STENTED CORONARY ARTERY PHANTOM FOR PARTICLE IMAGE VELOCIMETRY

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ABSTRACT

Irregular inner surfaces of a stented blood vessel can cause blood perturbations that have physiological and perhaps pathological consequences. To study these flow perturbations, a new 3D geometrically correct scaled up cylindrical phantom was developed for use in conjunction with an optically clear blood analog and particle imagery velocimetry.

INTRODUCTION

Blood flow perturbation can occur as blood encounters the irregular surfaces of a stented blood vessel. Little is known about recirculation and secondary flows around the stent struts, which have been associated with platelet and inflammatory cell transport potentially leading to intimal hyperplasia[1]. Understanding these secondary flows will eventually allow for the optimization of next-generation stent geometries.

The small size of the stent struts requires the construction of scaled up physical models of stented blood vessels for experimental flow perturbation visualization. The simplest hydraulic model consists of having the stent pattern of interest laid flat inside a rectangular flow box. The simplicity of this configuration permits for easy and rapid flow visualization of various stent geometries. However, the results obtained from this simplified model must be quantitatively validated by data obtained from placing the same stent pattern in a 3D geometrically correct cylindrical phantom.

Constructing the cylindrical phantom with radial inward-protruding wall structures is a challenge by itself. To this end, we propose a method of creating a geometrically accurate cylindrical phantom of a scaled-up stented coronary artery that is optically transparent for blood flow visualization in combination with an optically clear blood analog and particle image velocimetry (PIV).

METHODOLOGY

The creation of the 3D cylindrical phantom consists of using a series of molds, in which an optically clear rigid plastic resin will be poured and cured. The cylindrical phantom must have the following characteristics:

- Optically transparent: flow visualization using PIV requires optical transparency.
- Refractive index must match that of the blood analog used[2].
- Requires no dangerous or overly specialized substances or handling procedures[2].

In a first phase, a master mold is created on an aluminium cylinder. The stent pattern used is that of a *Symbiotech* coronary stent[3], scaled up 12.5 times to accommodate a Ø0.03125 in end mill. The *Symbiotech* stent pattern is modeled using *ProEngineer 2001*, a computer-assisted design program, then milled onto a cylindrical aluminium bar (Ø38.1 mm × 30.48 cm) using a CNC machining centre. This creates an aluminium negative of the stented coronary artery. A Ø38.1 mm × 76.2 cm aluminium cylindrical extension is added using epoxy and a screw mounted at the center of the cylinders (Figure 1A). The extension will provide the adequate entrance length for a fully developed flow. The entire assembly is then carefully cleaned and polished to a high gloss.

The aluminium negative cannot be used directly to form the internal structures of the phantom because of the latter's non-compliant nature. Otherwise, removal of the negative would be impossible without the destruction of the phantom. The second phase therefore calls for the aluminium negative to be replicated on a thin hollow plastic cylinder that can be thermally deformed and removed when the phantom's body fully solidifies.

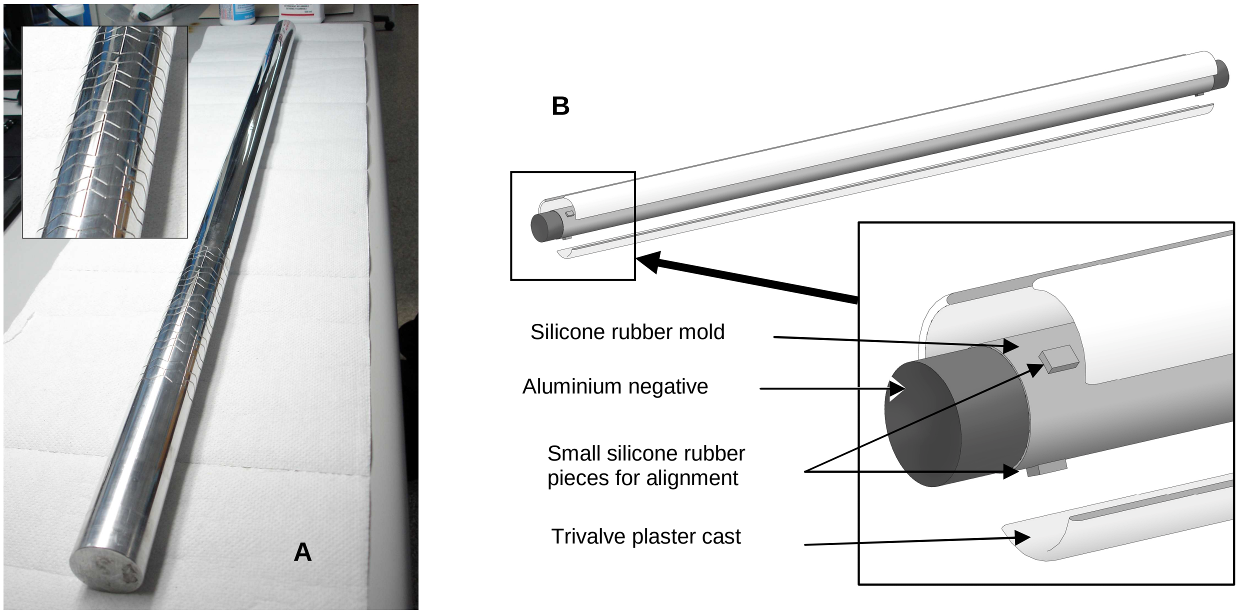

Figure 1: A) Aluminium negative. Inset shows stent strut pattern. B) Schematic of silicone rubber on aluminium negative, inside the trivalve plaster cast. The latter is displayed in exploded view.

