# RAPID PROTOTYPING OF 3D ANATOMICAL MODELS TO HEMODYNAMIC STUDIES

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Abstract: The purpose of this work is mainly to manufacture several anatomical models in a polymeric material – polydimensiloxane (PDMS) to study the blood flow through a carotid artery bifurcation. Over the last few decades, research has been shown that the geometry of the carotid artery is closely related to the development of serious cardiovascular diseases. Hence, there is a considerable interest in the development of *in vitro* experimental techniques able to obtain accurate measurements of the blood flow behavior through a realistic carotid artery. In this study we decide to apply rapid prototyping (RP) technologies combined with a PDMS casting technique in order to fabricate an anatomically realistic model of a human carotid to investigate, in a near future, the effect of the geometry on the local hemodynamics and consequently improve the understanding of the origin and development of these pathologies. Based on a human carotid computerized tomography (TC) it has been developed a 3D model through the application of two rapid prototyping techniques – Fused Deposition Modeling (FDM) and Tridimensional Printing (TDP). By combining the rapid prototyping techniques with a PDMS casting technique it was possible at the end to obtain an anatomically transparent model of a human carotid artery made by an elastomeric material, i.e. PDMS. Hence, we believe that this combination is a promising technique to perform *in vitro* blood studies through anatomically realistic models, such as a carotid artery.

## 1 INTRODUCTION

Large arteries that carry blood out from the heart and their branches are the most important blood vessels from human body. These arteries can be classified as elastic due to their big diameter and predominance of elastic fibers in their walls. Aortic and carotid arteries are included in this classification (Williams and Warwick, 1995).

Cardiovascular diseases are responsible for more morbidity and mortality than any other disease, being atherosclerosis, the most common and significant in a clinic perspective (Collins et al., 2001). Hemodynamic studies have been shown that the geometry of the carotid artery produces favorable conditions for the development of cardiovascular diseases such as, atherosclerosis and thrombosis. Hence, it is important to investigate new *in vitro* experimental techniques able to obtain accurate measurements of the blood flow behavior through anatomically realistic artery models.

In the conversion process of a computerized tomography in to a 3D model, it is needed a sequence of cross sections from the studied object. Using a 3D reconstruction software it is possible to transform these bi-dimensional images in a three-dimensional model that can be used to produce a



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solid model in rapid prototyping equipment (Foggiatto, 2006).

With the objective of obtain a real model from the anatomical structure a TC image set was used once this technology was able to provide us the definition wanted and allowed us to identify the arteries in the main anatomical area.

After the identification is done, the image processing starts with the goal to do the artery segmentation, which means, to isolate the arteries from the other existent anatomical structures, visible in the images.

Rapid prototyping technology has been applied to the previously rendered images in order to obtain a good quality, low cost and fast manufacture 3D anatomical model.

After converted into a STL (stereolitography) file, the 3D digital model is sliced and processed by the RP equipment that builds the model, layer, by layer, where each layer is added to the previous one. In this process we choose two different techniques – Fused Deposition Modeling (FDM) and Tridimensional Printing (TDP or 3DP).

Once obtained the wanted tridimensional structures, these are placed in a molding box to manufacture the PDMS transparent anatomical model. This polymer belongs to a group of organometalic polymers usually known by silicon and is a biocompatible, transparent, inert, non-toxic and non-flammable material with a great elastic effect and, therefore, is used to simulate blood vessels and other soft tissues.

This structure will allow, in the future, hemodynamic studies and simulations.

# 2 EXPERIMENTAL PROCEDURE

## 2.1 Image Processing

With the objective of obtain a real model from the anatomical structure a TC image set was used once this technology was able to provide us the definition wanted and allowed us to identify the arteries in the main anatomical area.

After the identification, the image processing starts with the goal to do the artery segmentation, which means, to isolate the arteries from the other existent anatomical structures, visible in the images.

