A numerical and experimental approach for the design of a novel 3D printed bioinspired cardiac pneumatic pump

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Introduction - Mock heart circulation loops serve as in-vitro platforms to investigate the physiological interaction between circulatory systems and cardiovascular devices. .They are currently used for new device testing and surgical training. The final achievement of a mock heart circulation is to replicate functionality and behavior of a real heart [1]. However, current solutions present different limitations. First, compatibility with the magnetic resonance environment (Figure 1) is required to obtain accurate flow measurements though 4D flow technique. Second, full reproduction of heart / ventricle movement, including twist movement, is required. This last feature is particularly important to obtain a physiological helical flow at valve level (Figure 2).

Aim – The objective of this study is the development of a MRI compatible pneumatic mock cardiac pump able to reproduce the complete left ventricle motion. A first design phase with numerical validation through Finite Element (FE) simulations has been set and then a fabrication and experimental validation phase has been imposed.

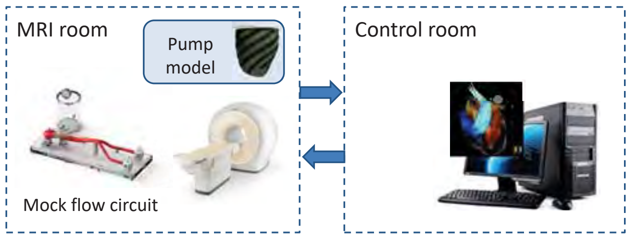

Figure 1

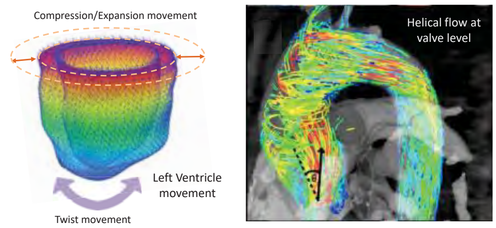

Figure 2

Design and Numerical Evaluation

Design and Numerical Evaluation - Numerical evaluation of the different pump CAD designs has been carried out through structural FE simulation with ANSYS

MRI segmentation - Healthy patient left ventricle volume has been manually segmented and post processed from MRI images (Figure 3).

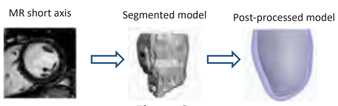

Figure 3

CAD Design – To replicate the fiber action, different layers of pipes/grooves have been designed on idealized/anthropomorphic ventricle geometries. The design strategy is summarized in Figure 4

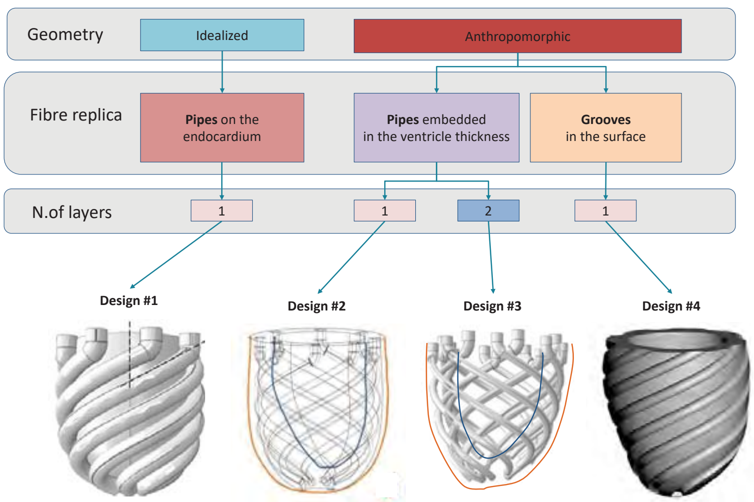

Figure 4

Structural FE analysis - Each CAD design model has been evaluated through structural FE simulation of the pressurization process and the corresponding displacements and twist angles have been evaluated and compared with the physiological values of the ventricle. The material chosen is Tango Black Plus (E=0.5 MPa, ν=0.47, ρ=1.2079 g/cm³). The simulation setup for each design is summarized in Table 1 and the simulation results are reported in Figure 5. The design #4 has been chosen as the final design due to the lower error values.

