Feasibility of the Fabrication of the Silicone Carotid Model by 'Multi-Piece-Mold-injection' Method

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***Abstract*—In order to carry out in vitro experimental simulations of blood fluid in carotid artery, the precise models are essentially required. So far, there are numerous researches about the fabrication methods of vascular models but few ones which focus on the evaluation of the fabricated models. The aim of this work is to confirm the feasibility of the 'multi-piece-mold-injection' method which is used by our research team to fabricate silicone carotid models. We have tested the dimensional precision by using 3D scanner as well as the mechanical and dynamic properties. In consequence, we have found that the model's dimensional precision, mechanical and dynamic properties are all satisfactory, the feasibility is therefore confirmed.** [1]

***Index Terms*—carotid, silicone model, 3D scanner, properties evaluation**

I. Introduction

Carotid bifurcation is generally in the form of Y, in reality, the carotid has a complicated structure which makes the blood fluid here very complex [1], [2]. Because of the special structure, many diseases can be found in carotid such as atherosclerotic plaque [3]. In order to pursue the researches of carotid blood fluid in vitro, a lot of fabrication method has been applied. Firstly, the Y-shaped or Tuning-Fork-Shaped models are fabricated in many researches as a simplified model of carotid [4], [5]. Furthermore, patient specific models are also developed to promote the fidelity [6].

So as to adapt the hemodynamic simulations, a desired elastic model should be in form of hollow pipe with homogenetic thickness. However, up to these days, our rapid prototyping cannot print soft elastic objects with highly transparent appearance directly. After studying the bibliographies, in our previous work, we have presented a fabrication method of the elastic transparent carotid model by injection of the silicone elastomer in the molds designed specially [7]. The method is mainly in 3 Steps: 1. Design of the molds adapted to the injection method; 2. Production of the molds by 3D printer with high resolution; 3. Injection of desired materials in the molds. The accuracy of the models of carotid plays an important role in the hemodynamic study and it can seriously affect the patterns of the flow such as vortex at the carotid bifurcation. Thus, it is necessary to know precisely the deviation of the dimensions, of the size, of the characteristic elastic, and also of the dynamic properties of the vessel wall beating during a cardiac cycle.

The aim of this evaluation of the models is to verify the degree of fidelity between the theoretic models and those manufactured by the method of rapid prototyping.

II. Materials & Methods

A. Dimensional Evaluation of the Fabrication of Models

1) Analyses of errors

The challenge of this evaluation is to estimate the exact dimension of the elastic carotid models. For this purpose, it should firstly well understand the errors that can be made in the different steps during the fabrication.

By conclusion of the different procedures of fabrication, we have observed that several steps can lead to errors: 1) the errors of the internal and external theoretic molds saved as format "STL" and fabricated by the 3D printer. The possible cause is the resolution of the 3D printer of rapid prototyping; 2) the errors introduced by the treatment of the surface of internal and external molds; 3) the errors introduced by the steps of injection and of the hardening. So this understanding permits us to design a protocol of measure of the errors of each step.

For the first type errors, we have compared the dimensions of theoretic molds that are designed by CATIA and the molds measured. For the second and third type, we have carried out the comparison between the elastic theoretic models and the fabricated ones in silicone (Fig. 1).

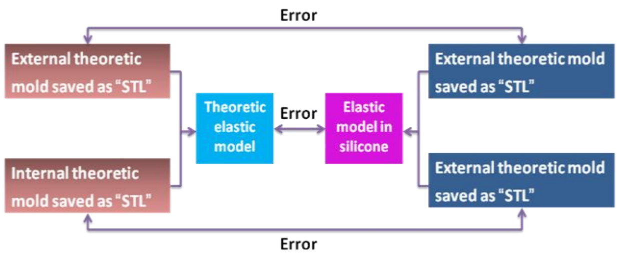

Figure 1. Protocol scheme of comparison for estimating the errors during the manufacturing process of the elastic carotid models.

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2) Equipments of measurement

The micrometric calipers are often used for the dimensional measure. It is capable of obtain the results with a precision of 0.001mm. However, it permits to measure the rigid objects only, so it doesn't adapt to our soft models: a direct measure is impracticable. To solve this problem, we have chosen 3D scanner with high precision for the measure.

