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Experimental modelling of aortic aneurysms: Novel applications of silicone rubbers

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ABSTRACT

A range of silicone rubbers were created based on existing commercially available materials. These silicones were designed to be visually different from one another and have distinct material properties, in particular, ultimate tensile strengths and tear strengths. In total, eleven silicone rubbers were manufactured, with the materials designed to have a range of increasing tensile strengths from approximately 2 to 4 MPa, and increasing tear strengths from approximately 0.45 to 0.7 N/mm. The variations in silicones were detected using a standard colour analysis technique. Calibration curves were then created relating colour intensity to individual material properties. All eleven materials were characterised and a 1st order Ogden strain energy function applied. Material coefficients were determined and examined for effectiveness. Six idealised abdominal aortic aneurysm models were also created using the two base materials of the study, with a further model created using a new mixing technique to create a rubber model with randomly assigned material properties. These models were then examined using videoextensometry and compared to numerical results. Colour analysis revealed a statistically significant linear relationship ($p < 0.0009$) with both tensile strength and tear strength, allowing material strength to be determined using a non-destructive experimental technique. The effectiveness of this technique was assessed by comparing predicted material properties to experimentally measured methods, with good agreement in the results. Videoextensometry and numerical modelling revealed minor percentage differences, with all results achieving significance ($p < 0.0009$). This study has successfully designed and developed a range of silicone rubbers that have unique colour intensities and material strengths. Strengths can be readily determined using a non-destructive analysis technique with proven effectiveness. These silicones may further aid towards an improved understanding of the biomechanical behaviour of aneurysms using experimental techniques.

1. Introduction

Silicone is a synthetic polymer consisting of a linear backbone of repeating, alternating silicone and oxygen atoms. Each silicone atom has two groups attached to it, referred to as R groups, representing any organic group that may be attached to the backbone. This structure forms a polymer called polydimethylsiloxane (PDMS), and is the most commonly used silicone. Rubber-like materials are comprised of very long-polymeric chains united by vulcanisation into a network structure. These rubbers can therefore undergo large recoverable deformations, hence the wide use of silicone rubbers as material analogues in the study of arterial vessels [1–4] and other soft tissues [5]. At relatively high strain rates, such as above 0.1 s^{-1} similar to those naturally found within the cardiac cycle, polymeric chain deformation is usually restricted to bending and stretching of the chemical bonds within the network. As a result the storage modulus of the rubber can increase by up to three orders of magnitude [5]. Abdominal aortic aneurysms (AAA) are permanent irreversible dilations of the infrarenal section of the aorta, which will eventually expand to the point of rupture if left untreated. Many previous studies have focussed on the numerical prediction of wall stresses and ultimately rupture prediction of AAAs [6–15]. However, there has been limited reports as to how these aneurysms behave experimentally [2,17,18], in particular, how these models react to increased pressure loadings above the average peak systolic pressure of 120 mmHg. Also, previous experimental work has employed the use of a single material to represent the

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AAA wall, even though it is known that a realistic AAA may have differing material properties at various locations throughout the aneurysm [19].

The primary aim of this study was to develop a range of silicones of known colour and known material properties. Commercially available silicone was used in conjunction with a method of colour analysis in order to develop calibration curves. These calibration curves consist of a direct relationship between material colour and both tensile strength and tear strength. The developed materials can then be used in further experimental tests, mimicking arterial soft tissue. Material characterisation was determined from uniaxial tensile tests and also from tear strength tests. These rubbers were then used to form the arterial wall analogue for experimental testing of idealised abdominal aortic aneurysms. These rubber models can be created using previously reported techniques [1,4] for use with videoextensometry. These novel materials could be used to create more physiologically realistic *in vitro* arterial models. The use of a combination of silicones to create a diseased vessel wall could serve as a useful tool in future experimental work. In particular, these materials could be incorporated into experimental rupture studies to provide more accurate material analogues than those used in previous reports [2].

2. Materials and methods

2.1. Material selection

The commercially available Sylgard silicone from Dow Corning was chosen as the base material for this study, in particular, Sylgards 160 and 170. Both Sylgards are supplied as a two-part silicone elastomer with Sylgard 160 appearing grey and Sylgard 170 appearing black. These two rubbers are prepared in a 50:50 by weight arrangement, which facilitates mixing and preparation. These silicones were identified as appropriate materials as each material is easily identifiable due to its colour, and importantly, they have dissimilar material properties.

2.2. Material development

Sylgard 160 is naturally grey in appearance with an ultimate tensile strength (UTS) of 4 MPa, whereas, Sylgard 170 is naturally black in colour with a UTS value of 2 MPa. These UTS values were obtained from the Dow Corning specification sheets. These two materials were mixed together in various ratios in order to create a range of new silicones, with gradually increasing colour intensity from grey to black and gradually decreasing failure properties from 4 to 2 MPa. The ratios of each mix were increased by 10% for each new silicone, resulting in 11 complete materials, including the original Sylgards 160 and 170, as shown, for example, in Column I of Table 1.

