A New Hydraulic Model of the Left Ventricle for the Assessment of Wall Deformation

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Abstract—**Assessment of left ventricular (LV) wall deformation is of great importance in clinical assessment of cardiac function. As such, biomechanical models of the human heart ideally account for realistic wall deformation.. In previous experimental model investigations, wall deformation has generally been studied using thin-walled passive models, in which the effect of active muscle contraction and, hence, natural wall deformation cannot be simulated. To mimic both the active and passive mechanical properties of the LV wall, we designed a novel hydraulic thick-walled LV model, composed of a large number of individual pressure-controlled inflatable chambers. After connecting it to an artificial vessel system, we validated our model by measuring aortic pressure and flow and ventricular pressure. Wall deformation was evaluated visually. The agreement between our preliminary measurement results and physiological data from a human adult was overall acceptable, still a few considerable discrepancies were observed. Once our experimental setup is optimized, this new LV model will likely provide useful insights in LV wall deformation and its interaction with blood flow.**

Keywords—*Left ventricle, wall deformation, phantom*

I. Introduction

Heart failure is an increasingly important health problem in most developed countries [1]. Research of biomechanical processes in congestive heart failure primarily concentrates on the assessment of blood flow in the left ventricle. However, at present, the focus shifts towards the role of the active deformation of the ventricular wall in the interaction with the blood flow. Previous investigations [2] studied wall deformation by means of thin-walled passive experimental models. These models consist of a silicone membrane in a closed box, which is squeezed passively by an external connected piston pump. Hence, the membrane deformation remains uncontrolled and the effect of active muscle contraction and hence natural wall deformation, can not be simulated.

The aim of this study was therefore (1) to construct an experimental hydraulic model of the ventricular wall that mimics both the active and passive mechanical properties of the left ventricle, in which active control can be exerted on the wall deformation, (2) to optimize this model in terms of practical feasibility, (3) to validate this thick-walled LV model by measuring aortic pressure and flow and ventricular pressure, and (4) to compare the results to physiological data from a human adult.

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II. Materials and Methods

A. Design of a hydraulically based wall deformation control

We conceived the left ventricle as a thick-walled hydraulic model composed of an external stiff shell and an internal flexible wall. This wall is composed of a large number of individual inflatable hexagonal chambers. By applying pressurized air within the chambers, the internal membrane compresses. This will result in a reduction of the ventricular volume. This wall deformation can then be controlled by a regulation of the individual chamber pressure valves. The higher the resolution of the segmentation, the more accurate the control of the wall will be. Due to its hexagonal structure, we called this design the Honeycomb Model (Figure 1).

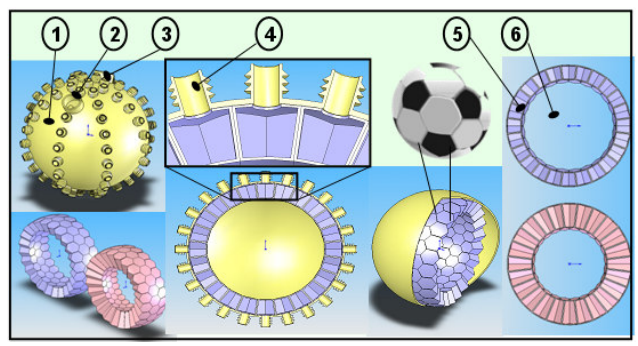

Fig. 1: Composition of the Honeycomb Model: (1) stiff shell, (2) aortic gate, (3) mitral gate, (4) connection pressurized air, (5) flexible wall and (6) ventricular cavity.

B. Optimization in terms of practical feasibility

Although the Honeycomb's principle shows potential, it had to be optimized in terms of practical feasibility. This resulted in the modular composed Frame Model (Figure 2). The internal flexible wall and external stiff shell are replaced by flexible sticks and a membrane, and an anchor frame respectively. This allows us to actuate all the segments of the wall with only one pressure valve. The membrane is shaped as a truncated ellipsoid. Its end diastolic volume amounts to 130 ml. The base-apex length is 85 mm and the short axis diameter is equal to 45 mm. The overall wall thickness of the membrane is 3 mm. In the membrane we placed 31 anchor points. These are connected by flexible sticks to the anchor frame. The sticks can be tensed up or loosened by modular discs in order to exert control on the wall deformation. The membrane and anchor frame are incorporated in the transparent exterior casing and are at the top sealed by a valve-embedding component. Two mechanical heart valves were fixed in the valve housing. We realized the Frame model by a combined application of Rapid Prototyping Techniques: Selective Laser Sintering (SLS), Stereo Lithography Apparatus (SLA) and Casting by the use of a silicone mould. These techniques use different materials: polyamide powder, UV polymerizing resin and a 2-component polyurethane respectively.

