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A New Production Method of Elastic Silicone Carotid Phantom Based on MRI Acquisition Using Rapid Prototyping Technique

Peng Cao, Yvan Duhamel, Guillaume Olympe, Bruno Ramond and François Langevin

Abstract— **In vitro experimental simulations of blood fluid in carotid artery require ideal phantoms that are as precise as possible. The purpose of this work is to demonstrate a method for carotid phantom fabrication by rapid prototyping technique (RP). By using 3D reconstructed projection of the 3D time-of-flight (TOF) Magnetic Resonance Imaging (MRI) sequence, a 12.5cm multi-dimensional spatial structure of a carotid artery has been set up. Y-shaped and patient specific models have been generated respectively using silicone elastomer, which has a high resilience and a good tensile strength. The final patient specific model has internal carotid artery (ICA) with a highly spiraling siphon and an external carotid artery (ECA). Elastic properties of carotid walls have also been evaluated by Young's elastic modulus test and dynamic behaviors in optical and echography simulation experiments**

I. INTRODUCTION

Among the hypothesized mechanisms for atherosclerotic plaque development, blood dynamic behaviors in the artery are frequently considered. In vitro studies are an essential mean in uncovering the reason for vessel pathology. Previously, many researchers developed simple phantoms to represent the carotid artery for in vitro studies, for example, those forms are 'Y', 'T' or simplified carotid structures designed from average literature data. In terms of material for manufacturing, glass and plastic are often considered [1-3]. However, the real geometry of carotid artery is complex and not rigid. Specific geometry and wall beating are significant factors impacting the carotid hemodynamic characterization. With the help of 3D scanners and medical imaging reconstruction techniques, acquiring real geometry of vessel is not difficult to realize. However, with traditional fabrication methods, it is difficult to achieve a complex geometrical phantom which represents with fidelity such characteristics as the angle of bifurcation, curvature and variable vessel diameter etc. The emergence of rapid prototyping techniques in conjunction with 3D reconstruction data makes the complex geometric carotid phantom possible.

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Today, several fabrication techniques can be utilized. Mold Dipping is a simple method which could be easily implemented: beginning with a carotid specimen or printing a solid mold in form of carotid by RP machine, then dip them in silicone or latex liquid repeatedly several times to coat the surface and wait for curing. After disposing of the solid parts inside, a carotid phantom coated with elastic walls can be produced. The advantage of this technique is simple and economic; the geometry of the phantom is close to the original [4]. However, the coated silicone forms irregular thicknesses and that cause a bumpy surface in the final product. Building upon this method, Arcaute K et al. invented a Dip-Spin system for coating silicone on the surface of the mold. This new technique requires a two-axis rotation machine and provides a uniform silicone coat with different thicknesses at desired section. However, it has a problem of inconsistencies in vessel wall thickness [5]. The wax lost method utilizes a wax printer that can produce arbitrary wax molds, so that injection or dipping method may be applied and the wax mold could be removed in chemical solution or by thermal method. Nevertheless, this wax is very expensive and its printing resolution is not as good as solid object RP machines. Normal wax molds are not suitable for complex structure production in high precision [6-8]. In this work, we present a new method to produce a carotid phantom in form of 'Y' and real carotid vessel respectively using rapid prototyping technique.

II. PHANTOM GENERATION

A. Model Design

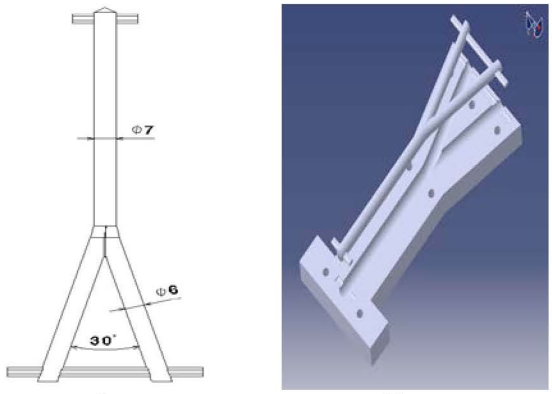
1) Y-shaped model

This Y-shaped phantom designed using CATIA software (CATIA V5R19, France) represents the real carotid vessel size. The carotid bifurcation is replaced by a straight tube (common carotid) with two daughter-branches (internal carotid and external carotid). The diameters for the tube and its daughter branches are 7mm and 6mm respectively. The thickness of the wall is 1mm and homogeneous. The angle between the branches is 30°. (Figure 1, A)

