Development of a patient-specific phantom model

Research Techniques

Doctoral Program in Biomedical Engineering

Author:
Pedro André Gonçalves Morais
Student nº UP201400020
June of 2015
Contents

1 – Summary ......................................................................................... 1

2 – Introduction.................................................................................... 2

3 - State of the art................................................................................ 3

4 – Methods........................................................................................... 9

  4.1 - Generation of personalized anatomical atrial models............ 10

  4.2 - Virtual modeling of the phantom mold......................... 11

  4.3 - Construction of the phantom mold using a 3D-printer ....... 13

  4.4 – Flexible Materials................................................................. 14

Experiments.......................................................................................... 15

Results................................................................................................ 16

Discussion and Conclusions............................................................... 18

References.......................................................................................... 19
1 - Summary

In this work, we present a patient-specific phantom model of the human atria. This patient-specific model was virtually design using a high-resolution image acquisition based on computed tomography. Then, a mold was 3D-printed using an Ultimaker II. Flexible material was injected into the mold creating a realistic and elastic phantom model.

This elastic model will be crucial throughout the current PhD project, in order to assess the performance of the developed image-based algorithms and to validate novel augmented reality solutions to help the physician during the minimally-invasive transseptal puncture intervention. Note that, during this intervention a catheter is inserted into the right atrium via the venous system, through which a needle can be moved forward, in order to puncture the interatrial septum and to access the left atria chamber.

An experimental setup was created to validate the novel phantom. This setup relies on a water tank, a 4D ultrasound machine and transesophageal echocardiography ultrasound probe. The phantom was placed into the water tank and a 3D ultrasound image was obtained.

The image acquired proved that a realistic ultrasound image of the atria chambers was achieved. Moreover, a clear definition of the inter-atrial septal wall was obtained, proving that this model can be used to simulate in vitro the transseptal puncture technique.
2 - Introduction

Access to the left atrium (LA) of the heart is required for several minimally invasive cardiac interventions of the left heart, such as catheter ablation for atrial fibrillation, mitral valve repair/replacement, pulmonary vein interventions and left atrial appendage closure [1-3]. Hereof, the inter-atrial septal (IAS) wall is punctured using a catheter inserted in the right atrium (RA) via the venous system under fluoroscopic guidance. Although this approach, termed transseptal puncture, has been used for many years, complications are common. Moreover, the exact location at which the septum needs to be traversed, in order to avoid these complications and/or to enable reaching a given LA target site, is currently entirely based on experience [2].

The aim of this PhD project is to develop an integrated interventional planning and guidance framework to assist the physician in successfully performing TSPs. The proposed framework will increase the success rate of TSPs and will avoid complications or the need for secondary punctures. Moreover, it will increase the level of confidence of the physician during the procedure, thereby reducing the interventional time and thus cost. The advantages are particularly relevant for surgeons with less experience (e.g. trainees) and in patients with an abnormal septum, in which TSP remains difficult even for the most experienced operator.

During this report, we explain the technique used to construct an experimental validation system based on patient-specific phantoms. This system will allow to properly assess the performance of the different strategies developed throughout the PhD. Moreover, these phantoms will be the ideal scenario to simulate the TSP technique and to test/validate the abovementioned integrated augmented reality framework.

Regarding the phantom construction, several requirements were imposed: 1) the phantom anatomy should be realistic and similar to the patient; 2) a realistic ultrasound image should be obtained; 3) flexible material should be used to create the cardiac wall; and 4) the entire IAS wall and the remaining cardiac chambers, should be visible in high-resolution images (e.g. computed tomography – CT) and intra-procedural image, namely volumetric echocardiography.

The current report is divided in five main sections, namely: 1) a review about cardiac phantom models; 2) a description of the method used to construct the elastic model; 3) the experimental setup used to validate the in vitro system; 4) the results obtained; and 5) a discussion of the results, main conclusions and future work.
3 - State of the art

During this section, we will present some strategies previously applied to develop cardiac phantoms. Moreover, commercially available cardiac systems will be described.

