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Analysis of the biomechanical behaviour of gastrointestinal regions adopting an experimental and computational approach

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A B S T R A C T

An integrated experimental and computational procedure is provided for the evaluation of the biomechanical behaviour that characterizes the pressure–volume response of gastrointestinal regions. The experimental activity pertains to inflation tests performed on specific gastrointestinal conduct segments. Different inflation processes are performed according to progressively increasing volumes. Each inflation test is performed by a rapid liquid in-flaw, up to a prescribed volume, which is held constant for about 300 s to allow the development of relaxation processes. The different tests are interspersed by 600 s of rest to allow the recovery of the specimen mechanical condition. A physio-mechanical model is developed to interpret both the elastic behaviour of the sample, as the pressure–volume trend during the rapid liquid in-flaw, and the time-dependent response, as the pressure drop during the relaxation processes. The minimization of discrepancy between experimental data and model results entails the identification of the parameters that characterize the viscoelastic model adopted for the definition of the behaviour of the gastrointestinal regions. The reliability of the procedure is assessed by the characterization of the response of samples from rat small intestine.

1. Introduction

The aim of the present work pertains to the definition of a procedure for the characterization of the mechanical behaviour of the gastrointestinal structures. The action requires a multi-disciplinary approach, accounting for competences from different areas, as physiology and anatomy, experimental and computational mechanics. The different gastrointestinal regions present common structural characteristics [1]. The digestive tract is a hollow tube composed of a lumen surrounded by a wall made of four principal layers: the mucosa, the submucosa, the muscularis externa and the serosa (Fig. 1). The mucosa is composed by an epithelial lining, a lamina propria of loose connective tissue and a muscularis mucosa [2]. The submucosa is mainly made of dense soft connective tissue, whose main mechanical components are collagen fibres [3–6] that are disposed according to a criss-cross pattern [7–9]. The muscularis externa is composed of an internal and an external muscular layers whose fibres are arranged along circumferential and longitudinal directions, respectively [1,2,8,10]. The serosa is a serous

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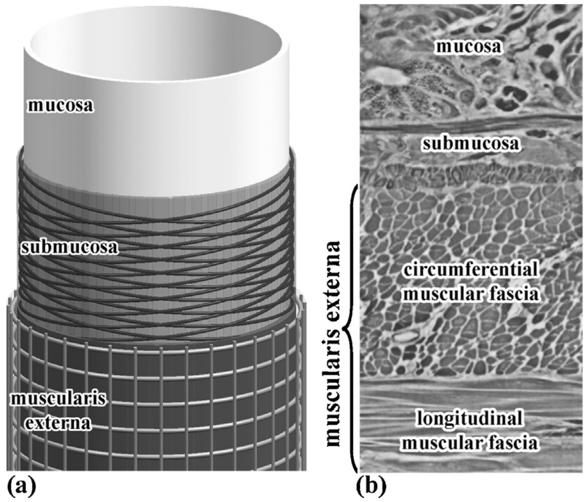

Fig. 1 – Schematic representation of the layered structure of the gastrointestinal tract (a) and corresponding histological section (b).

membrane consisting of a layer of simple squamous epithelium and a small amount of underlying connective tissue [2]. The specific mechanical properties of the different tissues and the mutual interactions phenomena determine the overall mechanical behaviour of the composite biological structure. Such a complex configuration leads to the non-linearity and the time-dependence of the mechanical response, which can be preliminarily investigated by experimental methods.

Mechanical testing of gastrointestinal tissues can be performed on different specimen typologies. Tests can be developed at the structure level, as mechanical tests that are performed on tubular segments from a specific gastrointestinal region, as inflation tests [11,12]. The achieved data are usually adopted to evaluate the overall structural response of the gastrointestinal region [13]. Otherwise, the mechanics of the gastrointestinal tissues can be evaluated by standard mechanical tests, as tensile, compressive and shear tests. Such experimental activities are performed, at the wall level, on specimens obtained from the gastrointestinal wall according to shapes that depend on the specific loading condition to be investigated [10,14–18]. The achieved data provide information about the overall mechanical behaviour of the gastrointestinal wall, as a combination of the different tissue layers. The further approach to gastrointestinal tissues testing entails the analysis at tissue level and pertains to standard mechanical tests performed on the specific tissue layers [19]. Tests are usually performed on specimens from submucosa or muscularis externa, because of their main contribution to the overall gastrointestinal wall mechanics. The latter experimental activities, as mechanical tests at the wall and the tissue level, may entail potential damage of tissues because of the wall and the layers cutting procedure. Furthermore, such experimental tests do not account for the pre-stressed configuration of the gastrointestinal tissues and structures that affects their mechanical response [20].

The challenge pertains to the definition of a coupled experimental and computational procedure that makes it possible to promptly evaluate and quantitatively identify structural parameters that characterize the mechanical response of gastrointestinal regions. The here proposed approach requires the development of inflation and relaxation tests on the investigated region of the gastrointestinal tract. Physiological saline (0.9% NaCl) is progressively inflated within the tubular structure up to the specific volume. Subsequently, the volume is held constant up the end of relaxation phenomena. The experimental data are processed according to a specific physio-mechanical model, which allows the interpretation of the elastic and the time-dependent properties of the gastrointestinal region. The mechanical characterization of samples from the proximal region of rat small intestines allows for the evaluation of the capability of the procedure to interpret the mechanics of gastrointestinal regions.

2. Materials and methods

2.1. *Experimental activity*

Inflation tests are performed on small intestine samples from six male and female Albino Wistar rats (weight: 290 ± 62 g). The rats were previously housed and treated in accordance with the Italian law on animal experimentation (L.116/92) and with the EU directive 2010/63/EU. The experimental protocol was authorized by the local ethical committee for animal experimentation. Every rat is anesthetized using an intraperitoneal dose of 50 mg/kg chloralose, followed by a short abdominal manipulation to ensure a more complete and rapid absorption. After the rat weighing, the abdomen is surgically opened and the first portion of the small intestine, as the duodenum, is harvested. The sample is gently washed with saline to remove any residual chime. The morphological characteristics, as the length, the external diameter and the wall thickness are measured by a digital calliper. More in detail, the experimental sample is placed over a Teflon plate and the conformation is straightened along the longitudinal direction to correctly measure the sample length. A small portion of the sample (about 3 mm in length) is removed and placed with the longitudinal direction perpendicular to the Teflon plate. The external diameter and the thickness are measured by a digital calliper according to different circumferential positions. The results are averaged to identify the mean external diameter and the mean thickness of the sample.

The proximal extremity of the sample is fixed by a surgical seam to a Teflon cannula (internal and external diameter 2 and 3 mm, respectively) coming from a pump (SP 2000 Series Syringe Pump World Precision Instruments, USA), while the other one is hermetically sealed, again by a surgical seam, to prevent any liquid leak. The sample is placed over a Teflon plate and straightened along the longitudinal direction. The distance between the surgical seams is measured by a digital calliper to evaluate the actual sample length. The cannula is also connected to a mechano-electrical transducer (142 pc 01d pressure transducer, Honeywell, USA) that is interfaced to a data storage device (1326 Econo Recorder, Biorad, Italy). The inflation test is performed using physiological saline (0.9% NaCl) and according to a two step procedure. The first step pertains to liquid in-flaw up to a prescribed inflated volume