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## Experimental study of the different layers of the human oesophagus

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### 1. Introduction

The human oesophagus is a primarily mechanical organ, and its function depends on both the passive and active properties of its tissue wall. It is composed of a superposition of layers, with a muscular layer and a mucosa-submucosa layer with different functional properties. 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 the development of medical devices and for the understanding of illnesses. These properties can be used in finite element modelling and necessitate the most accuracy to represent the physiological conditions.

The human oesophagus has been little studied in the literature, particularly with regard to the characterisation of each of its layers (Egorov et al. 2003; Vanags et al. 2003). The authors have recently proposed a study on the mechanical behaviour of the different layers of the human oesophagus (the muscular one and the mucosa-submucosa one), the samples having been taken from formaldehyde bodies (Durcan, Hossain, Chagnon, Peric, Bsiesy, et al. 2022; Durcan, Hossain, Chagnon, Peric, Karam, et al. 2022).

It is known that the preservation conditions of tissues influence their mechanical properties. In the study proposed here, the experimental study focused on fresh bodies, i.e. they were not formalized or frozen before tissue harvesting to give the most representative mechanical properties possible.

### 2. Methods

Three oesophagus were used for this study, they were extracted by means of dissection from fresh cadavers at the Laboratoire d'Anatomie Des Alpes Françaises, Grenoble, France. The three oesophagus specimens were from two women and one man, and the three individuals were 89, 96 and 97 years old respectively.

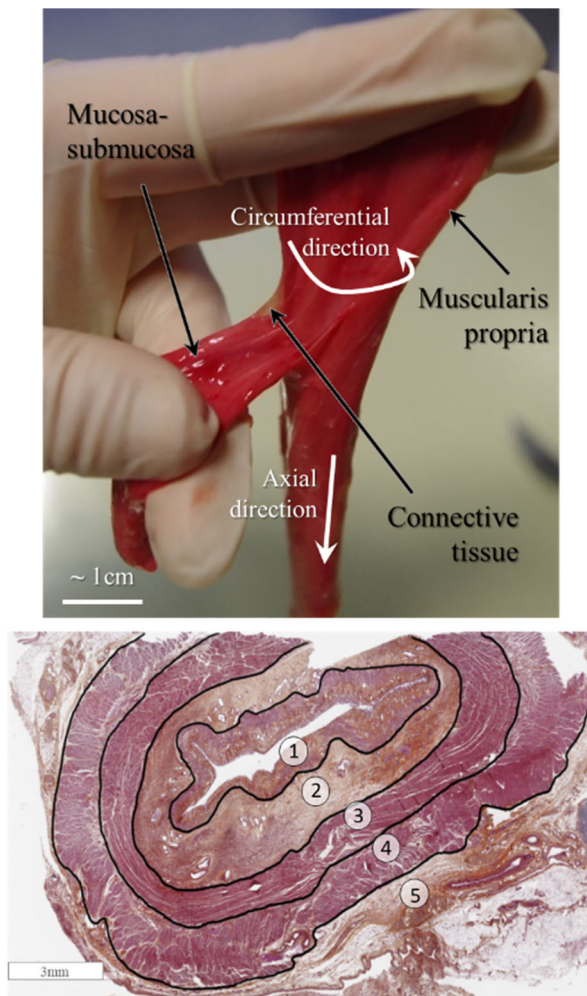
After death and before dissection, the cadavers were stored in a 4 °C refrigerated room. The precise procedure for dissection is as outlined in our previous studies (Durcan, Hossain, Chagnon, Peric, Bsiesy, et al. 2022; Durcan, Hossain, Chagnon, Peric, Karam, et al. 2022). Once removed from the cadavers, the oesophagus were taken immediately for sample preparation for the mechanical tests. The protocol for this study was approved by a local scientific committee at Université Grenoble Alpes, and the study was performed in compliance with French regulations on postmortem testing. Due to constraints regarding the time and number of tests carried out, all tests were conducted within 5 days of explantation, during which, other than when testing, the tissue was stored in physiological saline solution (0.9% NaCl) at 4 °C. The tests were performed on both layers of the oesophagus, the muscular layer and the mucosa layer. The two layers, i.e. the mucosa-submucosa and the muscularis, were separated for testing. An illustration of the division is shown in Figure 1.

