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3D Printed Cardiac Phantom for MR Imaging

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Abstract: The cost effective cardiac phantom is to mimic the cardiac motion during Magnetic Resonance Imaging (MRI). Cardiac motion for the phantom is simulated using peristaltic pump. As the peristaltic pump is capable of forward flow and reverse flow, which leads to the benefit of both diastolic and systolic motion per cycle. The focus is to design a Graphical User Interface (GUI) which accepts the inputs from the user and correlate those inputs in to pump parameter. GUI accepts the input parameters for BPM, Stroke volume and Acquisition time. Depending on these inputs, the pump parameters like flow rate, forward time, reverse time and cycles per minute will be calculated and also display on UI. The calculated values will be updated in the peristaltic pump software and then pumping action takes place the fluid is sent to cardiac phantom for image acquisition. After imaging pot-processing is done using OsiriX tool, to get the output parameters. Obtained output parameters are given to GUI to plot the relation between Input and output parameters.

Keywords: cardiac phantom, Magnetic Resonance Imaging (MRI), Graphical User Interface (GUI), OsiriX.

1. INTRODUCTION

Phantom is a model of the human body or any of its parts. Cardiac phantom is a 3D printed heart model. Cardiac phantoms are mainly classified as two types: numerical phantom and in-vitro phantom. Numerical phantoms are also known as mathematical models which uses mathematical concepts for developing the phantom. In-vitro phantoms are also known as test-tube experiments in which performed with components of an organism that have been isolated from their usual biological surrounding. Cardiac phantoms have been employed as testing and validating tools for newly developed techniques focused on sampling and reconstruction strategies. In this work, a 3D printed cardiac phantom is being developed to mimic the cardiac cycle during magnetic resonance imaging (MRI). Cardiac motion for the phantom is simulated using peristaltic pump. As the peristaltic pump is capable of forward flow and reverse flow, which leads to the benefit of both diastolic and systolic motion of cardiac phantom per cycle. The focus is to design a Graphical User Interface (GUI) which accepts the inputs from the user and correlate those inputs in to the peristaltic pump parameter. GUI accepts the input parameters for BPM, Stroke volume and Acquisition time. Depending on these user inputs, the pump parameters like flow rate, forward time, reverse time and cycles per minute will be calculated and also display on UI. The calculated values will be updated in the peristaltic pump software and then pumping action takes place, the fluid is sent to cardiac phantom for image acquisition. Results depict the structural and functional behaviour of the cardiac phantom, based on MR imaging on 1.5T scanners from 2 vendors. Ongoing work involves implementing the post-processing pipeline to correlate UI parameters with those derived from images. After image acquisition the output parameters are taken, which are set side by side with input parameters and are valid. The valid result will be plotted

2. LITERATURE REVIEW

The human heart present in front of thorax, in the midline, slightly towards left side. Heart is a muscular pump that resembles cone shape and the size of a fist. In adults, it weighs around 300 grams. The base comprises mainly the left atrium. The left ventricle and right ventricle are laterally connected to lungs. The left ventricle is 10mm in thickness where as right ventricle is 3-5mm[1]. The left ventricle have an important impact on diagnosis and therapy. There is a technology called C-arm CT, through which it is possible to reconstruct intraprocedural 3D images from angiographic projection data of 4-chambered heart. While carrying out this process there is more chance of blurring the images. So, to overcome from this problem 4D XCAT phantom with contrasted left ventricle is used to acquire the data [2].

Anatomical model of a numerical phantom has been developed by analysis cardio-vascular structures contours from a 3D acquisition in Magnetic Resonance Imaging (MRI) of a human healthy subject. Cardiac motion has been tracked by 3D non rigid registration between the consecutive linearly interpolated volumes from dynamic MRI sequences. The obtained

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numerical phantom is structurally rich and its motion is realistic [3]. Hydrogel material phantoms are also can be made which simulate the elasticity of human soft tissue, and is composed of anatomically correct left and right ventricle structures [4]. Computerized heart phantom is also used for imaging in medical research. These phantoms are based on flexible geometry. Non-uniform rational B-spines (NURBS) are a four dimensional heart model contains 200 control points which are selected from gated MRI study of a normal patient. NURBS are an efficient way that describes a heart as well as anatomical objects for a realistic phantom [5]. To produce physiological realistic left ventricular wall thickness and rotation, non-ferromagnetic left ventricular motion phantom is used. This phantom is able to mimic cyclic motion patterns of human left ventricle during systole. Motion of the phantom can be able to generate varying degrees of wall thickness [6]. A low cost cardiac phantom was developed using PVA to mimics cardiac motion and measure thermometric profile based on applied B1+ fields during MR imaging. The cardiac motion inside the phantom was simulated using the mechanical gear setup. To obtain the thermometric profile of the cardiac phantom 12 probes were inserted into the phantom with required thermal insulation. The phantom also provides an opportunity to correlate local SAR findings with temperature measurements in the heart phantom [7].

