EXPERIMENTAL INVESTIGATIONS AND CONSTITUTIVE MODELLING OF THE LAYER-DEPENDENT BEHAVIOUR OF THE HUMAN OESOPHAGUS

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The human oesophagus is a primarily mechanical organ, and its function depends on both the passive and active properties of its tissue wall. Knowledge of these properties can be used to investigate the effect of pathophysiology on the oesophagus' function; to determine the tissue's material parameters for finite element modelling of the organ for applications such as medical device design and surgical simulations; and to compare the mechanical properties of the tissue engineered oesophagus to that of the native organ. However, as of yet, outside of the authors' own work [1,2], the passive properties of the human oesophagus have not been studied in regard its layer-dependent or viscoelastic behaviour [3,4]. The authors' previous work involved mechanical testing of oesophagi retrieved from embalmed human cadavers, while the experimentation presented here is from oesophagi excised from fresh, recently deceased cadavers. Once excised, the three fresh oesophagi were separated into their two main composite layers: the mucosa-submucosa layer and the muscularis propria layer, as seen in Figure 1.

Figure 1: Separating the human oesophagus into its mucosa-submucosa and muscularis propria layers.

Samples were then cut in both the longitudinal and circumferential directions, and a series of uniaxial tensile tests in the form of increasing stretch-level cyclic tests and multi-step stress-relaxation tests were performed to study the anisotropic, viscoelastic behaviour of the oesophageal layers. The cyclic tests were conducted at $1\%s^{-1}$ and $10\%s^{-1}$ to investigate any strain rate-dependency. The experimental results showed the fresh oesophageal layers to have a greater stiffness in the longitudinal direction compared to the circumferential direction, and that the mucosa-submucosa layer is stiffer than the muscularis propria in both directions. Histological analysis was carried out to establish the fraction and orientation of collagen and elastin within the layers and to discuss how this relates to the layers' macromechanical behaviour. The results of the histological analysis were used to inform a matrix-fibre constitutive model based on the internal variable method [5]. For the model, the identification of the material parameters was carried out in a modularised way: the hyperelastic parameters were first determined by comparing the equilibrium stress-stretch data obtained from the stress-relaxation experiments to the hyperelastic portion of the first Piola-Kirchhoff (PK) stress. Then, the viscous and damage parameters were established by comparing the full first PK stress to the $1\%s^{-1}$ cyclic data. Finally, the model was validated by predicting the response of the tissue at $10\%s^{-1}$ and comparing this to the $10\%s^{-1}$ cyclic experimental data. The model was able to successfully capture the anisotropy, visco-hyperelasticity, stress-softening and permanent set observed in the experimental results.

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