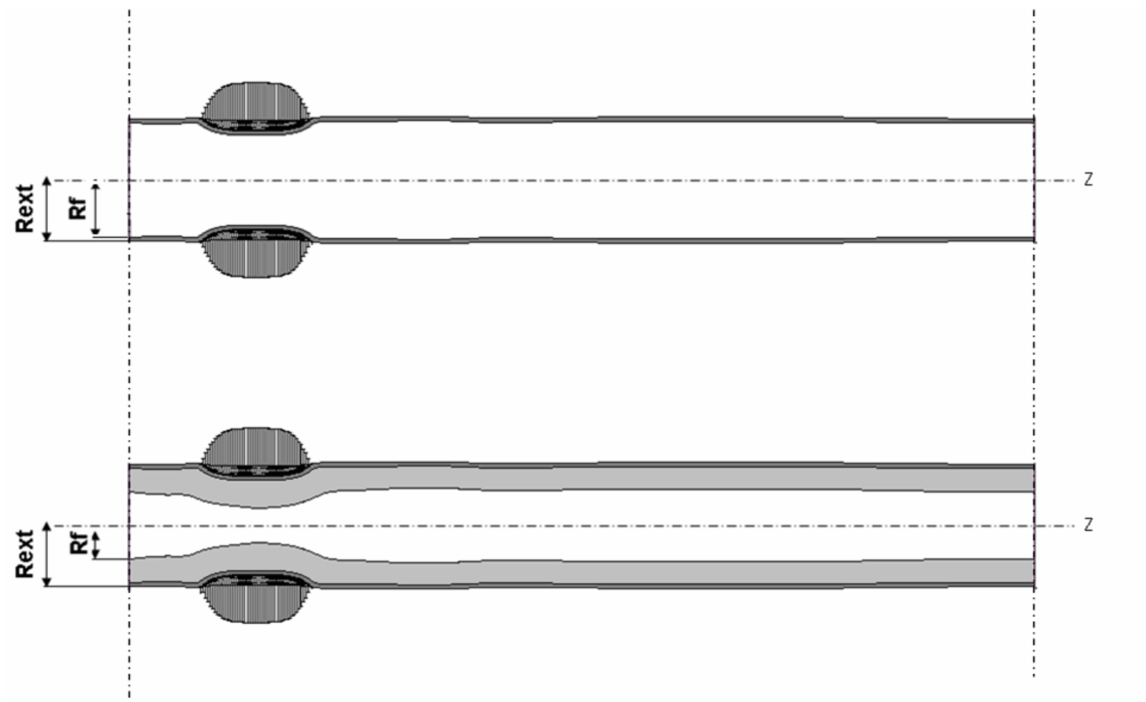

Figure 24. Comparative 2D axisymmetric longitudinal views. (Top) Single layer IP. (Bottom) Gelatin-coated multilayer IP.

6.2.3 Compared performances

Using the equivalent Poiseuille model introduced in section 3.13 we compute and compare the performances of the two pumps. Due to the thickness of its walls, the work to actuate the MIP is about 3 times greater than the work dispensed to actuate the SLIP. However, for the small excitation imposed, the SLIP is not capable of producing neither bulk flow nor pressure. As a consequence, its efficiency is practically zero. Using a gelatin layer in an IP configuration promotes the elastic wave interactions, and results in higher pressure and flow. By the addition of the layer the efficiency jumps from 0% to 35%.