2.2 Problem Definition
Human heart testing and validating will be remains difficult for doctors. Even doctors need specific tool, for testing and validation. The previously prepared cardiac phantom was pumping through mechanical arrangement made manual action must be there for pumping action.

2.3 Objective of the Project
Cardiac phantoms have been employed as testing and validating tools for newly developed techniques focused on sampling and reconstruction strategies. The cardiac MR phantom developed in this work aims to meet the following three objectives:

(i) Anatomically accurate representation of the human heart with potential for subject specific phantom imaging through 3D printed heart model

(ii) MR characterisation of structural and functional behaviour of human heart

(iii) Cost-effective, reproducible and repeatable phantom setup at lab scale.

The execution phase or stage of project is conversion of the detailed or complete design into operational code. This phase aims at converting the design to a probable solution with the use of appropriate programming language. It provides the details about provides an outline about core modules with line by line in flow.

3. METHODOLOGY

3.1 Block Diagram

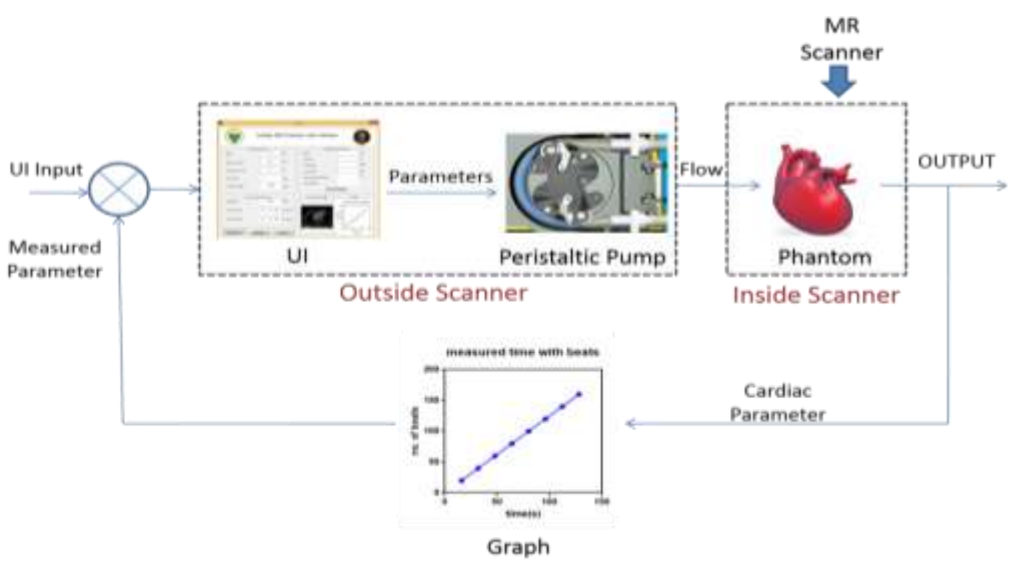

Figure1: Block diagram of the Cost Effective 3D Printed Cardiac Phantom

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Cardiac Phantom setup: The setup consisted of a laptop, peristaltic pump (Ravel Hiteks Pvt Ltd) and a 3D printed cardiac model . The laptop was connected to the pump and to the model through silicon pipes as shown in figure 1. One end of the pipe was connected to aortic arc and other end of the pipe was connected to left pulmonary artery. The laptop interfaced with the pump through a designed User Interface developed in Matlab (The Mathworks Inc). The UI inputs were clinically relevant parameters such as beats per minute (BPM), stroke volume (SV), cardiac output (CO) and acquisition time. These determined the pump parameters of flow rate, forward time, reverse time and number of cycles. UI outputs included BPM, volume, aortic flow, Left ventricular volume, Myocardial thickness and stress/strain as determined by MR images. The peristaltic pump was controlled to mimic the systolic and diastolic cycles.

4. INTERFACING MATLAB AND PERISTALTIC PUMP GUI DEVELOPMENT AND CALIBRATING WITH THE PUMP

The execution phase or stage of project is conversion of the detailed or complete design into operational code. This phase aims at converting the design to a probable solution with the use of appropriate programming language.