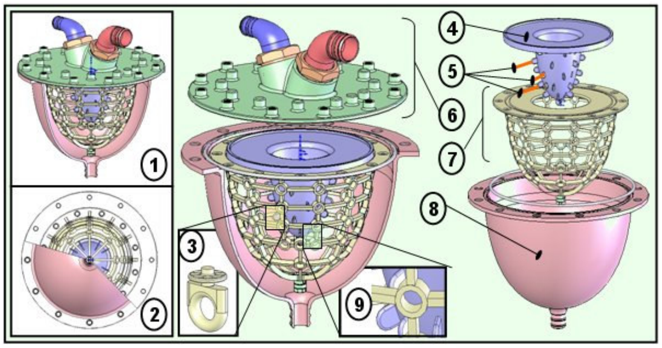

Fig. 2: Composition of the Frame Model: (1) section and (2) top view of the model, (3) anchor point of the membrane (SLS) that are placed as inserts in the (4) membrane (made by the combination of 4 techniques: SLS, SLA, Casting and implement anchor points as Insert), (5) flexible sticks, (6) valve piece (SLS) containing an aortic and a mitral mechanical heart valve, (7) anchor frame (SLS) with anchor points (9) and (8) transparent exterior casing (SLA).

C. *Description of experimental setup*

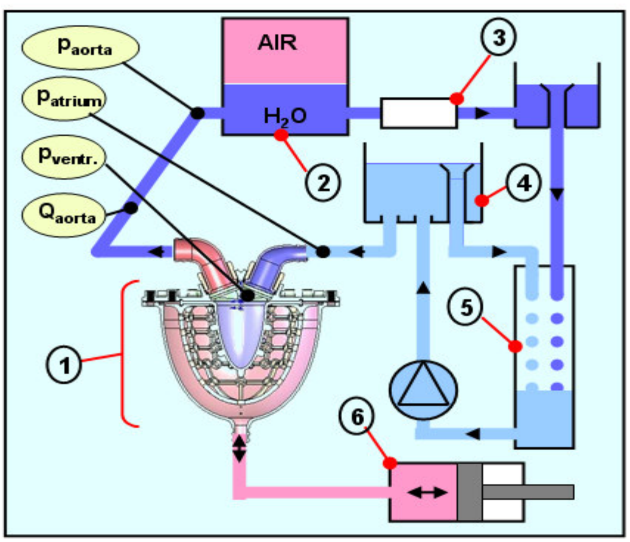

Fig. 3: Overview of the experimental setup: (1) LV phantom, (2) compliance, (3) resistance, (4) preload in atrium, (5) water reservoir and (6) Harvard pump that actuates the LV phantom.

The phantom is actuated by a Harvard pump and squeezes the test fluid out of the ventricle, through a mechanical heart valve into the artificial vessel system. After connecting it to an artificial vessel system (figure 3), we validated our model by measuring aortic pressure and flow and ventricular pressure. Wall deformation was evaluated visually.

D. *Measurement protocol*

The Harvard pump was set up at 60 bpm, %systole/%diastole = 35/65 and a stroke volume of 60ml was applied. Pressure measurements at the ventricular base have been performed for end-systolic pressure of 120 mmHg and filling pressures of 22.6mmHg. We used water as a test fluid. Labview 7 (National Instruments, Austi, TX USA) was used for measurements.

III. Results

Visual inspection of the model during testing revealed a controlled wall deformation. To evaluate the efficiency of the Frame Model, we preliminary measured ventricular, aortic and arterial pressure and aortic flow. Results are depicted in figure 4.

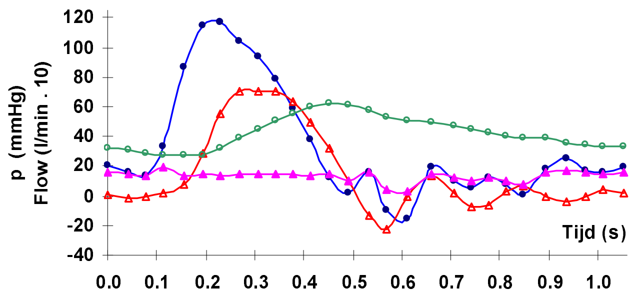

Figure 4: We validated our model by measuring ● ventricular, ○ aortic and ▲ arterial pressure and △ aortic flow.

Overall, our results show acceptable agreement with physiological data. However, we observe also a few considerable discrepancies, for example a phase difference between ventricular and aortic pressure, and negative values of pressure and flow. These, however, are largely attributable to the long distance between the pressure sensors on one hand, and the sucking property of the Harvard pump on the other.

IV. Discussion and Conclusion

This paper briefly describes the design and development of a new hydraulic LV-phantom to assess more physiological wall deformation than obtained in the existing thin-walled membrane models. Despite the notable improvement of the new design, the wall still tended to collapse. By tensing the flexible sticks this phenomena was less pronounced, but still occurred, which lead us to formulate some guidelines for further improvements. We believe the most important one to be the optimisation of the actuating system to avoid non physiological negative pressure values. Once our experimental setup will be optimized, this new LV model will likely provide useful insights in LV wall deformation and its interaction with blood flow.

Acknowledgements

The authors would like to acknowledge the collaboration of ir. G. Meyns and his team (Rapid Prototyping & Tooling, University College Ghent) during the rapid prototyping realization and the technical assistance of J. Deviche during the experiments.

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