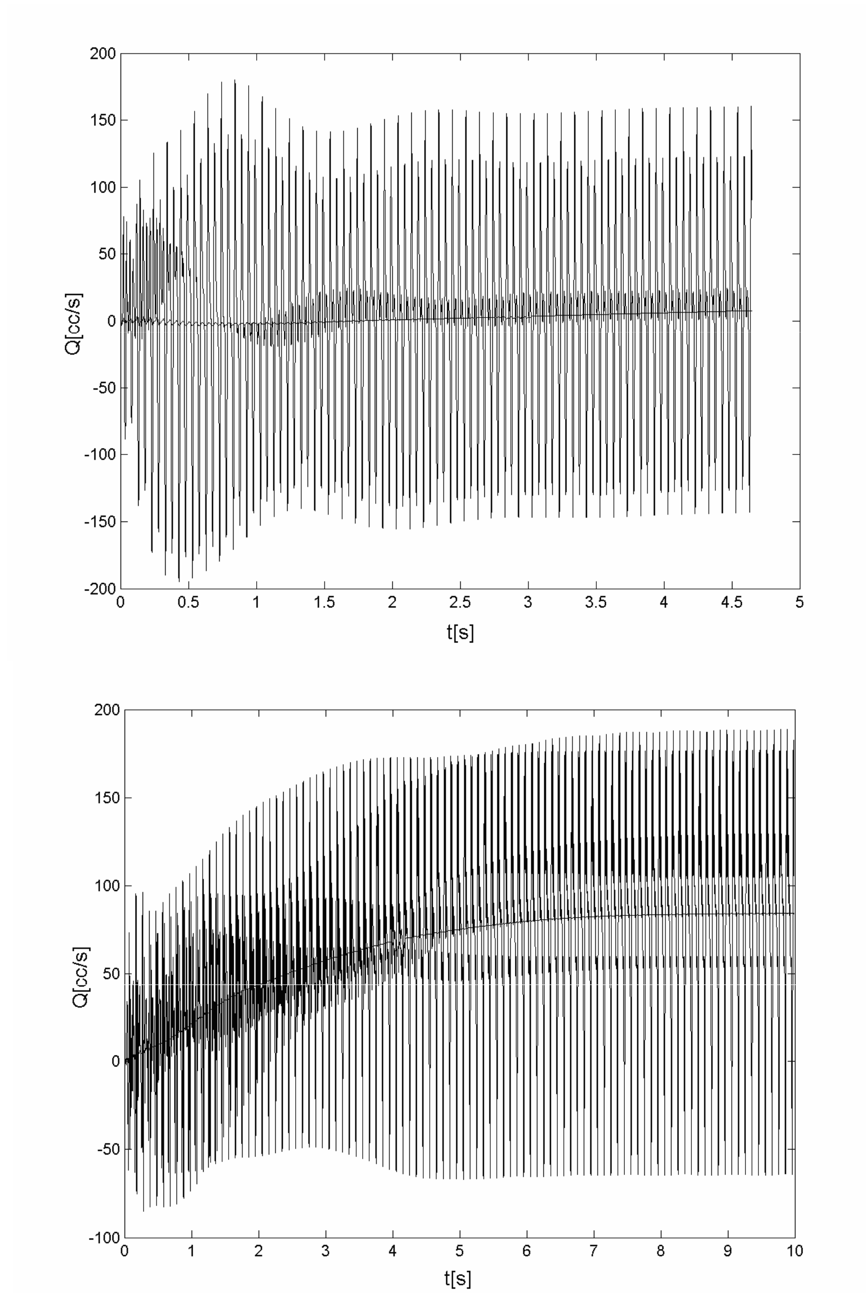

Figure 25. (Top) Exit flow rate history plot for the SLIP. (Bottom) Exit flow rate history plot for the gelatin-coated MIP. Excitation frequency is *f*=10 Hz. The solid line is a filtered curve of the flow rate using a moving average window of one cycle. Mean flow in the SLIP is 7.77 cc/s. Mean flow in the gelatin-coated MIP is 84.28 cc/s.

Table 4. Comparison of the flow, typical pressure inside the pump, pumping work, actuation work, and efficiency between the SLIP and MIP for the same excitation conditions.

	Single Layer IP	Multilayer IP
Exit flow	7.77 cc/s	84.28 cc/s
Axial Pressure Peaks	-3 e+4 dyn/cm^2 +2 e+4 dyn/cm^2	-0.6 e+4 dyn/cm^2 +3 e+4 dyn/cm^2
Pumping Work	25.25 erg	3.82 e+3 erg
Actuation Work	1.07e+4 erg	2.9 e+4 erg
Efficiency	0.0024	0.35

6.2.4 Validation with a second MIP model

We carried on a second comparison test with a different gelatin-like layer. A slightly modified MIP that featured a stiffer (E_{gel}= 5 e+5 dyn/cm2) and thicker (h_{gel} = 0.7 cm) gelatin layer was compared to the SL_IP, the latest being the same as the one introduced in section 6.2.1. The modified MIP and the SL_IP were actuated at 10 Hz.

