

Design of an anatomically accurate, multi-material, patient-specific cardiac simulator with sensing and controls

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Abstract

We present the design, development and fabrication of an anatomically accurate, inhomogeneous, elastomeric cardiac model for in vitro testing of cardiac devices. Segmentation of clinical data was performed with Mimics software (Materialise). Mold creation and optimization was performed in 3-Matics (Materialise) using the tooling module. A total of twenty-one molds were designed including sixteen two-part molds (cardiac chamber internal volumes and endocardial walls, main vessel internal volumes and outer walls), four one-part molds for the valve annuli and one two-part mold for final myocardium cast. Molds were optimized for alignment and degassing in 3-matics and then 3-D printed (Objet Connex 500). Internal volumes were cast with paraffin wax. Endocardial and vessel walls and annuli were subsequently cast in elastomeric materials that matched material properties of corresponding native tissue. Internal volumes were then melted out, and internal structures were sutured together, separated by functioning valves created using an involuted tube surgical technique. Finally, these internal structures were aligned in an outer mold and a final elastomeric layer was cast to representing the myocardium. We describe the subsequent attachment and passive actuation of this synthetic model using a modification of a commercially available pump, so that heart rate and systolic and diastolic volumes can be user-modified, and sensing capabilities can be incorporated and controlled through a general user interface. The final design is a patient specific, easily modifiable synthetic benchtop model that can be used to provide meaningful data on the design of cardiac devices before moving to pre-clinical testing.