Initially, some authors focused on *in silico* models of the left ventricle (LV) to validate segmentation strategies and image-tracking approaches.

Olszewski *et al.* presented a dynamic phantom of the LV to validate the developed numerical model of the myocardial function [4]. The phantom had a shape of a tube with internal diameter of 5 cm (Figure 1a-b), wall thickness of 1 cm and length of 12 cm. Polyvinyl alcohol (PVA, 99+% hydrolyzed) was used to generate an elastic model and to mimic the mechanical and acoustic properties of the real tissues (Figure 1-c). As a result, the follow acoustic properties were achieved: speed of sound of 1546 m/s and absorption coefficient of 0.28 dB/cm. Finally, a commercial available computed-controlled dynamic piston pump (Vivitro Inc., Canada) was used to pump water into the model, consequently deforming the elastic model. This pump system is widely used to simulate cardiac flow, where the piston motion is easily controlled by a preconfigured waveform (e.g. electrocardiography – ECG signal) [4].

Plewinska *et al.* developed a two chambers (left ventricle and right ventricle - RV) phantom model to study the mechanical properties of the myocardium [5]. The system relies on a biventricular model, which was constructed through a mold made of casting polyurethane (Figure 2-a).

![Figure 1](image1.png)  
(a)  
(b)  
(c)

*Figure 1 - (a) (b) LV phantom developed by Olszewski. (c) Ultrasound image obtained [4].*
Figure 2 - (a) Biventricular phantom developed by Plewinska et al. [5]; (b) - Geometry of the model (dimensions in millimeters).

The mold had the shape of a truncated thick-walled ellipsoid with an inner partition (interventricular wall). Regarding the dimensions, a total of 100 mm was used between base-to-apex, the major axis and minor ellipse axis presented 60 and 40 mm, respectively, resulting on a LV and RV intracavity volume of 60 mL and 30 mL, respectively. Myocardial wall thickness uniform along across the phantom and equal to 10 mm was used (see Figure 2b).

In order to generate the elastic model, a PVA solution (99+% hydrolyzed) combined with water was used. Moreover, the phantom model was kept into a water tank coated with ultrasound-absorber material (Aptflex F28P) to improve the ultrasound image obtained.

A hydraulic system was used to deform the phantom model and to simulate the heart motion. As such, a two reciprocally moving pistons were used to cyclically (inflate and deflate the model) deform the cardiac model. These pistons are connected to a step motor (QMOT QSH6018-65-28-210, Trinamic Motion control GmbH and co. KG) to electronically define the cardiac flow rhythm (Figure 3).

Figure 3 - Hydraulic system used to deform the cardiac phantom. 1 - Water container, 2- Biventricular phantom, 3 - constant pressure control container, 4 - air chamber, 5- piston pump and 6- computer-controlled pump driver [5].
Heyde et al. modified this last phantom model in order to validate a novel strategy to estimate three-dimensional regional cardiac motion and strain in ultrasound imaging [6]. Instead of the biventricular mold, the authors used a univentricular phantom with realistic LV dimensions and an intracavity volume of 100 mL (Figure 4a-b). Moreover, a glycerin solution was combined with PVA and water to generate the elastic phantom material, resulting in a scattered myocardial wall. These scatters will result on speckle patterns on ultrasound acquisition, consequently creating a more realistic image (Figure 4c).

Similarly, Cygan et al. used the abovementioned univentricular model for cardiac motion assessment in ultrasound and magnetic resonance image (see Figure 5) [7]. One modification of the system was required: instead of step motor combined with cyclic pistons, the authors applied a commercial available integrated pump system (Vivitro Inc., Canada). The ultrasound image acquisition was performed without any special attention. Regarding the magnetic resonance image acquisition, the pump system was kept outside of the room.
Regarding the commercial available solutions, two different setups have been reported in literature, namely: beating heart phantom (Chamberlain Group, Great Barrington, MA; see Figure 6a) [9, 10] and dynamic multi-modal heart phantom (Shelley Medical Imaging Technologies, London, ON, Canada; see Figure 6b) [8]. The beating heart phantom uses an air pump attached to the cardiac structure to inflate and deflate the LV chamber, creating a realistic cardiac contraction. The pump system is controlled through an external micro-controller, where a simulated real-time ECG trigger is used to define the heart rate [9, 10]. The second commercial phantom includes an accurate and realistic representation of the LV and RV. A two servo motors controlled by an external software is used to define the heart torsion motions, heart stretching and compress motion. In order to acquire realistic ultrasound images of the cardiac muscle, PVA hydrogel doped with iodine & graphite was used to mimic the myocardial tissue [8].