Segmentation process has been performed in the software ScanIP® to where TC images can be transferred in DICOM format. To do this step, binarization and thresholding techniques have been applied to the images in order to obtain a mask in a range of grey values that includes, in each image, the tissues from the study object – carotid artery.

By evaluating the type of anatomical structure in question, the chosen range has been from 204 to 255:

$$g(x,y) = \begin{cases} 0, f(x,y) < 204 \\ 255, f(x,y) \geq 204 \end{cases}$$

where g(x,y) is the resultant in the image after the application of binarization technique and f (x,y) is the image obtained from TC (Alves et al., 2001).

The result after the first iteration has not been satisfactory due to the existence the other areas in the same grey range so, in a complementary phase, it was needed to process each image, pixel by pixel by removing the structures that were not needed. It was created a mask to each one of the arteries (right and left) to allow us to have available, if needed, both of them.

Once concluded artery model finishing by smoothing all the surfaces, it was kept the main structure with the bifurcation where most of the pathologies are developed and erased all the ramifications that will not make part of this study. The result can be seen in figure 1 where transversal, coronal and sagittal plans are illustrated as well as the 3D rendered model.

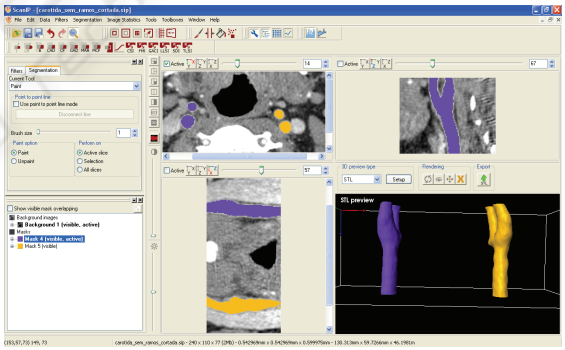

Figure 1: Different working plans in ScanIP® software.

When all the image processing phases are concluded, the file is converted in a STL format file through internal software translator models and then processed in printing management software that will slice the model and allow choosing the printing parameters to each of the used equipments.

Figure 2: Carotid arteries 3D rendered models.

## 2.2 Rapid Prototyping

By the STL file conversion into a SLI (slice) format file we are able to print the model, whatever is the RP method choosen. This type of file contains the information to each one of the layers to be printed, as well to the orientation in which the model should be printed.

This situation is due to the additive-constructive characteristic in which the RP processes are based (Rocha and Alves, 2000).

### 2.2.1 Fused Deposition Modeling

Fused Deposition Modeling – FDM, builds the model by extruding ABS polymer filaments through a printing head. This polymer is heated and melted when going through the printing head and each layer is deposited over the previous one melting it, partially, and becoming a continuous structure. During work, printing head moves along the coordinates (x,y) and the depth (z) is obtained by the platform movement where the model is being printed.

This process has as particularity the need of use of a second material as supportive layer where the main structure doesn't have any contact with the previous material layer. The printing head has two extrusion nozzles to feed, when needed, both materials in the same layer. At the end of each layer printing, the working platform is descended in a distance equal to the deposited layer depth. This process is made until the entire model is printed.

The model obtained by this process has a good surface quality and is ready to use after the supportive material is removed, which is easily done.

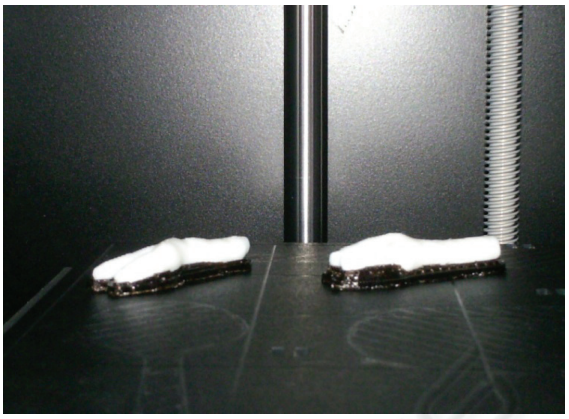

Figure 3: Carotid artery model manufactured by FDM process.