To achieve this phantom by material-injection methods, a mold constituted of two parts has been designed: outer mold and inner core. The thickness of the phantom wall was controlled by the space between the two parts of the mold. Each side, a transverse support can be fixed in the groove to avoid the inner core shift when elastomeric liquid is injected (Figure 1, B)

2) Patient specific model

A healthy volunteer's 3D-TOF-SPGR (Time of Flight Spoiled Gradient Recalled) carotid Magnetic Resonance



A B

Fig 1: Design of Y-shaped model of simplified carotid vessel

Angiography (MRA) was used for the source of imaging acquisition. This optimized 3D-TOF sequence was realized by multi-slab method with a 1.5T MRI system. Three sections of carotid with a length of 46.8mm were acquired. Each two neighboring sections have a common overlap of 5-6mm (Figure 2). The mean parameters are the following: TR=7.7ms, TE=26ms, Flip angle=35°, FOV=20cm, BW=31.25 kHz, matrix=256x224, Tck=1.2mm).

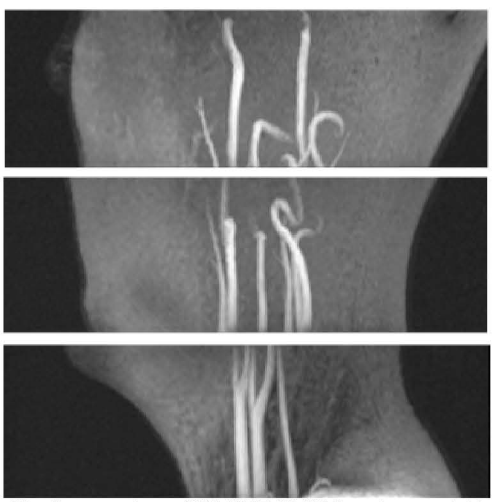


Fig 2: The three sections of 3D-TOF-SPGR imaging acquisition

ScanIP (Version 4.2, Simpleware Ltd, UK) was used to formulate the 3 sections of the carotid into a 3D model. After segmentation and reconstruction processing, a 12.5cm length of carotid model has been built (Figure 3).

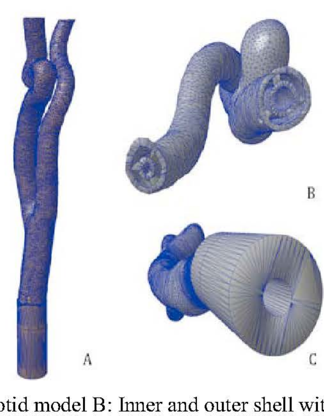


Fig 3: A: 3D carotid model B: Inner and outer shell with thin thickness. C: Silicon injection end

B. Model Fabrication

Multi-jet Modeling (MJM) rapid prototyping system (InVision® XT 3-D Modeler 3D Systems, SC, USA) was used for realization of Y-shaped and patient specific mold fabrication (Figure 4, 5). Two materials were used to print the mold: Acrylic plastic (SR200) and Wax (S100). For the patient specific model: Acrylic plastic played a role in shaping the two-shell support. Wax acted as the substance that filled in the space between the two shells and will form the blood vessel wall with different thicknesses. The waxes were melted and removed in an oven at 70°C. A continues pump has been used to circulate hot water (80°C) to eliminate the rudimental wax in the space of the two shells. For Y-shaped model, the method is similar.