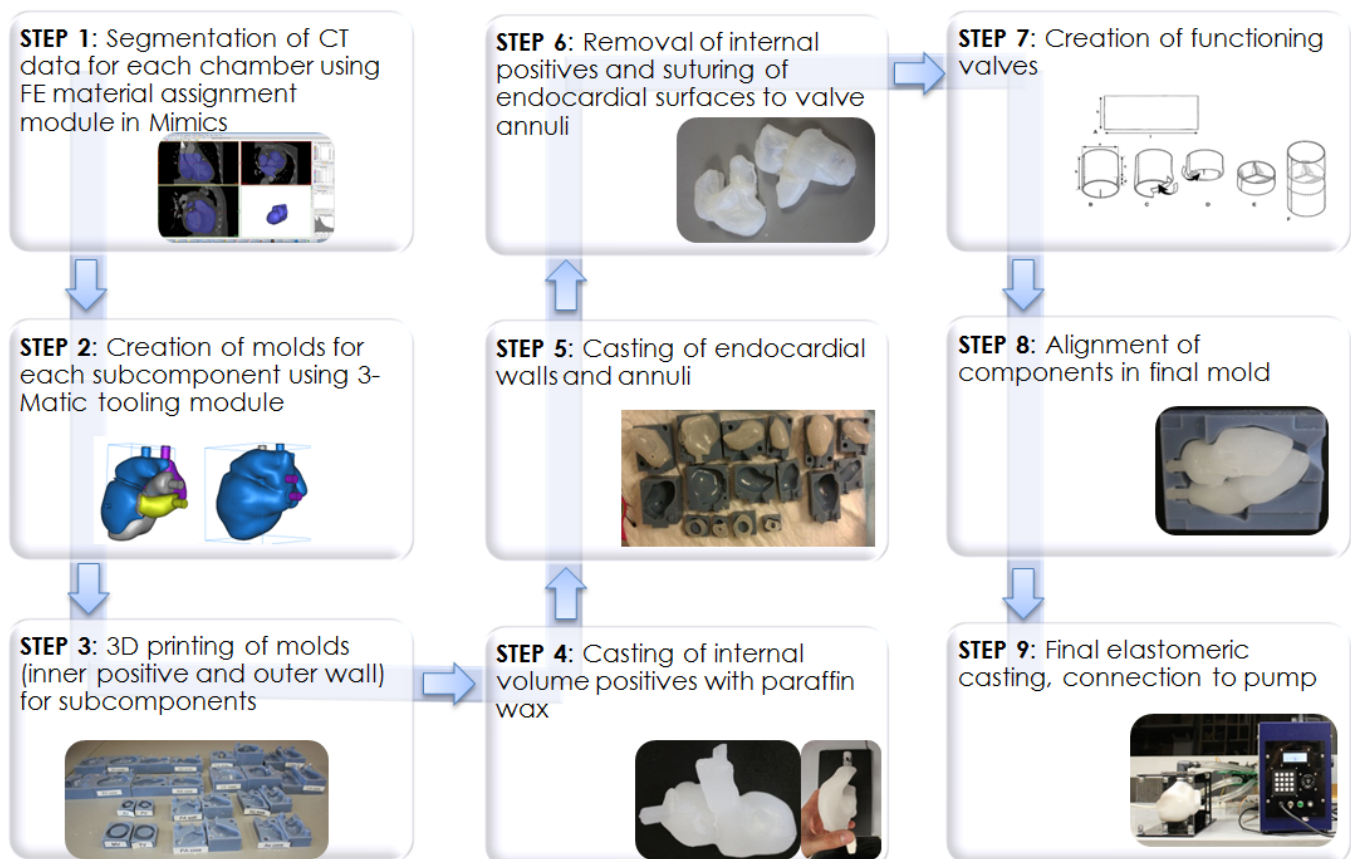


Figure 1: Workflow for creation of anatomically accurate, inhomogeneous elastomeric cardiac model

1 Introduction

In vitro bench-top cardiac simulators for realistic testing of cardiac devices are critical for rapid design iterations and physician training in the laboratory. Currently, synthetic cardiac models are typically passively driven, isotropic, homogeneous elastomeric models. With the recent increase in the amount of minimally invasive off-pump cardiac surgery, there is an increased need for anatomically accurate, anthropomorphic *in vitro* cardiac simulators that represent more closely the anatomy and anisotropy of cardiac tissue for meaningful before moving to pre-clinical testing. Ideally, synthetic models should be easily exchanged to allow testing on patient-specific anatomies, and pathological states. We set out to design, develop and fabricate a synthetic model that; 1) possessed inhomogeneous properties simulating the material properties of different structures and layers of the cardiac tissue 2) can be easily exchanged for patient-specific and pathological cardiac anatomies and 3) can be actuated and controlled. Specifically pump should have physiological flow and pressures and user-modifiable heart rate and systolic and diastolic times.

2 Prior Art

Synthetic cardiac models exist as clinical training tools that simulate some or all of the following: torso anatomy, heart sounds, artery palpations and lung sounds auscultations [1,2]. These do not simulate cardiac wall motion, a property that is key for testing of cardiac devices used during beating heart surgery. Beating heart trainers do exist for training on these off-pump procedures, but are not easily modified for patient specific anatomies [3]. Mechanical simulators also exist that simulate the motion of the ventricles of the heart [4], but do not mimic the bulk tissue properties and internal surface friction of the heart. Dynamic, multi-modality heart phantoms commercially available for cardiac imaging, but can be prohibitively expensive and don't simulate the inhomogeneity of the heart tissue [5]. Complex computer models exist [6,7,8,9] and are useful for simulations of procedures and virtual training tools, but not for physical bench testing. The Langendorff preparation is desirable for testing, but expensive and time consuming for correct preparation, and hearts can be difficult to obtain.

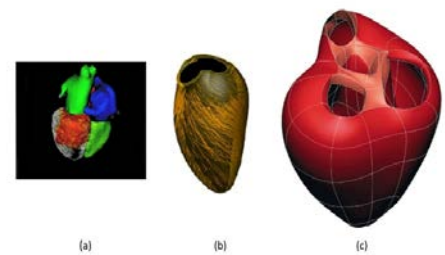


Figure 2: Different examples of cardiac anatomy models. a) 3D model segmented from MRI data as presented by Neizel et al. (2012) b) myocardial streamline model as presented by Nordsletten et al. (2010) c) Surface mesh of the myocardium as presented by Stevens and Hunter (2003)

3 Materials and methods

3.1 Creation of anatomically accurate, inhomogeneous synthetic model

Fabrication of the synthetic heart followed the workflow outlined in Figure 1.