### 2.2.2 Tridimensional Printing

In this RP process, the model is built from a composite dust material (a specific combination of materials). In printing process, the composite material is prepared by a cylinder action that flattens the surface each time a layer is printed. In each layer the printing head draws the correspondent section in the material surface in glue aqueous liquid. When the new material is deposited to the new layer, it is glued to the previous one by the cylinder action.

Also, in this case, the printing head covers the coordinates (x,y), being the depth fulfilled by the movement of the working surface. Each time a layer is printed the working surface descends and the new material is deposited maintaining the distance to the printing head.

All process is repeated until the model is completely built.

After the model manufacture it is needed to remove the model from the non-glued material that can be recycled.

In TDP process, however, some additional tasks must be performed, once the model surface is dusty and non-stable. To remove the excess of material not glued, it is needed to perform a surface cleaning through the application of a compressed air flow. Most of cases, to stabilize the surface, it is applied a layer of cyanoacrylate or epoxy resin (Queijo et al., 2009).

In this work, two models were printed with different finished surfaces. To one of them it was applied one cyanoacrylate layer while the other was left with unstabilized surface.

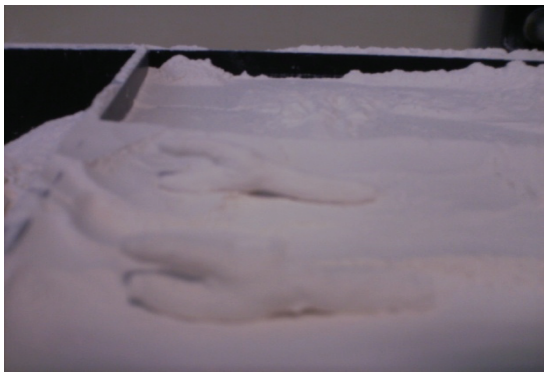

Figure 4: Carotid artery model manufactured by TDP process.

## 2.3 Fabrication of PDMS Anatomical Channels

*In vivo* animal research is an excellent way of performing experiments with in environments that closely mimics the human body. However, *in vivo* experiments are laborious, expensive and difficult to control several parameters and consequently it is extremely complex to obtain accurate measurements. On the other hand, by using *in vitro* models, besides reducing the number of sacrificed animals, this kind of models have many other advantages over *in vivo* models, such as the ability to control important parameters, obtain accurate measurements and reproducible experiments. For hemodynamic researchers *in vitro* models have been extremely attractive as this kind of models allows systematic flow studies. Hence, many studies on the blood flow behavior *in vitro* models have been performed over the past years. However, most studies have been done in rigid or simplified models (Goldsmith et al., 1996)(Lima, 2007). As a result, there is a need to develop more realistic *in vitro* models with geometries and environments that closely mimics the human body. In this study we applied two rapid prototyping techniques – Fused Deposition Modeling (FDM) and Tridimensional Printing (TDP) combined with a PDMS casting technique to obtain anatomically realistic models of a carotid artery.

The PDMS carotid artery was fabricated by using two kinds of rapid prototyping techniques, i.e., Fused Deposition Modeling (FDM) and Tridimensional Printing (TDP). The main steps for fabricating the PDMS carotid channel (Figure 5) were as follows. First, the human carotid geometry was obtain by computerized tomography (TC) and then printed by means of FDM and TDP. By applying the FDM we were able to obtain the carotid model in a copolymer of acrylonitrile, butadiene, and styrene (ABS), whereas by using a TDP we have obtained another kind model in a composite powder. Next, carotid models with clay supports where positioned in the bottom of a molding box in order to pour an elastomeric material into the mould. Note that, the model obtained by FDM technique needed to be cut around the branch in order to pull the model from the casting material without breaking it. The elastomeric material selected was the polydimensiloxane (PDMS) due to its outstanding properties, including good optical transparency and biocompatibility, easily reversible sealing to glass, elasticity, replication of fine and complex geometries, permeable to gases, thermally stable, and low cost (Lima, 2008). The PDMS prepolymer was prepared by mixing a commercial prepolymer and catalyzer (Silpot 184; Dow Corning, USA) at a weight ratio of 10:1. After removing the bubbles, created during mixing, by a vacuum pump the PDMS mixture was poured into the mould containing the carotid model and then baked into a oven for about 2 hours at a temperature of about 60°C. Both model and mould with PDMS were then cooled to room temperature.