	Design #1	Design #2	Design #3	Design #4
Elements	Shell	Tetrahedral	Tetrahedral	Tetrahedral
Load	Internal pressure @ pipes	Internal pressure @ pipes	Internal pressure @ pipes	External pressure @ grooves
Load Range	[-0.4 MPa 0.4MPa]	[-0.4 MPa 0.4MPa]	[-0.4 MPa 0.4MPa]	[-0.03 MPa 0.03 MPa]

Table 1

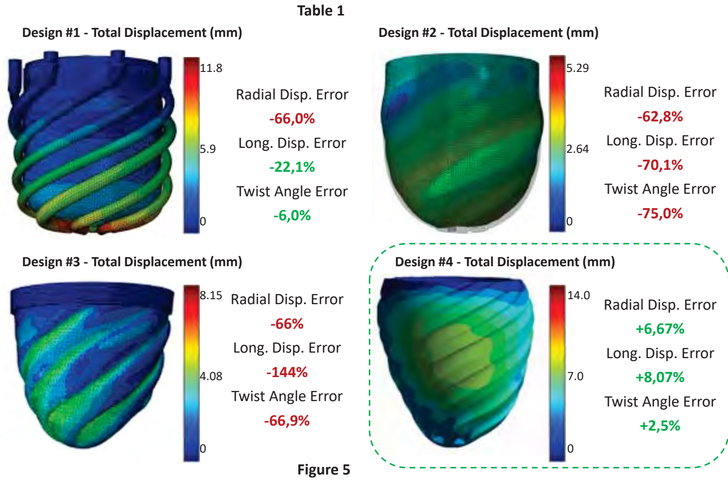

Figure 5

Experimental Validation - After assessing the best design, the pump prototype has been realized through a 3D printing process via polyjet 3D printer (Stratasys). The pump has been then inserted into a experimental setup, which is summarized in Figure 6. The main components are a pressurized chamber to actuate the pump, a pressure sensor to provide a feedback signal for a proportional electro-valve and a camera to provide the ventricle displacement by tracking 6 markers (2 longitudinal – 4 radial). The experimental twist angle values have been compared with simulated and literature data [2] (Figure 7)

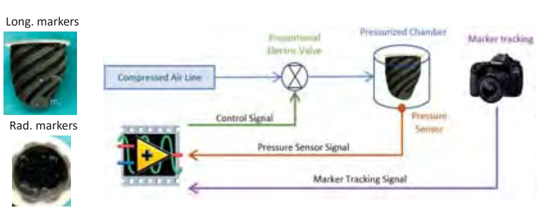

Figure 6

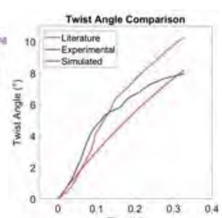

Figure 7

Future Work - SPH Simulation - An additional numerical validation phase has been set up to further investigation of the pump design performances. A SPH simulation has been imposed with the setup summarized in Figure 8. The software used for this task is the Autodyn module from ANSYS. The tracking of the solid particles will provide additional information on the fluid dynamic performance of the system. The results we expect to obtain from this last simulation are:

- The assessment of flow helicity as a consequence of the twist movement of the ventricle
- The corresponding ejection fraction

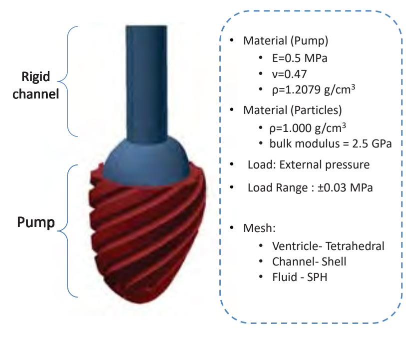

Figure 8

Conclusion - This study has shown the feasibility to obtain a 3D printed pump able to reproduce a ventricle compression comparable with real patient data. The FE simulations confirmed that the full anatomical design of the pump with oriented grooves is able to reproduce with accuracy the physiological conditions of the compressed ventricle both in terms of displacements and twist angle. The pump feasibility has been successfully demonstrated by the development of an experimental setup for the prototype pressurization: the experimental data confirmed the simulation results with an error below 1%. Additional results will be provided in the future by evaluating the pump SPH simuation.

[1] Roche et al, Advanced Materials, Volume26, Issue 8, February 26, 2014
[2] Iris K. Rüssel et al, JACC: Cardiovascular Imaging (2009)

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