Instead of LV chamber, Holmes et al. suggested a low-cost technique to generate patient-specific models of the atria region [11]. This model was used to validate commercial available image-guidance solutions for catheter ablation intervention.

A pre-interventional CT dataset was semi-automatically segmented, consequently generating a virtual model of the relevant structure, namely blood pool of the LA and RA. The segmented model was posteriorly converted on a polygonalized model, and a real/physic 3D model (see Figure 7a) was created through a stereolithography system (Zcorp Spectrum Z510 System).
Finally, a platinum silicone material, called Dragon Skin, embedded the printed models in order to create a personalized elastic phantom (see Figure 7b-c). Note that, after the silicone application, a water bath was used to dissolve the rigid part.

Similarly, Sun et al. developed a static left-atria phantom to simulate the catheter ablation intervention [12]. In this case, a 3D virtual model was obtained from CT datasets and the resulting model was 3D-printed in flexible material.

Jeevan et al. validated a novel strategy to percutaneously access the LA in a commercially available phantom model of the atria chambers (Elastrat Sàrl) [13]. This phantom uses a standard shape of the atria region, with 3 mm hole in the inter-atrial septum in order to simulate an atrial septal defect. Moreover, the superior vena cava, inferior vena cava and pulmonary veins were included on the model (see Figure 8). Regarding the dimensions, a model with 26x20x14 cm was placed into a plexi glass cube.

Finally, some authors focused on different cardiac phantoms, namely: 1) dynamic phantom for Doppler measurements [14], and 2) dynamic phantom to simulate the aortic and mitral valve motion [15].

Martensson et al. developed phantoms that enable tissue Doppler measurements of displacements, velocity, strain, and strain rate [14]. Both phantoms were created using polyurethane (RenCast 5073, Huntsman Advanced Materials, The woodlands, TX, USA) combined with glass powder. Note that glass powder is used to introduce speckles on the image, consequently creating a realistic image. Regarding the phantom motion, a force generator ElectroPuls E3000 (Instron, Norwood, MA, USA) was used.
Vannelli et al. developed a heart phantom with functional mitral and aortic valves [15]. This system was used to simulate valve repair/replacement procedures and it can be used with fluoroscopy-guidance, ultrasound-guidance and magnetic resonance imaging.

The phantom consists of a left ventricle, an atrial reservoir capable of holding left and right atria, a valve sheet containing mitral and aortic valve, and a microcontroller-based pneumatic actuator system (Figure 9). The phantom model was constructed using silicone (Smooth-On Ecoflex 00-30) for the LV, a separate silicone assembly (Smooth-On DragonSkin-10) for the mitral and aortic valves and a box for the LA. The aortic valve and mitral valve showed a diameter of 23 mm and the long-axis of LV measured 130 mm.

Regarding the dynamic system, a total of six pneumatic cylinders controlled by an Arduino Uno microcontroller were used to define the three contractile loops namely: LV contraction, mitral-valve and aortic-valve motion [15].

Figure 8 - (a) Commercial available phantom of the atria region; b) 3D reconstruction created from a magnetic resonance image acquisition [13].

(a) (b)

Figure 9 - (a) Cardiac phantom developed by Vannelli et al. (b, c) Ultrasound image obtained [15].

(a) (b) (c)
4 - Methods

In this section, we present the strategy used to develop a patient-specific phantom model of the atria region (see Figure 10).