The 3D scanner is often used for collect the geometric data of the object in 3 dimensions. To measure the positions of a sample of points of the surface of object, we can obtain the reparation of a point cloud. Because of its high precision, it can be introduced in the case of untouchable. However, there is a limit in this measure by 3D scanner: it doesn't work with the object which is brilliant or transparent. The reason is that the reflection and the diffraction will lead to incorrect result [8].

The system Metris MCA has an arm of measure by coordinated. Because it consists of 7 axis of rotation of certain flexibility, the pieces in small size and the form winding like the soft patient specific model can be scanned and measured. Another interesting specificity of this system is its speed of measure and precision which can achieve the level of 40 μm (Fig. 2).

Figure 2. 3D Scanner system of Metris MCA, measurement arm (left) and laser probe (right). Source: Metris.

3) Protocol of measurement

The materials of the object are transparent (silicone for elastic model and acrylic plastic for the molds) and the surface is smooth. The reflection of the laser prevents the detection by the measure machine. In order to solve this problem, we have applied a spray of powder (Spray Crick 130) which is very thin on the surface of the models. However, this layer will surely change or influence the measured results. If we know the thickness of this layer, we can consider this value in the analysis. We have prepared a cylinder as standard, whose size is known, scanned twice, the first time is scanned without spray while second time with spray. Before these scans, we have marked 1 point as reference.

The samples to scan are divided in 3 groups: 1. a standard cylinder; 2. a Y-shaped model and its internal and external molds; 3. a patient specific model and its internal and external molds.

B. *Evaluation of Mechanical Properties (Elasticity)*

The mechanical property of RTV3040 silicone is the elasticity. In order to evaluate the elasticity of the carotid model walls, it needs to know the elasticity module (or Young's modulus). The Young's modulus of the walls can associate with the vascular behavior of the arterial wall and it can be measured by the test of traction on the sample of wall. The test of traction is based on the Hooke's law. This law permits to connect to a simple way to measure and evaluate the elastic properties. The force F acting on a surface S exercises a stress tensor noted σ as shown in (1):

$$\sigma = F / S \quad (1)$$

It is ε who represents the elongation of material and E the Young's modulus of the wall, this equation can be written as (2):

$$E = \sigma / \varepsilon \quad (2)$$

In practice, since the models are in the form of cylinder, we carry out 2 measure directions: 1. the deformation from R to R_0 with radial force; 2. the variation of the elongation L of a material proportionally to its length L_0 with longitude force. These 2 directions of measure permit increasing the precision of test, and also testing the inhomogeneity of silicone wall (Fig. 3).

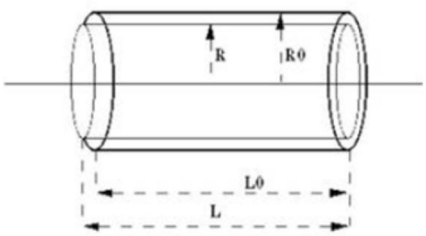

Figure 3. Measure of the wall elasticity.

C. *Dynamic Properties in the Physiological Condition*

The studies and measures in-vivo of blood fluids in carotid depend on the physiological properties of tissues. For example, we can find that the measure of a speed can be done by ultrasound Doppler. In order to ensure that the conditions approach the reality as much as possible, we have adapted our system of simulation depending on the terms.

We know that the carotid arteries in vivo submit to the pressure of the circumferential tissues in three dimensions. For representing a state of artery the most close to the reality and simulating the pressure of tissue, the agar-agar has been used. The mechanical properties and the acoustic propagations are important during the study by ultrasound. The most simple to realize is the immersion of model in a liquid that doesn't adapt to our situation because the movement caused by the beats can result in artifact of the MRI. Many imitations in polyethylene are principally used for destining to control ultrasound quality. In spite of their unsatisfying mechanical and acoustic properties and useful life, they are difficult and expensive to fabricate. Meanwhile, the hydro-gel tissues are widely used, they are principally made of a mixture of water, agar or gelatin. The addition of glycerin permits to modify the acoustic impedance of environment and bring it closer to the real human body.

The soft model is placed in a box in transparent acrylic. 300 ml distilled water, 20 g agar powder and 160 ml glycerin are pulled into the box too. The mixture is stirred to obtain a transparent liquid, and then left to cool down to ambient temperature. It is later put in a box and hardens.