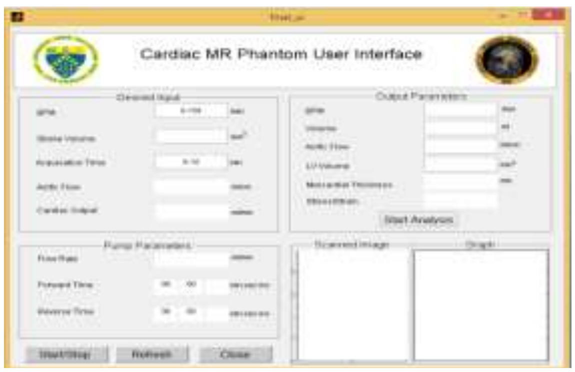

Figure 2: Front end of the GUI

The above figure shows the front end design that is loaded when the matlab code is executed. Left side panel have the inputs and the below panel is to show the converted values for peristaltic pump. Right side panels are used to display the images taken from the scanner and analysis can be done.

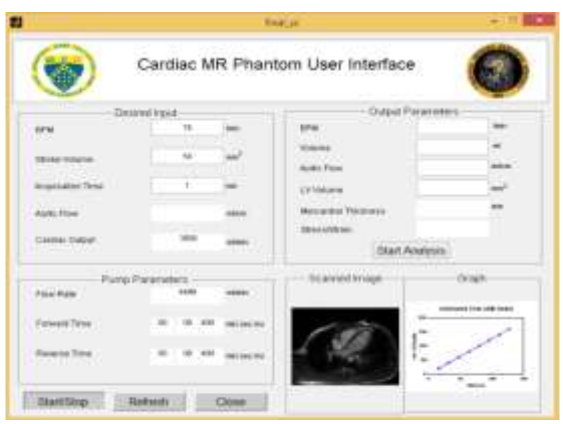

Figure 3: UI after loading the parameters

Figure shows the front end of the Matlab GUI, which enables user to enter their inputs based on the cardiac parameters. GUI accepts the input parameters for BPM, Stroke volume and Acquisition time. Depending on these inputs, the pump parameters like flow rate, forward time, reverse time and cycles per minute will be calculated and also display on UI. The calculated values will be sent to peristaltic pump software and then pumping action takes place, the fluid is sent to cardiac phantom for image acquisition.

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User input parameters are specified with the ranges, depending on BPM the flow rate of the pump will be decided. If BPM is less than 100, flow rate sets to 4499 otherwise sets to 1600.
The front end of the UI also contains static text box for cardiac output and pump parameters. Based on the input parameters the cardiac output and pump parameters will be calculated using below formulas.
$\text{Cardiac Output} = \text{BPM} * \text{Acquisition Time}$
Pump parameters such as forward time and reverse time calculations in the back end code is shown below,

$$\alpha = \frac{60}{\text{BPM}}\,\text{Sec} \qquad \text{Forward Time, Reverse Time} = \frac{\alpha}{2} * 1000\ \text{ms}$$

Then the final calculated value will be round up to nearby multiples of 100.

Test the peristaltic pump with required values

Figure 4: Peristaltic pump model no. RH-P100LS-200-2H-PC

Peristaltic pump is tested by giving different values within the specified range and working as per the specification. The pump rotates according to the input flow rate and the given time. Both the forward and reverse times are fixed and working normally.

Table 1: Obtained values with respect to beats

Beats Per Minute	$\alpha = \frac{60}{\text{BPM}}\,\text{Sec}$	$\text{Forward Time, Reverse Time} = \frac{\alpha}{2} * 1000\ \text{ms}$	Round-off value
60	1	0.5	500
65	0.923	0.461	500
70	0.857	0.428	400
75	0.8	0.4	400
80	0.75	0.375	400
85	0.705	0.352	400
90	0.666	0.333	300
95	0.631	0.315	300
100	0.6	0.3	300
105	0.571	0.285	300
110	0.5454	0.275	300
115	0.521	0.261	300
120	0.5	0.25	300
125	0.48	0.24	200
130	0.461	0.231	200
135	0.444	0.222	200
140	0.428	0.214	200
145	0.413	0.206	200
150	0.4	0.2	200
155	0.387	0.193	200
160	0.375	0.187	200

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Table 2: Experimented values of volume with respect to time