To get optical clarity appearance, the Y-shaped mold and the real carotid model are treated in different methods. For Y-shaped mold, firstly we polish the inner surface of the mold and core' surface by sand paper with grade P500, P1000, P3000 and P8000. A thin layer of transparent varnish was coated (0.05mm-0.1mm). After that, the polishing processing is repeated once more with finer sand paper. For patient specific model, because of the narrow space of carotid mold, it is impossible to manipulate the same polishing process as the Y-shaped mold. Therefore, a circulatory flow of hot water (about 80°) is forced through with a high pressure and tiny solid particles in the fluid to smooth the inner surface of the mold. (Figure 4)

Fig 4: Rapid prototyping product of Y-shaped mold and core

These two types of mold are both applied by Mold-Injection method. 200 ml Silicon RTV 3040 with 20% silicon oil and 20ml catalyst were filled separately in a special mixer cartridge with ratio of 10:1. To eliminate entrapped air, the two parts was degassed under a vacuum pressure of 600mgh until the bubbles rise above its surface and gradually disappeared. The degassing operation required repeating several times. After a few hours, injection of the mixture was carried out by using a manual pistol particularly fitting for the cartridge (Etraves, France) and positioned in a fixing place for curing which lasts at least 24 hours. All procedures were performed at room temperature (23°C) and 50% humidity. When the silicone was cured, we rupture the two fragile

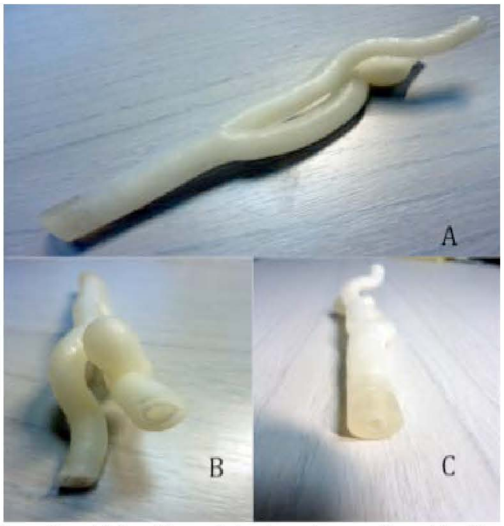


Fig 5: Carotid mold for silicone injection A: carotid mold with siphon. B: Two-shell structure. C: Silicone injection end

shells carefully and striped the silicone model. Finally, elastic Y-shaped and patient specific silicone phantoms have been finally generated. (Figure 6)

A B

Fig 6: (A) Y-shaped transparent silicone model (B) Patient specific carotid transparent silicone model with siphon

C. Phantom Preparation

Agar-agar preparation was used to mimic the surrounding tissues of the carotid. 360 ml of distilled water and 160 ml of glycerin was heated to 80° in a glass bottle placed in boiling water. 20g of agar-agar powder were added while stirring the mixture until it became translucent. We also added some black dye to facilitate the study of optical fluid simulation (this limits the reflection of the laser beam on the edge and improves the global contrast of the image between the phantom and surrounding gel). The liquid is then placed at the room temperature to cool down to 45°. The Y-shaped or patient specific phantom is placed in a transparent acrylic box and the mixture was cast in the box until it became firm. A rectangular "window" is cut in the agar-agar gel to allow the laser beam to reach the edges of the phantom and on the top to record particle displacement. The hole is filled with distilled water. An acrylic slab is placed at the top of the agar-agar gel with some pressure to reduce the movement of the phantom.

Fig 7: Carotid Phantom with agar-agar mimicking surrounding tissue

III. PHANTOM EVALUATION

A. Transparent appearance

Dynamic imaging acquisition of Particle Image Velocimetry (PIV) system (Figure 8) was obtained for verifying transparent appearance of this phantom.

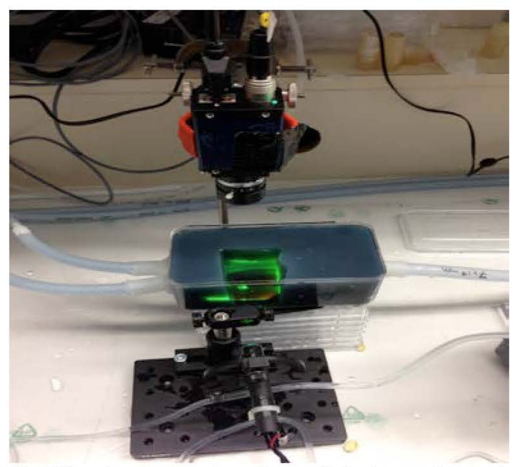


Fig 8: PIV system to record passing particles in carotid phantom

A closed flow circuit with a ventricular assist device (VAD) was used to simulate pulsate flow. For PIV system, a high-speed frame camera recorded the tiny particles passing through and the vessel wall beating process in the laser lighted zone. This phantom's transparent appearance makes particles in fluid imaged in high quality and can be accurately analyzed. (Figure 9)