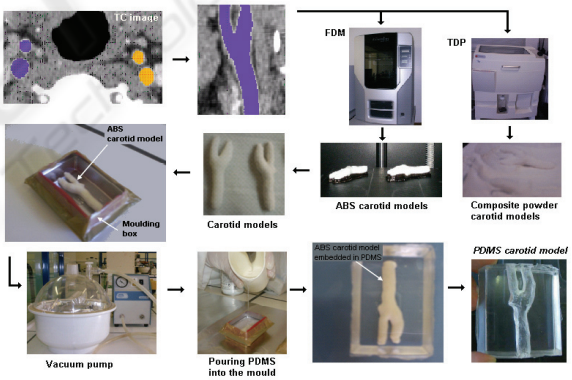


Figure 5: Main steps to fabricate PDMS carotid channels.

The embedded carotid model manufactured by the FDM technique was pulled out of the PDMS and as result it was possible to obtain an anatomically transparent model of a human carotid artery (see Figure 6). From Figure 6 it is possible to observe that the PDMS carotid model seems to have enough good transparency able to perform blood flow visualization studies. However, should be pointed out that walls of this PDMS carotid model have high levels of roughness due to the rapid prototyping technique (FDM) used to manufacture the ABS carotid model. In a near future, we are planning to polish the surface of the ABS carotid model to decrease roughness of the model.

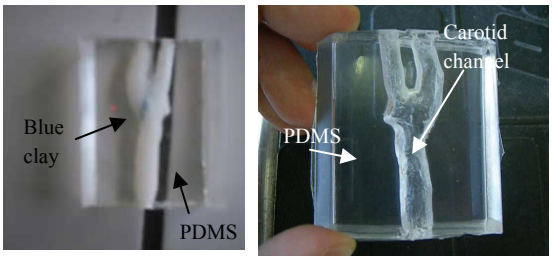


Figure 6: a) ABS carotid model manufactured by the FDM technique embedded in PDMS; b) PDMS carotid channel by means of a FDM technique.

For the case of the carotid model manufactured by the TDP technique it was not possible to pull out from the PDMS due to the extremely fragile characteristics of the composite powder. Hence, we decided to examine the solubility of several solvents in both PDMS and TDP carotid model in order to determine the most suitable solvent able to dissolve the embedded carotid model without significantly modifying the physical properties of the PDMS. In this study we used four kinds of solvents, i.e., acetone, hydrochloric acid (HCl), sodium hydroxide (NaOH), petroleum ether (PET). Table 1 summarizes the most relevant results obtained by using the selected solvents. Generally, we used 8 test tubes : 2 with acetone, 2 with HCl, 2 with NaOH and 2 with PET. For each solvent we have immersed a small piece of PDMS and the composite powder used to fabricate the carotid model by means of the TDP. First, both solutes were weighted before the immersion into the solvent. After 24 hours, the samples were first inserted into an ultrasound machine for 15 minutes and then into an oven for 4 hours at a temperature of 60ºC. Finally, by means of a vacuum pump the remaining water was completely removed from the samples and ready to be weighted once again. After 48 hours, this process was repeated once again and as a result we could obtain the data presented in Table 1.

