3D Reconstruction and Manufacture of Real Abdominal Aortic Aneurysms: From CT Scan to Silicone Model

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Abdominal aortic aneurysm (AAA) can be defined as a permanent and irreversible dilation of the infrarenal aorta. AAAs are often considered to be an aorta with a diameter 1.5 times the normal infrarenal aorta diameter. This paper describes a technique to manufacture realistic silicone AAA models for use with experimental studies. This paper is concerned with the reconstruction and manufacturing process of patient-specific AAAs. 3D reconstruction from computed tomography scan data allows the AAA to be created. Mould sets are then designed for these AAA models utilizing computer aided design/computer aided manufacture techniques and combined with the injection-moulding method. Silicone rubber forms the basis of the resulting AAA model. Assessment of wall thickness and overall percentage difference from the final silicone model to that of the computer-generated model was performed. In these realistic AAA models, wall thickness was found to vary by an average of 9.21%. The percentage difference in wall thickness recorded can be attributed to the contraction of the casting wax and the expansion of the silicone during model manufacture. This method may be used in conjunction with wall stress studies using the photoelastic method or in fluid dynamic studies using a laser-Doppler anemometry. In conclusion, these patient-specific rubber AAA models can be used in experimental investigations, but should be assessed for wall thickness variability once manufactured. [DOI: 10.1115/1.2907765]

Keywords: abdominal aortic aneurysm (AAA), 3D reconstruction, silicone

Introduction

An abdominal aortic aneurysm (AAA) can be defined as a permanent and irreversible localized dilation of the infrarenal aorta [1]. It has been proposed that an AAA is an aorta with a diameter 1.5 times that of the normal infrarenal aorta [2]. Currently, the timing of surgical intervention is determined by the maximum diameter of the AAA, with an AAA diameter greater than 5 cm deemed to be at high risk of rupture. Much work has been aimed at the rupture prediction of these aneurysms, in particular, the use of finite element analysis to determine wall stress [3–8]. Although the use of numerical studies to gain an insight into the stress acting on the AAA wall is of obvious benefit to the particular AAA case, validation of these techniques is of equal importance. The ability to manufacture patient-specific AAA models for experimental studies could extend the use of preoperative wall stress techniques. These realistic silicone models could be employed, not only for stress analyses, similar to the photoelastic work of Morris et al. [9], but also for fluid dynamics studies and postoperative experimental testing, such as stent graft distraction testing. The models are created by first reconstructing a virtual AAA model, leading to mould design, and then to manufacturing via the injection-moulding technique. Previous research has examined the use of rapid prototyping as a method of producing elastomeric replicas of arterial vessels [10]. This method, although quick and effective, does not produce the surface finish that can be achieved using the injection-moulding process. Surface finish is of paramount importance when using arterial models for experimental testing using the photoelastic method, such as that previously conducted at our laboratory [9]. Other techniques have been employed in order to make models for use in laser-Doppler anemometry (LDA) [11] and particle image velocimetry (PIV) flow studies, where surface finish was of lesser importance than when conducting wall stress studies.

The principal objective of this study is to describe the modeling and manufacturing process used and to determine the effectiveness of the technique. This process of converting a standard computed tomography (CT) scan to a patient-specific silicone model is of value to many researchers in this field.

Methods

3D Reconstruction. Four patients were chosen from our AAA database. The CT scans of each patient were then imported into the software package MIMICS (Materialise, Belgium). This software allows the transformation of 2D CT scans into realistic 3D models of exact geometry. This software uses a marching squares algorithm to threshold and segment the regions of interest of the CT scan according to a predetermined grayscale value. Once segmented, the software generates polylines around the segmented

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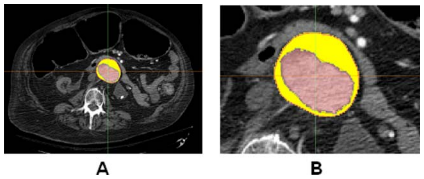

Fig. 1 Segmentation and polyline generation of CT scan. (*a*) shows the full CT scan, while (*b*) is a close-up of the region of interest. For the design of moulds, the AAA was regarded to be the full volume of the lumen and intraluminal thrombus (ILT).

regions, to a user-controlled level of smoothing. An example of this image segmentation and polyline generation can be seen in Fig. 1. In this study, polylines were created with approximately 20 control points per scan, allowing optimum smoothing without the loss of model accuracy. These polylines can then be exported as initial graphics exchange specification (IGES) format. Previous work has utilized various other forms of reconstruction software, such as SCION IMAGE (Release Beta 4.0.2, Scion Corporation, Frederick, MD) [12]. Validation of MIMICS against this work has been performed, with a percentage difference of 1.2% between the reconstruction methods.

