COMPLEX SILICONE AORTA MODELS MANUFACTURED USING A DIP-SPIN COATING TECHNIQUE AND WATER-SOLUBLE MOLDS

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INTRODUCTION

Cardiovascular diseases are the primary pathologic abnormalities that lead to the largest number of deaths in the United States today. Researchers have performed in-vitro hemodynamic experiments on bench-top cardiovascular system models to gain an understanding of the relationship between blood flow and disease. Although simplified models and materials provide insight into the disease process, compliant vascular replicas based on patient anatomy are required to better simulate hemodynamic flow in the laboratory.

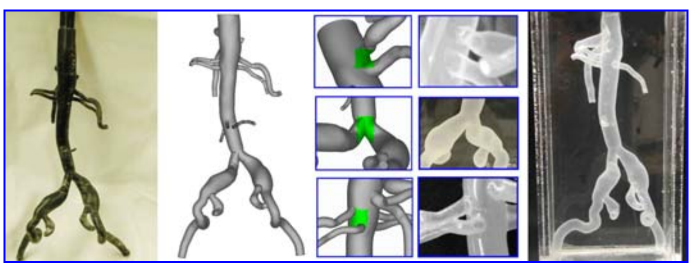

Figure 1. Abdominal aorta model.
WaterWorks mold (Left). CAD file (Left Center). Problem areas: CAD file and final silicone model (Right Center). Final complete silicone model (Right).

We present here updated developments to a previously published dip-spin coating process used to fabricate compliant cardiovascular system models based on anatomically accurate molds manufactured using rapid prototyping (RP) technology [1]. A human abdominal aorta extracted from patient CT data by Taylor *et al.* [2] was selected for process development and demonstration. As shown in Figure 1, the selected anatomy includes various elements, such as non-uniform radial geometry, small branches, and a bifurcation, that must be addressed in the dip-spin coating process. The previously published technique has been expanded and refined in order accommodate cardiovascular models of greater complexity.

MANUFACTURING PROCESS

The mold was fabricated out of WaterWorks (Stratasys, Inc., Eden Prairie, MN), and coated with implant-grade dimethyl silicone elastomer dispersion in xylene (Silbione 40000, Rhodia Silicones, Ventura, CA). Surface finish of the mold, viscosity of the coating solution, spinning of the mold after coating, and time between dips are the most important parameters in the manufacture of compliant vascular replicas. The dip-spin coating technique is divided into four stages: (1) mixing, (2) dipping, (3) spinning, and (4) curing. Details of the mold manufacturing and dip-spin coating processes are included in the following sections.

Mold Manufacturing

Cardiovascular molds are fabricated using a fused deposition modeling (FDM) RP system as described in Wicker *et al.* [1] and Wicker and Medina [3] and will not be elaborated here. The mold is made out of WaterWorks, a relatively high-temperature (~230 ^{o}C melting point, ~110 ^{o}C glass transition) and 100% water-soluble polymer typically used as a support material in FDM [3]. Because the FDM process creates models layer-by-layer, manufactured molds have a rippled surface. A material removal technique must be applied to RP manufactured molds before dip-spin coating can begin [3]. The average surface roughness value (measured using a Model TR100 Surface Roughness Tester, Time Group Inc.) of a model directly out of the RP machine is ~400 µm. Sanding and polishing reduces the roughness to ~15 µm making the mold suitable for the coating solution to flow easily around it and allowing the final membrane to have sufficient smoothness and optical clarity for experimentation [3].

Mixing

The silicone dispersion available from the manufacturer must be prepared for dip-spin coating. We recommend a uniform dispersion viscosity for complex aorta models similar to the one shown in Figure 1 between 1500-2000 centipoise. The wall thickness of the final model depends, in part, on the viscosity of the silicone mixture and the number of dips; wall thickness increases with increasing viscosity and number of dips [4, 6]. Xylene (PN 156-8684, Sherwin Williams, Cleveland, OH) is initially added to reduce the viscosity to the desired range (or xylene can be evaporated from the mixture to increase the viscosity) [6]. A pneumatic mixer (G-5 Motor, Arrow Engineering Co., Hillside, NJ) equipped with a special paddle for highly viscous liquids is used to mix the silicone while adjusting the viscosity. Mixing is performed at low speed to minimize the introduction of air into the solution. Viscosity is measured with a strain-based viscometer (VD-E Viscometer, Brookfield Engineering Labs, Inc., Middleboro, MA) repeatedly until the desired viscosity is obtained [6].