Step 1: Mimics was used to segment the following chambers; internal geometries and endocardial walls of the left atrium, right atrium, right ventricle, left ventricle, trunk and outer vessel walls of the pulmonary artery, aorta, vena cava and pulmonary vein, an outer mold for the overall myocardium and annuli of the mitral, tricuspid, aortic and pulmonary valves. The finite element module was used to aid with segmentation of the different anatomical structures (endocardial layers, vessels, valve annuli and myocardium).

Step 2: A total of 21 masks were exported as stl files to 3-matics (Materialise). A box was fitted around the internal volume, and a boolean subtraction of the internal volume was performed. Molds were split along the most convenient split-line for demolding using the tooling module. Cylinders were created using the design tools within 3-matics to help with alignment of the internal positives in the outer molds, and subtracted from the mold. Funnel-shaped reservoirs were added to the molds to help with subsequent degassing. Alignment pins were also created in the 2-part molds to ensure both halves were aligned correctly. Finally features were added along the split-lines to aid with demolding.

Step 3: 21 molds (17 2-part molds and 4 1-part molds) were then printed on a Connex 500 printer (Objet) using vero blue material (printed with internal side facing up in glossy surface finish mode. Molds were then cleaned with a water blaster to remove any support material and placed in an oven at 60°C for four hours.

Step 4: Internal volumes were cast using paraffin wax (generalwax.com). These internal positives were demolded and aligned in outer molds.

Step 5: Synthetic material properties were matched to literature values [10] for valve annuli, endocardial, and myocardial tissue. Dragon Skin, Eco-Flex 0050 and Ecoflex 00-30 (Smooth-on Inc.) respectively were used for these components. Once poured, the elastomer-filled molds were degassed in a vacuum chamber at -100kPa for five minutes, and placed in a pressure oven at 100psi at 100°F to cure.

Step 6: Paraffin wax was melted out of chamber and vessel casts by heating to 140°F. Endocardial layers and vessels were sutured to valve annuli in the correct orientation.

Step 7: Functioning tri-leaflet valves were created from tubes of Ecoflex 00-30 for each of the four valves using a published surgical technique where the tube is cut in three areas and involuted [11]. These were sutured into the corresponding molded valve annuli before final assembly of the internal structures.

Step 8: Components were aligned in the final outer mold and the myocardium was cast with Ecoflex 00-30. Degassing, and curing was carried out as previously described, and final heart was de-molded.

Step 9: Subsequent attachment to pump for actuation and sensors for flow and pressure measurement is described in the following section.

3.2 Attachment to pump and incorporation of sensing

A commercially available pump was acquired (Harvard Apparatus piston pump model 1423 - Harvard Apparatus, Holliston, MA, USA). A rig was designed to attach the heart so that the free wall was unsupported to get realistic motion for device testing. Pulmonary artery and aorta were connected to the outflow and vena cava and pulmonary vein were connected to the inflow of the pump using off-the-shelf tubing (secured with zip-ties) and connectors (McMaster-Carr). Plexiglass was laser cut to provide a four wall enclosure for the heart with adjustable plates for attaching tube connectors. To compensate errors in the connector slot position and make the overall process of connecting the heart model to the holding frame easier, the acrylic plates incorporating the connector slots are separate from the four plates building the main frame and can be moved linearly on these main plates. The plates holding the connector slots and the main plates are fixed to each other using screw connections. Figure 2b) shows the completed holding frame.