The second phase begins with 300 ml of *MoldMax 20* silicone rubber resin by *Smooth-On Inc.* being prepared and degassed for 7 minutes at -27 psig. The resin is first forcefully smeared into the machined grooves of the stent pattern so that no air pocket remains; the rest of the resin is then evenly applied to the aluminium negative and left to cure for 24 hours. Having the stent pattern pointing downward ensures that more silicone rubber envelopes the patterned section.

Once cured, the silicone rubber mold forms a sleeve around the aluminum negative. Small rectangular silicone rubber pieces (≈ 1 cm × 5 mm × 3 mm) are glued on the outer surface of the mold along the circumference at both ends using *Dow Corning*'s *732* RTV sealant. A trivalve plaster cast is then constructed over and around the silicone rubber mold (Figure 1B) that will give the mold structural rigidity once the aluminium negative is removed. The trivalve configuration allows for easy removal and reassembly.

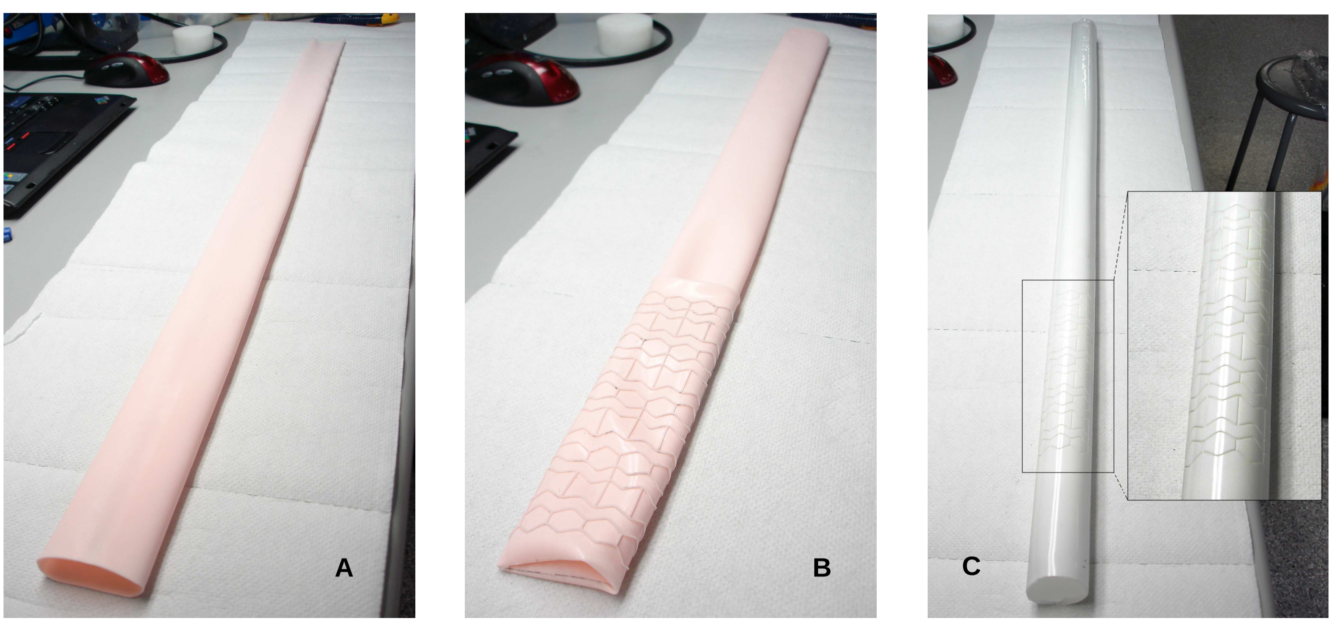

Figure 2 – A) Silicone rubber mold with aluminium negative and plaster cast removed, B) rolled inside out partially to reveal protruding stent pattern. C) Thin-walled plastic cylinder made with polyurethane. The inset shows the stent pattern in detail.

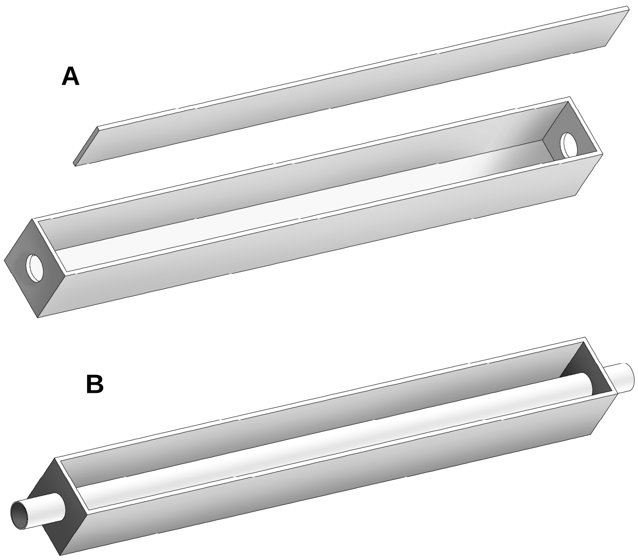

Figure 3: A) Acrylic view box. B) Cylindrical polyurethane shell inserted into view box.