Computer Aided Design (CAD). Polylines created in MIMICS are imported into PROENGINEER WILDFIRE 2.0 (PTC, Parametric Technology). Surfaces are then recreated along these polylines. These surfaces are then exactly split into two halves, thus creating a two-piece mould set used in the manufacturing technique. Each patient-specific mould design consists of two sets of moulds. The first mould is designed to produce the casting wax model of the AAA, and the second set to produce the outer silicone model. The outer mould is approximately 2 mm larger in all regions than that of the wax mould, so as to produce a silicone model with a 2 mm thick wall. As the wall of an AAA can range in thickness of 0.23–4.33 mm [13], a wall thickness of 2 mm is a reasonable assumption and has been used in previous studies [14].

Example mould designs can be seen in Fig. 2. Each outer mould design includes supports for the inner wax cast to ensure location of the wax model inside the larger outer mould. Of the four AAAs used in this study, three AAAs were modeled without the iliac arteries (Patients A, B, and C), and one AAA with the iliac arteries included (Patient D). For experimental studies involving stress analyses, the iliac arteries are believed to be unimportant, whereas for fluid dynamic and stent graft testing, the iliac arteries are of paramount importance. Moulds designed without the iliac arteries have cylindrical sections included both in the proximal and distal regions of the AAA, to allow attachment to experimental test rigs.

Computer Aided Manufacture (CAM). Once the mould sets have been designed in PROENGINEER, the designs are exported again in IGES format. These files are imported into the software package AlphaCAM in order to generate the toolpath commands used to control the milling machine. Each mould is set up with the same reference points so as that each mould piece fits exactly together, ensuring that the resulting model has an almost negligible seamline.

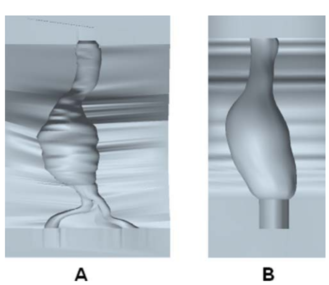

Fig. 2 Example mould designs of patient-specific AAAs. (*a*) is a mould design including iliac arteries and (*b*) without iliac arteries.

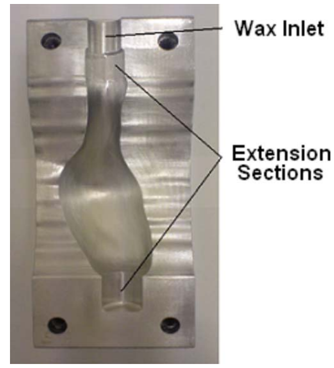

Fig. 3 Example machined mould piece of inner AAA model

Machining is performed by a three-axis computer numerical control (CNC) milling machine. Moulds are machined from solid aluminum blocks and are finished by hand to remove any unwanted burrs that result from the milling process. Figure 3 shows an example machined mould piece. This illustration shows regions where extensions have been included into the design in the proximal and distal regions of the AAA, and also the inlet through which the wax is poured. Necessary holes and vents were added to each model after machining.

Model Manufacture. All mould pieces were cleaned using acetone prior to use. The wax moulds were preheated to 40°C to minimize the contraction of the wax upon pouring. A casting wax (Castylene B581, REMET Corporation) was used to make the lumen casts. The wax lumen cast was then coated with Wacker protective film SF18 (Wacker-Chemie GmbH). The lumen casts were then placed into the outer moulds, which were coated with releasing agent (Wacker Mould Release) and then clamped. The silicone rubber (Wacker RT601) was then prepared and slowly injected into the preheated outer mould. Silicone rubber was employed as the material due to its nonlinear behavior when subjected to large strains [15] and is believed to be a good arterial analog. The mould is then placed into an oven at a temperature of 50°C and cured for 24 h. Once cured, the model is removed and the temperature is increased to 100°C in order to melt the wax from the mould. The resulting silicone model is then thoroughly cleaned, dried, and inspected for defects. The full procedure can be seen in the Appendix.