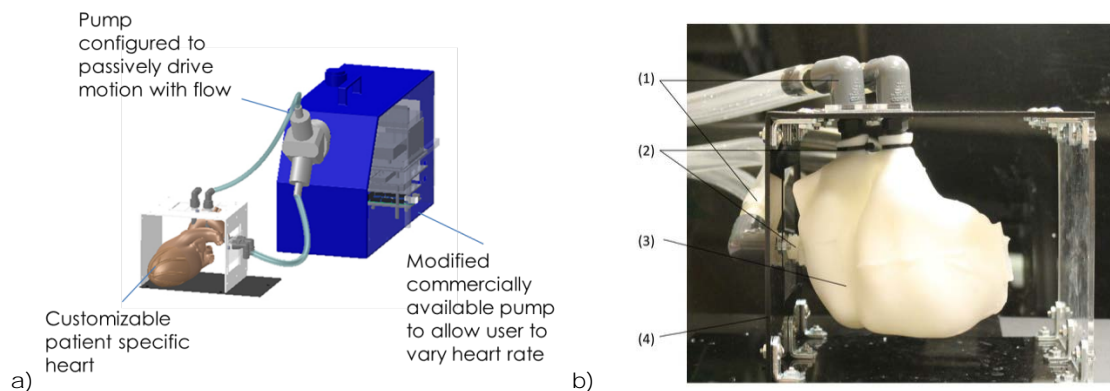


Figure 32: a) Design of pump and rig for attachment of synthetic heart to the pump b) Final heart model holding setup: 1) Tubing connectors - barbed ends are inserted into the tubing and into 2) the heart models access points. The connections are rendered water tight using zip-ties. 3) Casted silicone heart, suspended using the 4) holding frame and the tubing connectors

The pump was modified for the intended cardiac simulator. Electrical circuits were rewired to accommodate the new controls. A control box was integrated into the pump housing. The control box is connected to sensors, the pump and the computer. The microcontroller and the motor driver contained in the control box control the pumps speed, using the encoder switch signals for a closed loop control. This motion control manages not only the simulated heart rate, but also the heart models systole to diastole speed ratio. Additionally, the microcontroller manages the computation of incoming and outgoing signals (e.g. sensor signals). The connection between the control box and the computer is used to transmit the sampled sensor data and the heart model's current state (systole or diastole) from the microcontroller to the computer. This connection also makes command transmissions from the computer to the microcontroller possible.

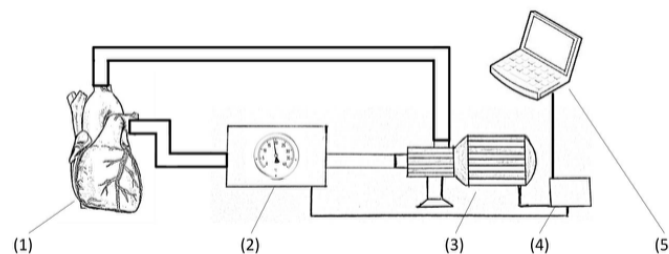


Figure 4: Sketch of the cardiac model featuring: 1) Heart model 2) Sensors for test surveillance 3) Pulsatile pump 4) Control box with interfaces to the sensors, the pump and 5) the computer.

An Arduino Mega development board was used. The board features an AT Mega 256 microcontroller, a preinstalled boot loader, a USB and a power jack and offers pin-and-socket connectors to the microcontroller's general purpose in-put/output pins. The microcontroller runs with a frequency of 16 MHz and provides 16 analog to digital converter pins. The Harvard pump was originally controlled in an open loop, regulated by two potentiometers connected to the motor's driver. To use the Arduino board for a closed loop control, the potentiometers are detached from the motor driver and a connection to the Arduino is established. Aside from the user interface provided by the computer, the control box also offers a standalone user interface, which may be used in test scenarios that do not need constant sensor surveillance. This standalone user interface is comprised of navigational buttons, a keypad and an LCD screen.

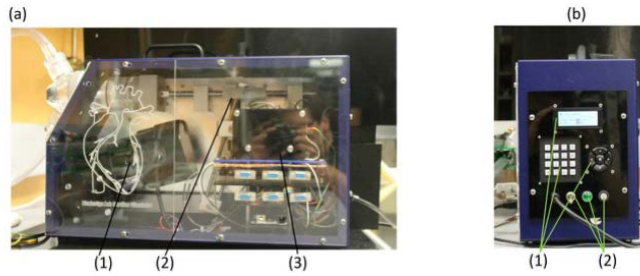


Figure 5: Harvard pump after redesign a) side view: 1) The Harvard Pump original motor. 2) The Harvard Pump original piston actuation mechanics. 3) A stack of added control elements (Arduino, breadboards and motor driver circuitry) b) Rear view 1) Altered user interface 2) Control elements adopted from the original Harvard Pump.

As the motor driver expects analog control signals, the digital to analog converter (DAC)MPC4921 (Microchip Technology Incorporated, Chandler, AZ, USA) is used to convert a 10 bit digital SPI based signal to an analog voltage signal. A process control module 4 (PCM4) (Minarik Corporation, Glendale, CA, USA) is used to convert the DAC's signal to the floating voltage difference output expected by the motor driver. As the Harvard Pump is already calibrated to simulate human physiological cardiac conditions, the calibration potentiometers of the pump's motor driver were not changed. Hence, the pump's maximum heart rate is equal to its original maximum speed of 100 beats per minute.