Table 1
Results of the uniaxial tensile testing for each mixture of silicone. ΔE and UTS results are mean values of the sample size. Standard deviation (S.D.) is also shown.

Silicone type	n	ΔE	S.D.	UTS (MPa)	S.D. (MPa)
160	18	47.72	2.57	3.822	0.51
10:90	6	40.16	0.97	3.537	0.498
20:80	6	36.91	0.7	3.599	0.635
30:70	5	31.92	0.95	3.289	0.357
40:60	6	32.52	0.45	2.611	0.33
50:50	12	29.88	0.7	3.206	0.377
60:40	5	27.33	0.39	2.473	0.093
70:30	10	26.41	1.01	2.445	0279
80:20	5	25.13	0.77	2.199	0.243
90:10	5	24.55	1.21	2.401	0.391
170	20	23.86	1.85	2.077	0.375

Silicone mixes are in ratios of Sylgard 170:Sylgard 160, therefore, 10:90 refers to 1 part Sylgard 170 to 9 parts Sylgard 160.

2.3. Colour analysis

The colour intensity of each silicone was analysed using a ColorLite sph850 Spectrophotometer (ColorLite GmbH). This device allows each silicone mix to be assigned an individual colour intensity value. Colour measurements are given in as a variation of ΔE, where pure black has a ΔE value of zero. This mathematical model for colour measurement was developed by the Commission International de l'Eclairage (CIE) and is often referred to as the CIELAB formula. ΔE is a single number that represents the "distance" between two colours. A ΔE value of 1.0 is the smallest colour difference the human eye can see, and therefore, any ΔE less than 1.0 is imperceptible. ΔE variations above approximately 2.0 are distinct. ΔE is defined by Eq. (1).

$$\Delta E = [\Delta L^2 + \Delta a^2 + \Delta b^2]^{1/2} \tag{1}$$

This equation is based on the most commonly used colour system $L^*a^*b^*$, values where the lightness value, or luminosity, (ΔL) indicates how light or dark the colour is, Δa represents the position on the red–green axis, and Δb shows the position on the yellow–green axis. $L^*a^*b^*$ values are calculated from the tristimulus values (X, Y, Z) which are the backbone of all colour mathematical models. These tristimulus values are dependent on the light source ($S(\lambda)$), the object ($\beta(\lambda)$), and the colour (red(λ), green(λ) and blue(λ)). The colour matching functions $x(\lambda)$, $y(\lambda)$ and $z(\lambda)$ mathematically transform red(λ), green(λ) and blue(λ) into imaginary functions, with the tristimulus values X, Y and Z values then calculated using Eqs. (2)–(4).

$$X = \sum \beta(\lambda) \times S(\lambda) \times x(\lambda) \times \Delta\lambda \tag{2}$$

$$Y = \sum \beta(\lambda) \times S(\lambda) \times y(\lambda) \times \Delta\lambda \tag{3}$$

$$Z = \sum \beta(\lambda) \times S(\lambda) \times z(\lambda) \times \Delta\lambda \tag{4}$$

The location of a colour is defined by a three dimensional Cartesian coordinate system which determines the numerical values of L^*, a^* and b^*, and is shown in Fig. 1a. Once the location of $L^*a^*b^*$ is determined, a modification of the CIELAB tolerancing is performed, known as CMC tolerancing (Colour Measurement Committee of the society of Dyers and Colourists of Great Britain). This technique mathematically defines an ellipsoid around the standard colour with semi-axis corresponding to hue, chroma, and lightness. Fig. 1b shows the variation of the ellipse sizes throughout the $L^*a^*b^*$ colour space. The actual values of L^*, a^* and b^* are calculated using Eqs. (5)–(7).

$$L* = 116 \times \sqrt[3]{\frac{Y}{Y_n}} - 16 \tag{5}$$

$$a* = 500 \times \sqrt[3]{\frac{X}{X_n}} - \sqrt{\frac{Y}{Y_n}} \tag{6}$$

$$b* = 200 \times \sqrt[3]{\frac{Y}{Y_n}} - \sqrt{\frac{Z}{Z_n}} \tag{7}$$

A typical use of the CIELAB colour system in a medical environment is described in Rubiño et al. [20] The spectrophotometer itself consists of a handheld device and an attached light-probe. In order to actually determine the ΔE value of the particular material, firstly the device is calibrated using a standard colour, in this case the standard reference colour was black. The light-probe is then placed against the material to be tested and allowed to operate. The light-probe illuminates the surface of the object, and thus determines the ΔE value using the above equations. Average colour intensity was recorded from three measurements taken for each sample.