Dipping

Dipping is the principal stage in the manufacture of the final product. The mold is dipped into the silicone, immersed completely, rotated at least once, and then withdrawn using a step-motor (Slo-Syn Motor, Superior Electric, Bristol, CT) and controller (VP9000 Controller, Velmex Inc., Bloomfield, NJ). The mold is immersed for 10 to 15 seconds to ensure silicone coverage. The withdrawal speed is slower than the speed at which the coating solution flows down the mold (we insert and withdraw the molds into and from the silicone mixture at a rate of 0.3 in/s). Film thickness is partially set by competition between viscous, capillary and gravitational forces [5].

Spinning

To obtain a film with uniform thickness, the mold is rotated in a fume hood after each coat is applied to partially evaporate the solvent and to remove excess silicone (excess silicone is flung from the mold and the amount removed depends on the rotation speed). After initial drying, the dip-spin process may be repeated to increase film thickness. For simple geometries, spinning in one axis sufficiently distributes the coating to achieve a uniform film [5, 6, 7]. However, complex cardiovascular molds require multi–axis rotation. Figure 2 shows a mechanism that was developed to spin complex molds in two axes.

Wait time between coats is determined by the evaporation rate of the solvent, which depends on solvent volatility, rate of transport of solvent molecules through the film, and the partial pressure of solvent vapor at the film surface [8]. Twenty to thirty minutes between dips is sufficient time for solvent evaporation from each silicone coat.

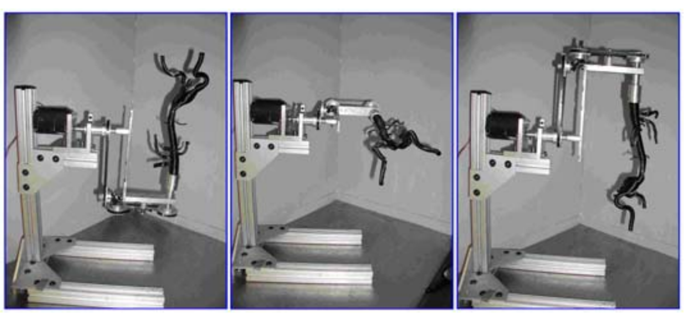

Figure 2. Mechanism used for two-axis rotation.

Curing

After the desired number of coats has been applied, the coated mold must be placed in an oven to cure the silicone. As the three-dimensional cross-linking network is formed, the silicone is solidified. A programmable oven (Model 1675 High Performance Oven, Sheldon Manufacturing, Cornelius, OR) with continuous air exchange is used to cure the silicone. A temperature profile is recommended for the curing process (the profile is provided in the following section), which cures the silicone without deforming the WaterWorks mold.

FINAL RECOMMENDATIONS

The manufacturing process described here was used to produce the compliant vessel shown in Figure 1. To summarize the dip-spin coating process, the following steps are recommended:

1. Manufacture cardiovascular molds out of WaterWorks with a surface finish of ~15 μm [process described in reference 3].
2. Remove trapped moisture from mold (pre-heat mold with air exchange at ~50˚C for 30 minutes).
3. Prepare the silicone coating solution (viscosity between 1500 and 2000 centipoise recommended).
4. Dip the cardiovascular mold into silicone mixture (leave in the silicone for 10 to 15 seconds and rotate once during immersion).
5. Remove from silicone mixture at ~0.3 in/s and spin the mold in two axes for 20 to 30 minutes.
6. Repeat dip-spin process until the desired thickness is achieved (Using the technique described here and the aorta shown in Figure 1, ten dips produced a film thickness between 0.040-0.060 inches for a 2000 centipoise silicone mixture).
7. Cure the silicone using a temperature profile as follows: one hour at 30˚C, twelve hours at 50˚C and twelve hours at 70˚C.
8. Remove WaterWorks mold by dissolving in water [3].

ACKNOWLEDGMENTS

This work was funded, in part, through Grant #11804 from the W.M. Keck Foundation.

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