The method requires a tridimensional CT acquisition (Figure 10a) to generate a high resolution model of the atria region (Figure 10b-c). This model is imported into a computer-aided design (CAD) tool (Figure 10d) to generate the negative of this structure, consequently creating external and internal molds (Figure 10e). Flexible materials, compatible with ultrasound properties, are injected into the mold, generating the cardiac wall of the atria (Figure 10f). Then, the external mold is removed and a small incision is performed at the cardiac wall to extract the inner mold (Figure 10g). This incision is recovered with flexible material, generating the 3D flexible phantom model (Figure 10h).

Figure 10 – Overview of the technique developed. (a) Starting from a 3D CT a manual segmentation of the relevant structures is performed (b). Then, using this manual contours a 3D representation of the atria is created (c). (d) This 3D model is imported in a CAD tool where the negative is generated in order to create a mold. (e) The mold is 3D-printed and (f) flexible material in introduced into the model. Then, we remove the inner rigid structures using two cuts (g). These cuts are recovered with flexible material and the final flexible phantom is generated.
4.1 - Generation of personalized anatomical atrial models

In order to generate a 3D model of the atria region, an initial search of atria anatomy was performed. As such, we observed that the RA shows larger volume and thinner walls (approximately 2 mm) than LA. Anatomically, the superior RA is composed by the superior vena cava (SVC) and the right atrial appendage. The inferior RA is constituted by the inferior vena cava (IVC) and the tricuspid valve. Regarding the LA, this structure is smaller with thicker walls (approximately 3 mm). LA presents a cuboidal shape, being limited superiorly by four pulmonary veins and the left atrial appendage (LAA). Inferiorly, LA is limited by the mitral valve.

Based on the abovementioned guidelines, a manual segmentation of the LA, RA and external wall were generated using the Medical Imaging Interaction Toolkit (MITK) software. MITK combines an interactive framework with robust image-processing algorithm to ease the manual manipulation of 3D medical image datasets.

Several assumptions were used during this manual delineation (Figure 11): 1) the RA model should include the main body, SVC and IVC. One entry point was used for the IVC and two entry point for the SVC. Although the tricuspid valve is not delineated, an entry is created to simulate the communication route between the RA and RV; 2) LA includes the main-body, LAA, and the initial portion of two pulmonary veins. Similarly to the RA chamber, the mitral valve structure was not used, being replaced by one entry point; and 3) since the atrial walls are thinner and not visible in CT images, an external wall with constant thickness was segmented.

![Figure 11 - Manual segmentation of the relevant structures. (a) Bidimensional contouring and (b) virtual 3D model of the atria.](image)
4.2 - Virtual modeling of the phantom mold

The 3D segmented meshes (LA, RA and cardiac wall) were initially transformed on three independent solids using the software GeoMagic (3D Systems). These solids were posteriorly imported on a 3D CAD Design Software (SolidWorks, Dassault Systèmes) where the phantom mold was created.

The mold is created in two different stages: 1) the LA and RA solids are subtracted to the cardiac wall. As such, a solid with cardiac wall and hollow cavities (Figure 12a) is obtained (see dimensions in Figure 13); 2) with the resulting structure we design the negative structure, consequently obtaining two internal and three external molds (Figure 12b). Moreover, the different entry points (pulmonary veins, IVC, SVC, left ventricle, right ventricle) were adapted to constant cylinders with specific diameter and thickness. Note that these adapted structures will be used in a future work to develop a dynamic phantom. As such, several tubes will be connected with these constant cylinders simulating the blood circulation into the atria.

![Figure 12 - Technique used to create the phantom mold. (a) The different solids (LA, RA and cardiac wall) are combined. (b) Using the combined solid, internal and external molds were designed.](image-url)
Figure 13 - Dimensions of the phantom model (in millimeters).
4.3 - Construction of the phantom mold using a 3D-printer

At this stage, the designed molds were converted on *gcode* format using Cura software (Ultimaker) and 3D-printer using an Ultimaker II (Figure 14). The follow parameters were used during the 3D-printing:

- Speed: 60%
- Nozzle temperature: 225 °C
- Build-plate temperature: 60 °C
- Material Flow: 100%
- Fan Speed: 50%

![Figure 14 - 3D-printing of the phantom mold.](image)
4.4 - Flexible Materials

Two different materials were used to construct the flexible phantom, namely: silicone and PVA.