In order to evaluate the dynamic properties of models, the ultrasound in mode TM has been used for measure the variation of the beats of carotid model during the systole and diastole in cardiac cycle.

III. Result Analysis

A. Evaluation Dimensional

1) Standard cylinder

By measuring three times the distance between the plan of the reference point and the plan of the ceiling of the standard cylinder without spray and with spray, we have estimated the thickness of the spray layer is 0.024 mm (Table I), it is lower than the measure precision (0.042 mm) by the MCA. So it is negligible.

TABLE I. Measurement of the Standard Cylinder with Spray and Without Spray

Measure	Standard cylinder with spray	Standard cylinder without spray	Difference
1	29.7917	29.7712	0.0205
2	29.7891	29.7564	0.0327
3	29.7912	29.7713	0.0199
Average	29.7906	29.7663	0.0243

2) Y-shaped model

The dimensions of the Y-shaped model designed by CATIA are known. The measures for the Y-shaped model are: 1. the transverse sections of 2 branches; 2. the transverse section of trunk; 3. the angle between 2 branches.

For these transverse sections, we can slice the internal and external molds for several slices in CATIA. So these surfaces can be obtained directly. Because of the measure functions of CATIA, we can also calculate the diameter of trunk and the branches. In this study, we have chosen 5 slices respectively in each branch and the trunk with a constant interval which is ensured by a reference point mentioned before (Fig. 4, Fig. 5).

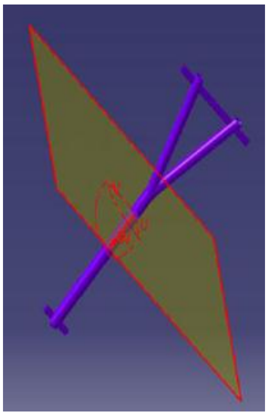

Figure 4. Measurement fulfilled by CATIA software.

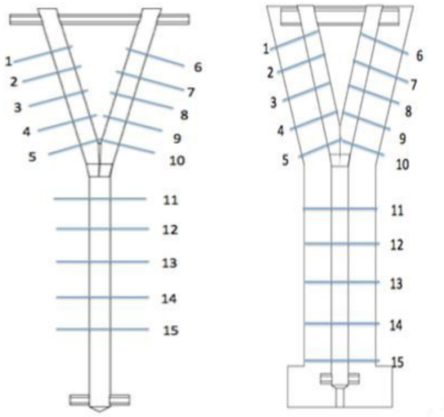

Figure 5. Transverse sections of internal and external mold for measurement.

We have then calculated the relative errors of diameters and the angle between 2 branches, which permits us to confirm the degree of reliability of our models (Table II).

TABLE II. Relative Errors of the Internal Mold, External Mold and the Final Model

	Internal mold			External mold A	External mold B	Soft Y-shaped model		
Section	Theoretic value (mm)	Measured value (mm)	Relative error (%)	Measured value (mm)	Measured value (mm)	Theoretic value (mm)	Measured value (mm)	Relative error (%)
1	6,000	5,788	3.5	25,030	24,652	50,265	49,682	1.2
2	6,000	5,769	3.9	25,481	25,259	50,265	50,740	0.9
3	6,000	5,769	3.8	25,470	25,774	50,265	51,244	1.9
4	6,000	5,779	3.7	25,945	25,694	50,265	51,639	2.7
5	6,000	5,780	3.7	26,087	25,599	50,265	51,686	2.8
6	6,000	5,757	4.0	25,491	25,202	50,265	50,693	0.9
7	6,000	5,769	3.9	25,928	25,685	50,265	51,613	2.7
8	6,000	5,758	4.0	25,934	26,033	50,265	51,967	3.4
9	6,000	5,749	4.2	26,033	25,948	50,265	51,981	3.4
10	6,000	5,777	3.7	25,718	25,789	50,265	51,507	2.5
11	7,000	6,703	4.2	32,662	32,184	63,617	64,846	1.9
12	7,000	6,713	4.1	32,945	32,382	63,617	65,327	2.7
13	7,000	6,702	4.3	32,954	32,748	63,617	65,702	3.3
14	7,000	6,701	4.3	32,553	32,654	63,617	65,207	2.5
15	7,000	6,718	4.0	32,562	32,469	63,617	65,031	2.2
Angle	29.9162 °	30 °	0.3	29.8688 °	30 °	29.4066 °	30 °	0.4

By analyzing the results of measure (Table II), we can remark that the relative errors of diameters of the mold internal are 3.5-4.3 %. The relative error of the angle is 0.3 %. The origin of these errors is possibly caused by the precision of 3D printer and the post-treatment of the surface. For the molds external (there are 2 pieces, noted A and B) we can obtain the relative errors between the theoretic values and measured ones. The relative error of the angle is 0.4 %, for the surfaces of transverse sections the relative errors are also acceptable: 0.9-3.4 %. In a nutshell, the method of fabrication for the models of carotid in form of Y is valid (relative errors are lower than 5 %).