Two pressure sensors (HSCMAND030PGAA5, Honeywell S&C) and two flowmeters (SeedStudio POW110D3B G, Electronic Inventory Online) were acquired. These were connected in-line using off the shelf fittings (McMaster-Carr). A graphical user interface supplied by the computer was implemented in Matlab using the GUIDE tool for user interface creation. The platform was chosen, as it offers powerful and easily implemented data storage, plotting and data manipulation capabilities.

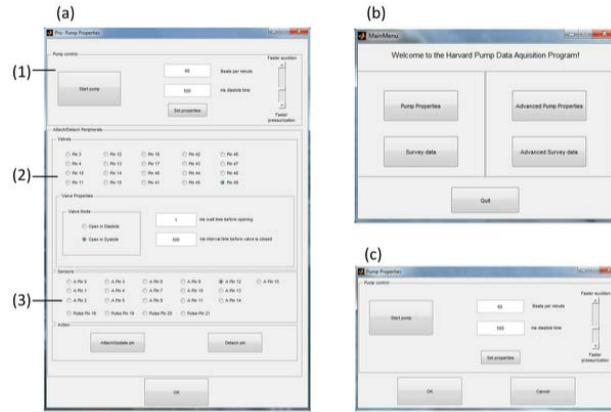


Figure 6: Matlab based GUI, a) Advanced Pump control window with 1) heartbeat control 2) Active peripheral control 3) Sensor control b) Main window c) Standard pump control window

In the user interface, the user has an advanced and a basic control window where the user can change the sensors and peripherals and control data output (advanced mode) or simply vary beats per minute and time in diastole (basic mode). A separate data acquisition window allows the user to measure flow and pressure at the inlet and outlet, and calculate ejection fraction.

4 Results and Conclusions

An inhomogeneous model of the heart was successfully created and connected to a pump and sensors so that it can be controlled by a computer user interface and output useful measurements. The model is anatomically accurate, and reflects the inhomogeneous nature of cardiac tissue properties. The synthetic model can easily be switched for patient-specific and pathological anatomies. The overall system can be used for testing of cardiac devices ranging from trans-apical valve delivery devices, intracardiac delivery devices, ventricular assist devices and extra-cardiac compression devices. We achieved the goal of designing, developing and fabricating a synthetic model that has inhomogeneous properties simulating the material properties of different structures and layers of the cardiac tissue, can be easily exchanged for patient-specific and pathological cardiac anatomies and can be actuated and controlled. This is hugely beneficial for rapid design iterations for cardiac devices before moving to pre-clinical testing.

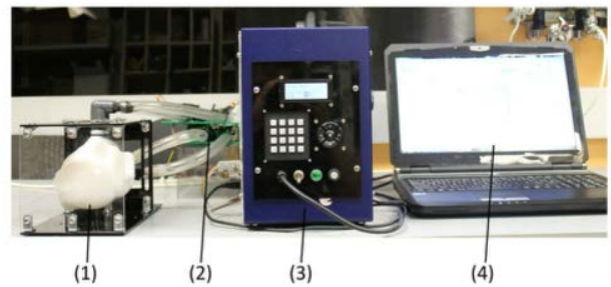


Figure 7: Cardiac simulator 1)heart model 2) sensors 3)pump 4) Matlab GUI

5 Future work

Mimics will be used to segment a thoracic cavity (including rib cages, lungs, pericardium) in order to create an *in silico* reconstruction and eventually physical models to provide an entire thoracic set up for surgical environment for testing of cardiac devices. An active cardiac simulator is currently being designed with actuators incorporated in the myocardium to mimic 3D twisting of the ventricles. For this work, the finite element module of Mimics will be used to create the geometry for a finite element simulation of this motion in order to optimize the design of the active simulator. Cardiac wall motion of the simulator will be tracked at anatomical landmarks using electromagnetic trackers, and compared to the finite element model, and to clinical speckle-tracked echo data.

6 References

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