Forward Time (ms) For 1cycle	Volume (ml)	Volume*2 (ml)
1	4	8
2	10	20
3	15	30
4	20	40
5	26	52
6	35	70
7	42	84
8	46	92
9	52	104

Table 3: Experimented values of number of beats with respect to time by keeping forward and reverse time as 400ms

Number of beats / 4499ml	Time(s) Forward time = 400ms, Reverse time = 400ms
20	15.96
40	32.2
60	48.42
80	63.92
100	80.42
120	96.45
140	112.96
160	128.42

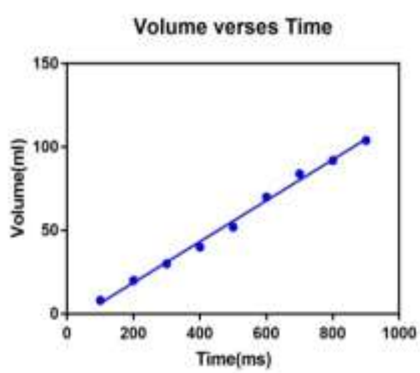

Figure 5: Plot for experimented values of volume verses time

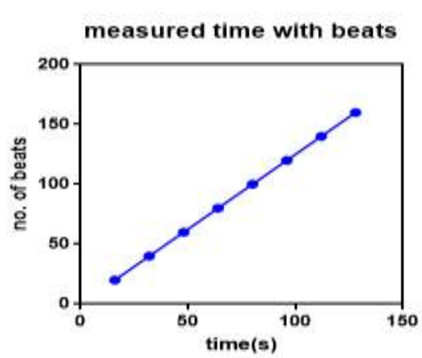

Figure 6: Plot for experimented values of number of beats with respect to time

Above plots shows the calibration curves for volume, beats with respect to time separately.

Store the data from Matlab to text file

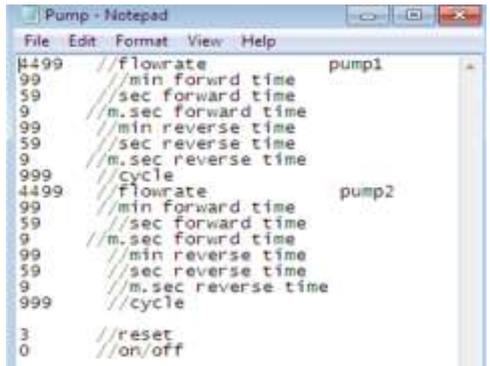

Figure 7: Different input parameters for Peristaltic Pump

The above Figure shows all the input values to Peristaltic pump Parameters are given in the text file. By editing the text file in order the first eight values for the pump_1 and second eight values for pump_2. The last two values are for reset and power on or off button.

Overwrite the text file

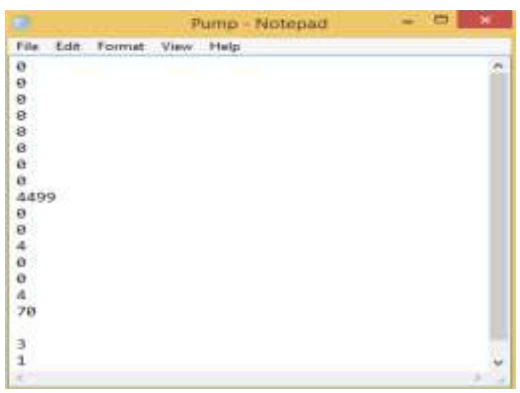

Figure 8: Pump.txt file controls the peristaltic pump

By overwriting the Pump.txt the file controls the peristaltic pump using file operation in Matlab inbuilt function fopen() for opening the existing file with write permission to overwrite the file and save the file as well.
To write the data into file using fprintf() command can be used and written in the Pump.txt file then it will be automatically overwritten. If the ON/OFF button is 1 then the pump will be switched on, if it is 0 then it is switched off.

3D printing of the cardiac phantom

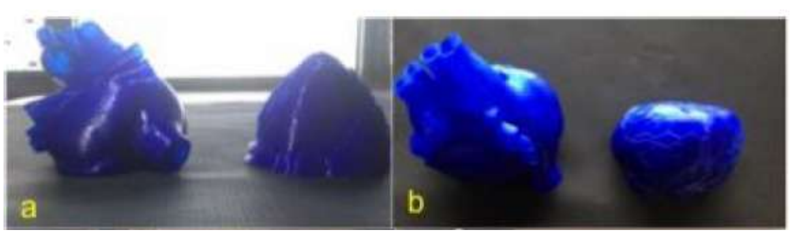

Figure 9: 3D printed cardiac phantom (a) phantom from side view (b) top view

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The cardiac phantom setup consists of 3D printed cardiac model and Peristaltic pump. The cardiac phantom was printed with ninjaflex material. The 3D printer base palate was covered with kapton tape for resisting temperature. The extruder temperature was set to 210^0 celsius and base plate temperature at 70^0 celsius. ssSupporting structures were removed after the print was completed. The cardiac phantom was printed as two parts. Two parts printing was done to easily remove the supporting structures after printing. The phantom was combined using a water proof gum material.