We find again a clear increase in the exit flow rate in this second version of gelatin-coated pump (figure 26). The mean exit flow in the gelatin pump reaches -61.31 cc/s. The negative sign means that bulk flow is directed toward the pinching zone.

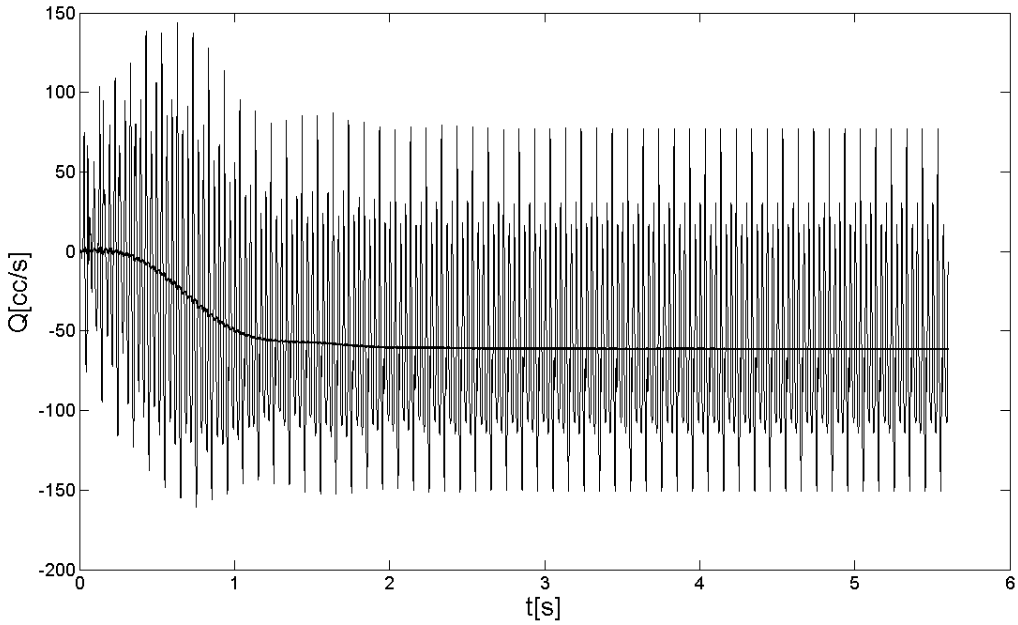

Figure 26. Exit flow rate history plot for the second test case of MIP with a modified gelatin layer. Excitation frequency is *f*=10 Hz. The solid line is a filtered curve of the flow rate using a moving average window of one cycle. Mean flow reaches -61.31 cc/s.

6.3 Nature's design: Importance of the cardiac jelly

We compared two models of IPs as models of embryonic heart pumping in the scope to understand the role of the cardiac jelly in the pumping performances. The first model is a classic SLIP. The second model is the exact same pump enliven by an internal gelatin-like layer, the MIP. This pump is a macroscopic model of the embryonic heart in which the gelatin layer represents the cardiac jelly. We excited the MIP and its single layer counterpart at a specific frequency (*f*=10 Hz). The pump that features the gelatin layer had an exit flow rate of more than 10 times higher than the exact same pump without the gelatin. It is all the more remarkable that adding the gelatin layer reduces the fluid volume by 42.1%. We tested a second model of MIP that featured a thicker and stiffer gelatin layer. Again, the exit flow of the gelatin-coated pump was much greater than the classic impedance pump (about 8 times). Therefore, for a classic impedance pump excited at a specific frequency, it is possible to design an associated gelatin pump that would enhance flow performance by the solely adjustment of the gelatin thickness and material properties. By extension, the cardiac jelly presence in the embryonic heart may be considered as an optimal designed layer. Its gel like mechanical properties makes it a wave amplifier and pumping enhancer. Because the gelatin allows better wave propagation, only small amplitude of muscle contraction is needed at the excitation location, which is in agreement with the small contractile capacity of the cardiac myocites.[9] In conclusion, the gelatin, by its thickness and intrinsic properties, may have a role in pumping in the embryonic heart before valve formation.