The silicone used is an additive HB FLEX 5513 A+B transparent (HBQuimica). This material presents a hardness of 13 shA, linear contraction <0.05% and stretching until the break of 450 %. The flexible material was prepared mixing 75g of part A and B. Then, the material was injected into the mold. After 24 hours, the external molds were removed. Regarding the internal molds, one small incision was used to remove them. Note that the small incision was recovered with silicone.

The PVA relies on Mowiol 10-98 (Kuraray Europe GmbH) with molecular weight of 61, 98-98.8 mol% hydrolysis, ~14000 polymerization, 1.1-1.9% of impurities, viscosity of 9-11mPa.s, 4% in H2O (20ºC) and ester number of 15-25. Initially, the PVA powder was milled and mixture with water (temperature 80ºC), creating a viscous solution. This solution is posteriorly injected into the mold. Then, two thaw-freeze cycles were performed. Each cycle consisted of 12-h freezing period in a freezer at -20ºC, followed by a 24h thawing period. At the end of the freezing stage, the freezer was turned off and temperature was allowed to increase until the environment temperature. Finally, after 3-days the external mold was removed and two incisions were performed to remove the internal mold. The viscous material was used to cover the incision site, and a novel freeze/thaw cycle (12 hour freezing and 24 thawing) was performed.
5 - Experiments

The phantom models were tested and compared using ultrasound images. As such, we construct an experimental setup as presented in Figure 15a. The phantom models were placed into a water tank with a transesophageal (TEE) ultrasound probe (General Electrics, Vivid E9 Breakthrough 2012) connected to a 4D-Ultrasound machine (General Electrics, Vivid E9).

As a final remark, the US image acquisition was performed by one non-expert.

Figure 15 - (a) Setup used to validate the phantom model; (b) Silicone-based and PVA-based phantom models developed.
6 - Results

Figure 16 shows bidimensional ultrasound images obtained with silicone-based and PVA-based cardiac phantom models.

Moreover, three-dimensional ultrasound images were also obtained for the silicone (see Figure 17) and PVA phantom (see Figure 18).

Figure 16 - Ultrasound image obtained with (a) silicone-based and (b) PVA-based phantom.
Figure 17 - Four-view ultrasound image obtained with silicone-based phantom.

Figure 18 - Four-view ultrasound image obtained with PVA-based phantom.
7 - Discussion and Conclusions

In this work we developed a personalized phantom model of the atria region. This model will be used throughout the current PhD project to validate the novel guided-puncture strategies and to validate the novel image segmentation/tracking techniques.

The results obtained showed that the different cardiac chambers can be easily detected in US image (Figure 16). Moreover, a clear definition of the septal wall was achieved in three-dimensional ultrasound image (see Figure 17 and Figure 18), proving that these models can be used to accurately simulate the transseptal puncture technique.

Regarding the silicone-based and PVA-based phantom models, the PVA model appeared to present a more realistic ultrasound image. Additionally, although both materials can be used to visualize the IAS wall, a two-chamber (LA, RA and cardiac wall) image was only obtained with PVA material (Figure 18).

However, the cardiac wall showed high intensity homogeneity, due the uniform material used. As such, we intend to combine graphite or glycerin with the flexible models to generate speckle in ultrasound image. Furthermore, measurement of the speed of the sound throughout the cardiac wall should be performed and presented in a next work. Note that, this factor will be crucial to identify the optimal flexible material to construct the phantom wall.

In a future work, we intend to develop a dynamic phantom using a hydraulic pump system, similar to the presented in Figure 3 [5]. Moreover, an ultrasound acoustic absorber will be included on the water tank to reduce the number of echoes, consequently improving the ultrasound image. Finally, the ultrasound image acquisition will be performed by one expert, simulating therefore the real situation.
8 - References