Phantom set-up in scanner room

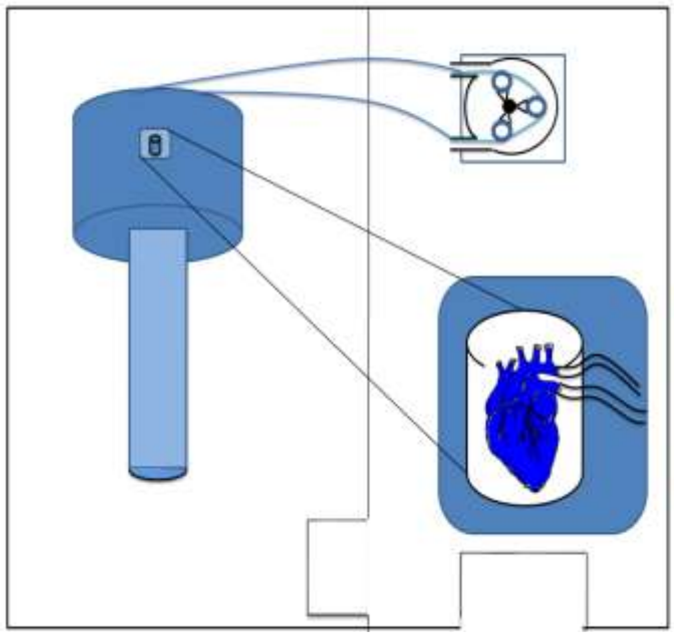

Figure 10: Phantom set-up in scanner room

The cardiac phantom is kept in the MRI scanner for imaging. The cardiac phantom is connected to peristaltic pump through silicon tubes. Air gap inside the silicon tube are completely removed by filling water inside the tube. The peristaltic pump is kept outside the scanner room and it is connected to laptop through RS232 cable. The laptop contains graphical user interface (GUI) which accept the user inputs for the heart parameters (BPM, Acquisition time and stroke volume). User input values will be further updated into the pump software that leads to systolic and diastolic flow. The 3D printed cardiac phantom was placed in a cylindrical plastic container filled with tap water which was kept in MRI scanner for imaging. The pump was placed in the adjacent room to that of scanner room and scanned on 2 1.5T scanners from 2 different vendors. SSFP sequence was employed for scanning the phantom. The acquisition parameters on the first scanner were: TR/TE=4.0/1.72ms, FA=20, slice thickness=8, matrix size= 256 x 256. The acquisition parameters on second scanner were: TR/TE=50.8/1.4, FA=64, slice thickness=6, matrix size= 192 x 156.

The imaging of the phantom is done by two scanners. One is from Siemens scanner (Sagar hospitals, Bangalore) and another from GE scanner (Wipro GE Healthcare, Bangalore). Obtain images are post processed.

5. RESULTS

Figure 2 shows the designed UI with panels for clinical parameters and pump related input calculations. Figure 3 illustrates that increase in BPM decreases time per cycle as expected. Figure 6 depicts that number of beats increases with increase in time while Figure 5 shows that water volume increases linearly with as the pumping time as expected. The two different views of the 3D printed heart model can be seen in figure 3 (a,b). Pipes inserted inside the two ventricles are visible in in-vitro data as two circular structures. The sinusoidal trend in the intensity plotted for cardiac- CINE demonstrates that the cardiac motion is mimicked during the scanning.

6. DISCUSSION AND CONCLUSION

Pipes were inserted deeper into the ventricles to allow suction of water as required by peristaltic pump for stable operation. The pipes inserted can be seen in the short – axis and four-chamber view of the in-vitro cardiac phantom in figure 9. Previous work carried out in [7] made use of polyvinyl alcohol (PVA) as phantom material. Current work involves implementing the post processing pipeline to correlate UI parameters with those derived from images. Future work focuses on employing PVA for preparing the heart model employing the 3D printing heart mold. The phantom developed here could also be employed to study the fetal heart.

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