The results from Table 1 show that the hydrochloric acid (HCl) has the highest solubility followed by the sodium hydroxide and the petroleum ether. Hence, we decided to immerse the PDMS containing the carotid model into hydrochloric acid (HCl). Although most of the solute was dissolved we have also observed that small amount of the composite power was still attached on the wall of the carotid channel and it was extremely difficult remove them from the walls (Figure 7). These preliminary observations show that this technique still needs to be improved in a near future.

Table 1: Experimental results obtained for four different kinds of solvents.

| Experimental results | | | | |
|---|---|---|---|---|
| Solvent | Solute | Initial weight (g) | Weight after 24 hours (g) | Weight after 24 hours (g) |
| Acetone | PDMS | 0.2578 | 0.2488 | 0.2488 |
| | TDP carotid model | 0.3361 | 0.3195 | 0.3128 |
| Hydrochloric acid (HCl) | PDMS | 0.3476 | 0.3449 | 0.3448 |
| | TDP carotid model | 0.2214 | * | * |
| Sodium hydroxide (NaOH) | PDMS | 0.3643 | 0.3642 | 0.3640 |
| | TDP carotid model | 0.2022 | 0.1274 | 0.1110 |
| Petroleum ether (PET) | PDMS | 0.2155 | 0.2040 | 0.2430 |
| | TDP carotid model | 0.2620 | 0.2043 | 0.2025 |

* All the solute was completely dissolved in the given solvent.

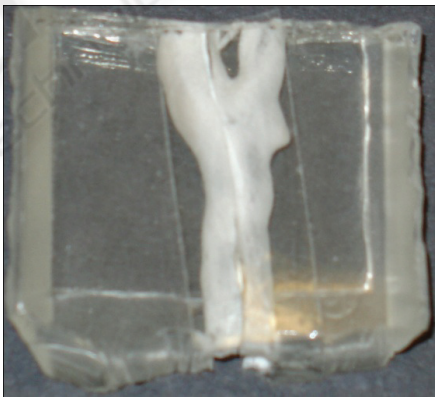

Figure: 7: PDMS carotid channel by means of a TDP technique.

# 3 CONCLUSIONS

The main objective consisted in applying two kinds of rapid prototyping technologies to manufacture several *in vitro* carotidal anatomical models in PDMS polymer for posterior hemodynamic studies. The conclusions drawn from this work can be resumed as follows:

- It was possible to conciliate several rapid prototyping techniques to obtain PDMS anatomical models;

- Rapid prototyping technology has proven that is a useful technology in the fast manufacture of good quality anatomical models from medical images, providing the ability of obtaining complex human structures that would very difficult to obtain by other means;
- The model obtained by using a FDM technique has shown the best surface transparency to perform *in vitro* blood flow visualization studies.

## 4 FUTURE DIRECTIONS

The PDMS transparent models obtained by the FDM technique seems to be promising way to perform *in vitro* blood flow studies through anatomically realistic replica of a human carotid artery bifurcation made by PDMS. Currently, an ongoing study to perform flow measurements trough the PDMS carotid models is currently under way. Figure 8 shows the experimental set-up that we planning to use to perform those studies.

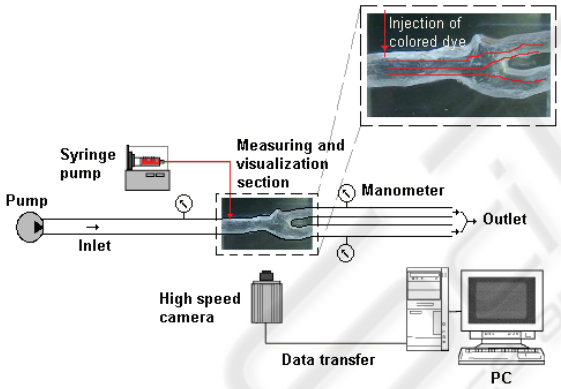


Figure 8: Experimental set-up to perform *in vitro* flow visualizations through the fabricated PDMS carotid channels.

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