The oesophagus shows structural anisotropy due to the orientation of the fibres in the two tissue layers. To measure this anisotropy, mechanical tests are performed in the axial and circumferential directions of the oesophagus. Uniaxial tensile specimens were cut from the different oesophagus available. Different types of mechanical tests (cyclic, interrupted by relaxation, at different speeds) were performed to evaluate the overall mechanical properties of the tissues. The tests were carried out on an MTS machine with a 25 N transducer. As the tests were not too long, they were carried out at room temperature.

### 3. Results and discussion

As an example, a cyclic tensile test with increasing cycles is shown in Figure 2 for both directions of mechanical loading for the muscle layer and the mucosa layer. The non-linear behaviour of the tissues is clearly visible with the phenomenon of stiffening of the tissues with deformation, as well as the stress-softening phenomenon after a first loading and the visco-elastic behaviour with the presentation of large hysteresis loops.

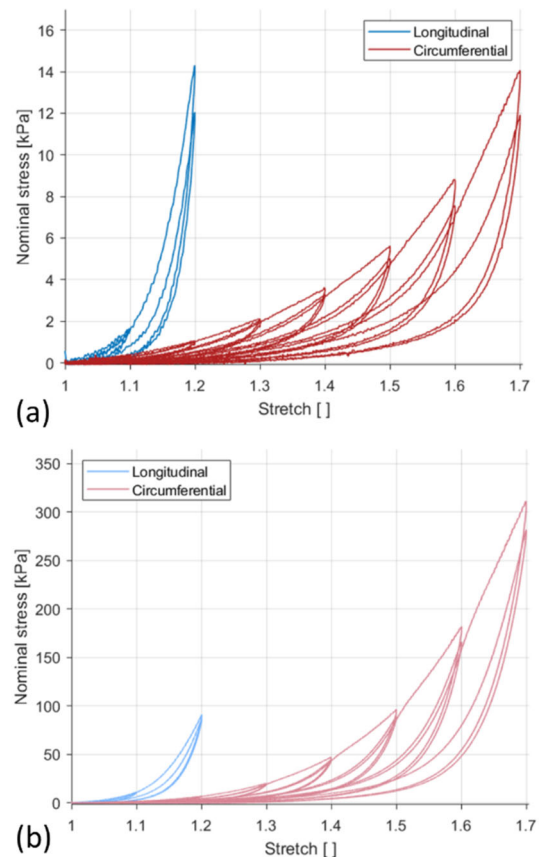
The results of these tests can be compared with similar tests we have performed in a previous study on formulated tissue (Durcan, Hossain, Chagnon, Peric, Bsiesy, et al. 2022; Durcan, Hossain, Chagnon, Peric, Karam, et al. 2022). The shapes of the behaviour curves are similar with the same phenomena visible. However, the levels of the phenomena are different depending on how the fabrics are stored. It



1- Mucosa 2- Submucosa 3- Circular muscular layer  
4- Longitudinal muscular layer 5- Adventitia

**Figure 1.** Cutting of an oesophagus with separation of the two layers.

was found that for almost all of the characteristics considered, the magnitude was statistically higher for the embalmed tissue compared to the fresh tissue. The rupture stretches, however, was statistically higher for the fresh tissue compared to the embalmed tissue. An analysis of the beginning of the tensile curves allows us to identify the initial modulus of the tissues. It was identified that the modulus of the muscle layer was multiplied by 3 or 6 depending on the direction due to embalming. The phenomenon is more marked for the mucosa-submucosa layer where the ratio between the moduli is in the order of 10–12. Even if the phenomena are similar from a trend point of view, it is clear that the numerical differences obtained between fresh and formalised subjects present very important differences that cannot be explained by differences between anatomical subjects alone (the bodies all came from elderly subjects in the two studies), but



**Figure 2.** Mechanical behaviour of the oesophagus tissues: (a) muscular layer, (b) mucosa-submucosa layer.

rather by a very important effect of embalming on the tissue. These results will make it necessary to adapt the constitutive equations as the phenomena present different relative importance.

#### 4. Conclusions

This study presents results on the mechanical properties of both layers of the human oesophagus. The mechanical tests were performed on fresh tissue. The results obtained show qualitatively similar results to the results of tests performed on embalmed biological tissues but numerically very different with a very marked effect of embalming on the mechanics of the tissues.

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**KEYWORDS** Oesophagus; mechanical properties; ex vivo experimental testing; fresh human tissue

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