B. Elastic property: Young's elastic modulus

Silicone liquid mixture with different ratio of silicone oil can be used to achieve desired elasticity. The Young's elastic modulus of two models' samples (0% and 20% silicone oil with Silicon RTV 3040 respectively) was measured. This test has been performed at the Roberval Laboratory of University of Technology of Compiegne. Young's elastic modulus of 0.52±0.15Mpa and 0.3±0.9Mpa has been obtained with 20% and 0% mixture of silicone oil respectively. This compares with the mean value(±SD) found in the literature (0.41±0.14MPa in young and 0.71±0.28MPa in older subjects [9]), 20% additive silicone blood vessel has an appropriate elasticity of a normal subject's carotid blood vessels.

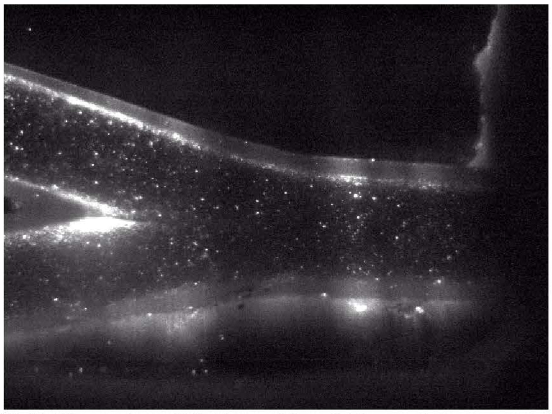


Fig 9: Tiny resin particles imaged by a high-speed frame camera

C. Dynamic behaviors

Echography in TM mode was used to evaluate the beating variation of carotid phantom during diastole and systole phases in cardiac cycles. With the dilatation and contraction of vessel phantom, the mean variation of the common carotid lumen diameters calculated by TM mode echography is 28.3%. (Figure 9) Compared with value of measurement in vivo 10.34±0.13% [10] and 29.6±0.2% [11][12], the phantom's characters are satisfactory to mimic real carotid arteries' behavior in terms of dynamically elastic property.

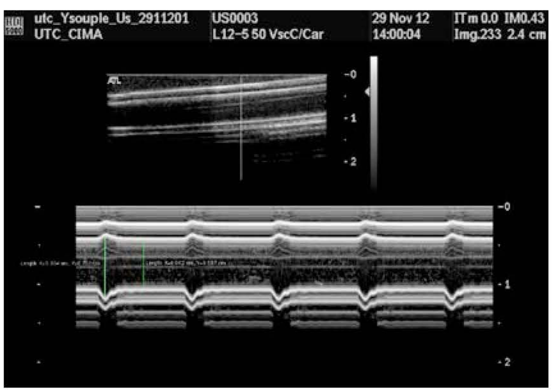


Fig 9: Diameter's variation of common carotid during cardiac cycle by TM mode echography

IV. CONCLUSION

In this paper, we present a new method to make economic transparent vascular models that have true-to-nature spatial structure geometry of the original carotid artery. Its elasticity approximates real anatomic blood vessels and it is compatible with MRI, Echography and PIV study. As different variation of vessel wall thicknesses have a significant effect on vessel pulsate pressure and result in complex flow formation, the different thicknesses act as an essential factor for carotid phantom. 'Black blood' MRI (named because the signal from flowing blood is suppressed rather than enhanced) can provide information about both the inner and outer boundaries of the vessel wall when imaged at relatively high-spatial resolution in a plane. It can be used to determine both lumen geometry and vessel wall thickness in a non-invasive manner [13]. The advantage of our fabrication method is we can control the variation of blood vessel wall thicknesses through the spacing for silicone injection. In future work, we will reconstruct 3D carotid model with vessel wall thickness information that is compatible with the Black Blood MRI technique.

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