Results

Sectioning the Model. Each model was sectioned at regular intervals to assess the dimensional accuracy of the resulting silicone model compared to the CAD model. Each silicone AAA model was carefully split using a scalpel longitudinally along the left and right sides, thus leaving each model in two halves. Each half-model was then axially sliced at 10 mm intervals along the length of the model, leaving a series of cross-sectional slices for each patient-specific model.

Wall Thickness Measurements. For each cross-sectional slice of the silicone model, the wall thickness was measured at four 90 deg equispaced locations around the edge. Therefore, wall thickness was measured along the left, right, anterior, and posterior walls of the full AAA model. Measurements were obtained using a digital micrometer. Measurement readings ranged from 40 to 60 readings per AAA model, depending on the patient. Measurement results were then averaged for each patient-tailored sili-

Table 1 Averaged wall thickness measurements at four locations on the AAA wall

		Axial position			
		Anterior	Posterior	Right	Left
Patient A	Average wall thickness (mm)	1.87	1.97	2.09	2.55
	Standard deviation	0.276	0.314	0.173	0.327
	Percentage difference	6.95	1.78	4.23	21.47
Patient B	Average wall thickness (mm)	2.12	2.29	2.09	2.31
	Standard deviation	0.207	0.418	0.235	0.248
	Percentage difference	5.82	12.56	4.26	13.42
Patient C	Average wall thickness (mm)	2.18	2.17	2.53	2.30
	Standard deviation	0.223	0.293	0.352	0.306
	Percentage difference	8.08	7.89	20.99	13.09
Patient D	Average wall thickness (mm)	2.65	2.11	2.38	1.97
	Standard deviation	0.653	0.282	0.414	0.281
	Percentage difference	24.73	5.19	16.11	1.64

cone model with the percentage difference between the actual silicone model and the 2 mm wall CAD model noted. The standard deviation was also included in the results. The measurement results can be seen in Table 1 and are summarized as a total model wall thickness for each patient in Table 2. Percentage difference refers to the difference between the silicone model wall thickness and the original 2 mm wall thickness in the mould design. The AAA model of Patient D included the iliac arteries.

Wall Stress Distribution. Figure 4 shows the resulting von Mises wall stress distribution for Patient A and the region of resulting peak stress. The results show how the peak stress in the AAA model was 0.533 MPa and was located on the anterior wall of the AAA. The combination of finite element analysis (FEA) results with validated experimental wall stress studies could further the use of numerical studies in the field of AAA rupture prediction. A more detailed study of the wall stress experienced in AAAs is currently in progress, and will expand on the preliminary FEA results presented here.

Table 2 Averaged wall thickness measurements for each patient-specific AAA model

	Average wall thickness (mm)	Average percentage difference
Patient A	2.12	4.24%
Patient B	2.20	9.01%
Patient C	2.29	12.51%
Patient D	2.22	11.09%

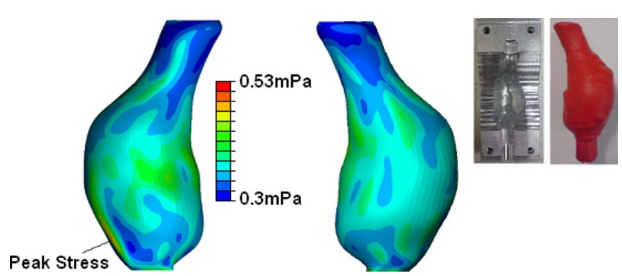

Fig. 4 Example FEA von Mises wall stress distribution for Patient A showing a region of peak stress on the anterior wall. The corresponding mould piece and resulting silicone model of the same patient can be seen on the right of this figure.

