Use of finite element analysis to simulate the hyperelastic behaviour of cardiovascular tissue

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Introduction

The mechanical behaviour of the vascular wall is very complex. Its non-linear elastic as well as viscoelastic properties make it difficult to estimate the forces involved during catheter insertion or balloon angioplasty as well as the compressive forces acting on vascular stents. To model these procedures, a constitutive model must be developed that accounts for the anisotropic non-linear elasticity of the vessel under high strains. In this study, hyperelastic theory is used to model the cardiovascular tissue behaviour. Hyperelasticity makes use of a strain energy function *W*, whose derivative with respect to a strain component determines the corresponding stress component as shown in equation (1) where *W* can be expanded (n=1,2,3) to utilise a two, five or nine parameter Mooney-Rivlin [1] strain energy function.

$$\sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}}, \text{ where } W = \sum_{k+m=1}^{n} a_{km}(I_1-3)^k (I_2-3)^m + \frac{1}{2}\kappa(I_3-1)^2 \quad (1)$$

I_1, I_2 and I_3 are the strain invariants, which are expressed in terms of the principal stretch ratios, λ_1, λ_2, and λ_3 where κ is the bulk modulus and $I_3=1$ for incompressible vascular material [2]. The hyperelastic constants, a_{km}, determine the material response and can be estimated from experimental load data. Hyperelastic constants for cardiovascular tissue are generally not available in open literature. One exception is Hayashi and Imai [3], who calculated four hyperelastic constants for wall media and atherosclerotic plaques, using uniaxial tensile data obtained for rabbit aorta. The purpose of this study is to estimate material constants using experimental data obtained from uniaxial tests of fresh cardiovascular tissue.

Materials and methods

Uniaxial tension tests were carried out using stainless steel grips on a displacement controlled Instron machine. Rubber coating and emery paper was attached to the contact surfaces of the grips to assist in gripping each specimen and prevent slippage during loading. Fresh descending thoracic aorta was harvested from six 25kg pigs and immediately stored in an antibiotic solution at 4°C prior to testing. Longitudinal strips were cut from the upper and lower thoracic regions and positioned in the grips. Each specimen was stretched to failure at a strain rate of 60% per minute and load/extension data recorded on a PC. The stress-strain data for the lower and upper thoracic was then inputted into the ANSYS finite element package and by performing a least squares fit, hyperelastic constants for two, five and nine parameter models were obtained.

Results

Fig. 1 displays typical experimental data obtained for upper and lower thoracic sections of pig aorta. Samples tested from the lower section of the aorta had a greater stiffness. A two, five and nine parameter strain energy function was fitted to the experimental data for both locations, (Fig 1). The two-parameter strain energy function was unable to model the non-linear behaviour of vascular tissue. The five and nine parameter models were in good agreement with the experimental results, with correlation coefficients of 0.998, and 0.999 for the five and nine parameter models respectively. Table 1. displays constants obtained for a five parameter model.

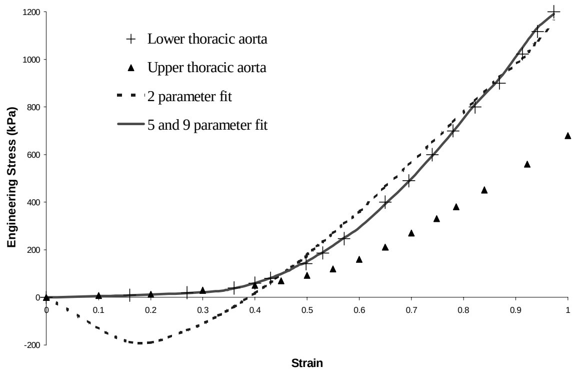

Fig. 1: Uniaxial stress-strain curves for thoracic aorta

Table 1. Constants (kPa) fitted to 5-parameter expression

Constants	Upper thoracic	Lower thoracic
a_{10}	224	-148
a_{01}	-223	204
a_{20}	185	-400
a_{11}	-55	2300
a_{02}	-98	-1800

Discussion and conclusions

The uniaxial results confirmed the non-linear behaviour of thoracic aorta. The results were found to be comparable to results obtained in previous studies, namely those measured by Vaishnav *et al* [4] and Sharma [5]. The two-parameter expression failed both in fitting the experimental data as well as meeting the thermodynamic constraints of positive definitiveness. The five parameter model provides a good fit and meets the constraints for positive definitiveness which require that ($a_{10} + a_{01} > 0$) and ($a_{20} + a_{11} + a_{02} > 0$). A five parameter fit will be used in future finite element models.

References

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