3) Patient specific model

For the patient specific model, the measure is similar to that of model in form of Y. Fig. 6 is the schema of the slices measured of the patient specific model. We have firstly measured the surfaces of the transverse slices at different positions of molds internal and external (A, B) and the patient specific model. By compare the surfaces of transverse sections, we can remark that the relative errors are 0.3-8.4 % for the mold internal. For the external molds, the relative errors are 1.0-8.7 %. The possible causes are the precision measure error.

For the model, we have obtained the result of errors (Table III). We remark that the relative errors are 6.5-9.0 % for the trunk and 3.6-6.8 % for the branches. Especially, at the level of the siphons where the structure is the most complex, the relative error is 6.5 %. Since the errors are small, this method of fabrication can be considered the most precise and reproducible comparatively.

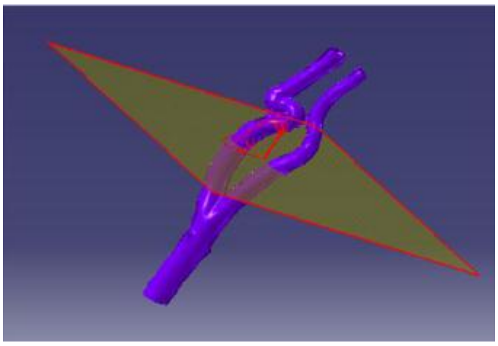

Figure 6. Measurement of the patient specific model by the software CATIA

TABLE III. RELATIVE ERRORS OF THE PATIENT SPECIFIC MODEL

Section		Soft patient specific model: Theoretic value (mm^2)	Measured value (mm^2)	Relative error (%)
1		78,478	85,551	9.0
2		84,413	89,899	6.5
3		85,654	91,369	6.7
4		115,926	123,785	6.8
5	Left	45,277	47,428	4.8
	Right	51,933	54,727	5.4
6	Left	48,555	45,418	6.5
	Right	54,649	52,698	3.6

B. Mechanical Properties (Elasticity)

This measure is realized by the increase of linear way of the applied force and recording the deformation of the sample on an instrument Instron (model 4505, Norwood, Mass) equipped in the laboratory Roberval of the University of Technology of Compiegne in France. For achieving a desired elasticity and also for approaching the reality as possible as we can), we have tested 3 prepared samples (Table IV):

TABLE IV. YOUNG MODULUS VALUES OF 3 SAMPLES

Sample	A	B	C
Components of mixture	RTV 3040 and 20% silicon oil mixture	RTV 3040 and 10% silicon oil mixture	RTV 3040 only
Young modulus (±standard deviation) (MPa)	0.52 ±0.15	0.39 ±0.07	0.3 ±0.09

According to the literatures, the average value of Young's modulus of vessel wall is 0.41±0.14 MPa for young people and 0.71±0.28 MPa for old ones [9]. We found that the silicone mixture with 20% silicone oil has an appropriate elasticity for represent a normal carotid vessel.

C. Dynamic Properties in the Physiological Condition

By observing the expansion and the contraction of model of the common carotid, the average variation of the internal tube is 28.3 %. Compared with the values measured in vivo: 10.34-29.6 % [10], [11], the characteristics of model are satisfied faithfully with the real dynamic elasticity of carotid artery.

IV. CONCLUSION

In this paper, we have confirmed the feasibility of the 'multi-piece-mold-injection' method to fabricate 2 types of the carotid models. The errors between designed numeric models and final fabricated models are acceptable, the dimensional precision is satisfactory. In addition, its mechanical and dynamic properties approximate the anatomic carotid artery in reality. Consequently, this fabrication method is competent, and the models are feasible in the subsequent experiments.

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