The plaster cast is carefully removed after 24 hours. The silicone rubber mold is then gingerly peeled back and off from the aluminium negative. The silicone rubber mold is complete, forming a sleeve about 1 mm thick, with the stent pattern protruding from its inner wall (Figure 2A, B). The rubber mold is cleaned then put back into the plaster cast. Repositioning and realignment of the mold within the cast is achieved by reinserting the small rubber pieces on the mold into their matching indentations inside the plaster cast. The stiffness of the silicone rubber should be sufficient in pushing the mold snuggly against the interior of the cast. A stick is used to smooth out the occasional wrinkle inside the cast.

The silicone rubber mold is sealed at one end and 100 mL of *Smooth-Cast 305* polyurethane resin (by *Smooth-On Inc*.) is prepared and poured into the mold.

The plaster-encased mold is placed horizontally inside a Ø4 in ID × 49 in cylindrical vacuum chamber. The vacuum chamber rests on a wheel bed so that the chamber can fully rotate along its longitudinal axis. The vacuum chamber rotates continuously as the polyurethane resin sets, so that the inner wall of the silicone rubber mold is evenly coated with a thin layer of polyurethane resin, while the entire assembly is degassed at -27 psig for 5 minutes.

The polyurethane resin is allowed to solidify for 45 minutes under continuous rotation. The entire assembly is then withdrawn from the vacuum chamber, the plaster cast removed, and the silicone rubber mold delicately cut and peeled away. The aluminium negative is now recreated on a thin cylindrical plastic shell (Figure 2C).

A view box is made with 6 mm-thick transparent acrylic sheets. The view box measures 3.75 × 3.75 × 35 in, with two Ø1.495 in holes at both ends (Figure 3A). The cylindrical polyurethane shell is inserted into the view box through the end holes, with a few inches protruding from both ends (Figure 3B).

The view box is filled with *Sylgard 184* silicone elastomer from *Dow Corning*. This elastomer is optically clear and has a refractive index of 1.41 measured at room temperature. The elastomer is prepared and degassed for 15 minutes, and poured gently into the view box to minimize air bubbles.

The silicone elastomer is left to cure for 48 hours at room temperature. With the elastomer solidified, the thin plastic shell is softened using a heat gun, and removed. A stick is used to separate the elastomer from the shell by deforming the latter, without scratching the smooth clear inner surface of the hardened elastomer.

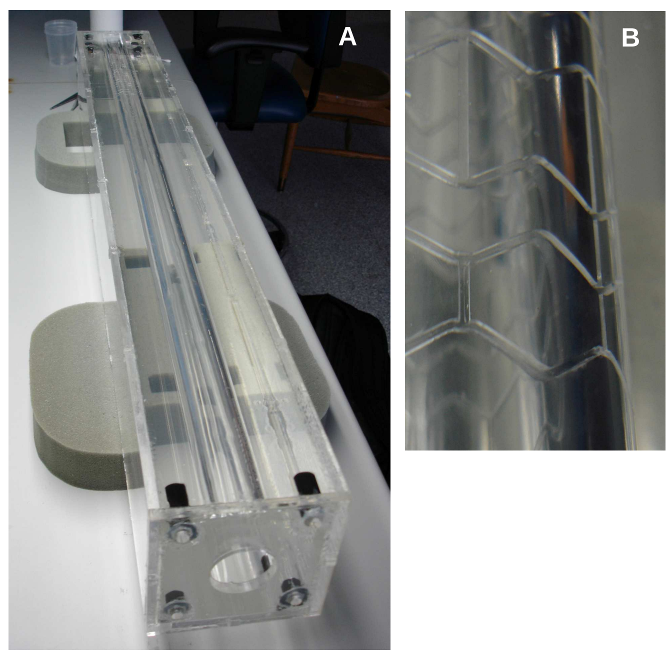

Figure 4: A) Final phantom, B) with struts in detail

DISCUSSION AND CONCLUSION

The result of the methodology described above is a geometrically correct optically transparent cylindrical phantom suitable for flow visualization studies using an optically clear blood analog. Figure 4A shows the final phantom, with strut details faithfully reproduced as shown in Figure 4B.

All materials used, including the plastic resins, are readily available and are fairly safe to handle without requiring special handling precautions. While the plastic resins used are capable of replicating minute details, each resin's maximal resolution (the smallest detail that the resin is able to reproduce) was not quantitatively determined as this was not necessary for the current application.

This fabrication process for stented cylindrical artery phantoms offers the possibility of replicating different stent geometries as well as other arbitrary intricate 3D artery wall structures for flow visualization studies using PIV.

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