Discussion

This study describes a procedure for manufacturing patient-specific rubber models of AAAs both with and without the iliac arteries. A 3D reconstruction technique using commercially available software is coupled to a CAD/CAM technique to achieve the desired mould designs capable of forming realistic AAAs using the injection-moulding method. Previous studies [14,16] have used similar techniques to produce rubber models of vascular vessels. The models developed in this study are of greater complexity. These reproducible silicone models can be utilized for experimental testing of vessel hemodynamics, wall stress analyses, and stent graft studies, all of which may contribute to experimental validation of numerical work. This technique may allow other researchers to begin manufacturing realistic AAA silicone models for use in their experimental work. In recent years, emphasis has been placed on the use of numerical studies to attempt to predict AAA rupture. The use of experimental research into this area is also of importance. Not only could these silicone AAA models help in validation purposes but may also become an important asset in AAA rupture prediction.

For each of the patient-specific models created, wall thickness is the most variable factor. It has been reported [13] how the AAA wall can range in thickness from 0.23 mm to 4.33 mm, with aortic wall thickness reported to range from 1.1 mm to 3.4 mm [7,17,18]. Average wall thickness over the four models was noted to be 2.26 ± 0.39 mm. In this study, wall thickness lies within the range recorded by previous researchers [7,17,18], and so can be deemed as acceptable. Wall thickness results also favorably compare with those found for a realistic aorta by O'Brien et al. [14], who recorded a wall thickness in realistic aortas of 2.39 ± 0.32 mm. Although wall thickness appears to be within an acceptable range, the moulds were designed to have a wall thickness of 2 mm. The resulting silicone models differ from the mould designs by an average of 9.21% in wall thickness, which can be attributed to the contraction of the casting wax during solidification and the thermal expansion of the silicone during the curing process. These limitations of the technique were also observed by O'Brien et al. [14]. This previous work recorded percentage differences in wall thickness to mould design ranging from 20% for a realistic straight section of an aorta to 58% for a section of a saphenous vein. The results observed in this study are deemed acceptable in that percentage differences are considerably less than those previously reported [14]. It should also be mentioned that the models produced here are full AAA models and not straight vessel sections and, therefore, one would expect the percentage differences to be higher than those previously reported [14]. Therefore, confidence has been established in the method used to produce these models.

The issue of uniformity in wall thickness should also be addressed. In the mould designs, the wall thickness was set at 2 mm, and therefore, the resulting silicone models should also have a uniform wall thickness. Due to reasons mentioned above, that is, wax contraction and silicone expansion, the wall thickness varies in each AAA model. These differences in wall thickness can be attributed to the complex and tortuous geometry of these patient-specific AAA models. This limitation was also noted by O'Brien et al. [14]. Both O'Brien et al. [14] and Chong et al. [16] produced idealized vascular models, and in these much simpler models, the wall uniformity issue was easily overcome, thus highlighting the fact that realistic geometries increase the difficulty of not only the CAD/CAM process but also the model manufacture itself.

The use of a uniform wall in these experimental models may be considered inappropriate, since it is known that the actual AAA wall tissue can include various forms of arterial tissue (calcified deposits and thrombus) and thus is usually nonuniform. While these regions of both calcified tissue and thrombus can be detected from the CT scan, their incorporation into the wall of the model introduces additional complexity. First, incorporating regions of varying material properties into the AAA wall results in greatly increased computations as the numerical equations used to solve for wall stress at these locations become extremely complex. Also, the primary purpose of producing realistic silicone models of known uniform wall is to experimentally validate numerical studies of the same AAA model. Most previous work regarding numerical stress analyses of AAAs [3–8,19–22] has conducted testing using uniform walls. Our earlier work [9] on idealized AAA models of known uniform wall thickness proved quite successful and has paved the way for the introduction of realistic AAA models to be tested using the same technique. This experimental photoelastic work was later numerically validated on an idealized AAA model by our group [23], which confirmed the locations of peak stress on the model. It is planned to revisit the concept of nonuniformity of the silicone models using this described procedure. Work has also begun in this laboratory on the inclusion of thrombus in the AAA models.

It has been suggested [6] that the use of a fluid-structure interaction (FSI) approach to stress analysis may yield more accurate wall stress results than FEA alone. Some researchers have shown that the wall stress is increased by amounts <1% [21], whereas others have reported increases ranging from 12.5% [6] to 20.5% [20]. As there are conflicting results in the benefits of FSI in wall stress studies, these uniform-walled AAA models can help toward validating both methods of stress studies. Work has begun within our laboratory on the use of FSI, employing mesh-based parallel code coupling interface (MPCCI 3.0.6, Fraunhofer SCAI, Germany) software, which couples both ABAQUS and FLUENT together to obtain realistic wall stress values. Notably, the use of a uniform wall is widespread among researchers conducting FSI studies [5,6,19–22], and so this future work will allow the numerical and experimental validation of wall stress in realistic AAA models based on the uniform wall thickness.

Conclusion

The procedure for the manufacture of patient-specific AAA models has been described. Confidence has been established in the reproducibility of the rubber models, and the limitations noted. In general, rubber models of good geometrical accuracy can be produced by sensible mould design and use of controlled parameters in the silicone production. Models showed a maximum percentage difference of 9.21% between the designed moulds and the resulting silicone models. Uniformity of wall thickness proved to be the most difficult parameter to control, with finished silicone models always inspected and assessed before commencement of experimental testing. This technique may aid in the validation of numerical methods through photoelastic validation [9] or also through experimental testing such as LDA or PIV.

In conclusion, 3D reconstruction and CAD/CAM techniques proved to be successful in the replication of patient-specific rubber AAA models and may help contribute to the use of patient-specific AAA models in experimental testing. Therefore, the use of silicone AAA models with uniformly thick walls will help toward the validation of numerical work, for both wall stress studies and flow dynamics.

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Appendix

Realistic Model Manufacture

In creating the male wax models, the following steps are given.

1. The first sets of moulds are used to create the wax models.
2. Clean the surface of the moulds with acetone; make sure it is free of loose debris and coat with mould release (Ambersil Formula 8, Chemcraft Industries Ltd. Dublin, Ireland).
3. Bolt the two mould pieces together tightly.
4. Melt the casting wax (Castylene B581, REMET Corporation) on a hot plate at a temperature of around 150°C.
5. Preheat moulds in oven to 40°C.
6. Position the mould at an angle of 45 deg to aid the liquid wax to flow into the mould and minimize the risk of trapping air, thus creating voids and bubbles.
7. Pour the wax into the mould as slowly as possible to prevent splashing, which can also create voids. As the cavity is filled, the mould is returned to the vertical position to finish pouring the wax.
8. The wax is then left to solidify at room temperature for up to 4 h. During this cooling period, the mould is gently tapped with a mallet to allow any trapped air to rise to the surface.
9. As the wax cools and solidifies, additional wax is added to the mould to ensure a complete wax model.
10. Open the moulds and carefully remove the wax model from the mould.

In creating the silicone model, the following steps are given.

1. Mix the silicone in the required ratio of silicone and curing agent (9:1).
2. Hand mixing the material components for a period of 2 min is sufficient. This liquid silicone will represent the aorta wall. The liquid silicone contains air bubbles once hand mixed which must be removed. The working time for the mixed, components at room temperature is around 90 min.
3. In order to remove the trapped bubbles, place the container of liquid silicone into a freezer until all bubbles have been naturally removed. Duration of time in the freezer depends on the viscosity of the liquid silicone and can vary from 1 h to 3 h.
4. Once all the air has been removed, suck all the liquid silicone into a 60 ml syringe.
5. Clean the second set of aluminum moulds with acetone.
6. Spray on a coat of silicone mould release (Ambersil Formula 8) onto both the aluminum moulds.
7. Carefully remove any excess material and flash from the wax model.

8. Coat Wacker protective film SF18 (Wacker-Chemie GmbH) onto the wax model. Once applied, leave it for 2 min.
9. Position the inner wax model inside the outer aluminum mould ensuring that the wax model sits in a way that will allow uniform wall thickness.
10. Bolt the two aluminum moulds together tightly.
11. Seal around the edges of the mould with sealant to avoid any unwanted leakage from the mould.
12. Slowly inject the liquid silicone into the aluminum cast using the filled 60 ml syringe.
13. Once the liquid silicone is injected, place the mould in an oven at a temperature of 50°C for a period of 24 h.
14. Once cured, open the cast and carefully remove the silicone and wax model.
15. Place the silicone and wax model into the oven at a temperature of 100°C to melt the wax from the mould.

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