SB[3]C2017
Summer Biomechanics, Bioengineering and Biotransport Conference
June 21 – 24, Tucson, AZ, USA

STENTING THE PATIENT-SPECIFIC, ACTIVELY CONTRACTING AND BUCKLING ESOPHAGUS: A FINITE ELEMENT ANALYSIS

M. Peirlinck[1], N. Debusschere[1], F. Iannaccone[1], P. Siersema[2], B. Verhegghe[1], P. Segers[1], M. De Beule[1]

[1]Biofluid, Tissue and Solid Mechanics for Medical Applications Lab (IBiTech, bioMMeda), Ghent University, Ghent, Belgium

[2]Department of Gastroenterology and Hepatology, University Medical Center Utrecht, Utrecht, The Netherlands

INTRODUCTION

The esophagus is responsible for the transport of a food or fluid bolus down to the stomach. Any malfunctioning of this multi-layer muscular tube organ easily leads to considerable discomfort and problems. Knowledge of the large deformations and transmural stress and strain distributions in the esophageal wall has been proven crucial in the understanding of esophageal physiology and pathophysiology [1]. A thorough understanding of the biomechanics of the (diseased) esophagus is also important in case of esophageal stenting, an effective treatment strategy for non-resectable tumors or benign obstructions. Indeed, reported migration problems and complications such as perforations, bleeding and fistula formation demonstrate the importance of a full biomechanical understanding of this gastro-intestinal organ and the interaction between stent and esophageal wall. This work set forth to develop a full mechanical framework, incorporating highly detailed numerical esophagi and stent models enabling an enhanced understanding of esophageal physiology on the one hand and symptoms or complications following stent implantation on the other.

METHODS

Esophagus model: The esophageal tissue shows, similar to other biological (e.g. cardiovascular) tissues, highly non-linear, pseudo-elastic and anisotropic behavior. Previous constitutive models focused on characterizing the esophagus's passive behavior, ignoring its active function. For that reason, we propose a new constitutive material model based on Hill's muscle model where a passive and contractile unit in parallel determine the muscle's mechanical behavior. The proposed strain-energy function (SEF) was additively decomposed in a volumetric Ψ^{vol} and deviatoric part Ψ^{dev}, where the deviatoric part constitutes the non-collagenous ground matrix, the collagen fibers and the muscle cells in the esophageal wall. The corresponding constitutive parameters were fitted based on the mechanical response of ovine tissue in biaxial tensile tests [2].

$$\Psi = \Psi^{vol} + \Psi^{dev} = \Psi^{vol} + \Psi^{mat} + \Psi^{fib1} + \Psi^{fib2} + \Psi^{smc}$$

Based on esophageal histology, the human esophagus was modeled as a five-layered system consisting of the mucosa, the collagen-rich submucosa, an interfacial layer, and the inner and outer muscular layer. As the output of numerical models depends heavily on geometry [3], a CT acquisition of a 69-year old male's esophagus suffering from an esophageal carcinoma was segmented in *Mimics* (Materialise; Leuven, Belgium) and meshed into a patient-specific finite element model using our in-house developed finite element pre- and postprocessor *pyFormex* (Ghent University; Gent, Belgium) (see Fig. 1).

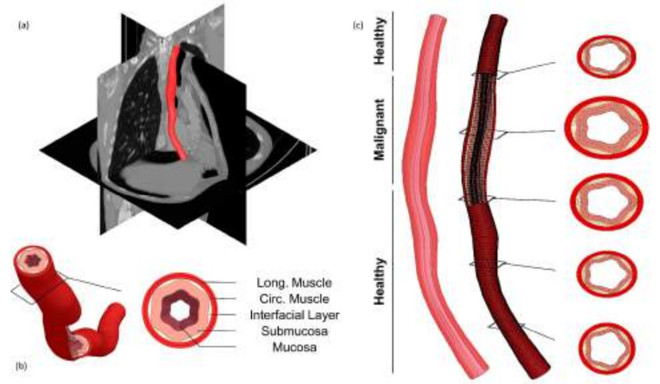

Figure 1: Patient-specific pathologic esophagus geometry – (a) CT segmentation, (b) 3D model with a cross-section depicting the 5 esophageal layers and (c) representation of the 8cm long malignant submucosal proliferation caused by the esophageal carcinoma.

As this CT acquisition was made in an in-vivo stressed organ state inside the human body, the axial residual strain and in vivo pressure-induced stress and strain state were incorporated in the model using a Backward Incremental Method [4].

Virtual Stent Implantation Procedure: A commercially available new biodegradable esophageal stent design (Ella-BD stent) was subjected to in-vitro stent compression and tensile tests to determine the radial strength of the stent and the elasticity of its braided wires. An in-vitro degradation study was performed, in which the full stent and separate stent wires were conserved in a phosphate buffered solution (pH=7.2) at 37°C for 10 weeks. These tests served to validate a numerical stent model, which was geometrically described and meshed in *pyFormex* and virtually bench tested in the finite element analysis (FEA) software *Abaqus* (Simulia, Dassault Systemes; Providence, Rhode Island, USA). A correct numerical implementation of the friction between the thick wires of the polymeric braided stent design was found in the incorporation of connector elements with rotary friction in between the braided stent wires. A tuning of the friction coefficients between the wires proved adequate to successfully capture the stent's temporally varying mechanical behavior [5]. The esophageal stent was virtually implanted in the patient-specific esophagus model. A user subroutine was programmed in which the stent got crimped onto a catheter, bended as if it were endoscopically inserted in the esophagus and implanted by withdrawing the crimping sheath.

RESULTS

The in vivo stress state of the patient-specific esophagus is depicted in Fig. 2 and shows clear stress differences between the (sub)mucosal and the muscular layers presenting stresses ranging between 0.001 kPa and 5.0 kPa and up to 0.001 kPa respectively.

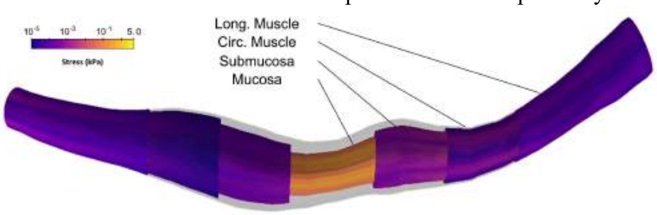

Figure 2: Patient-specific esophageal in vivo von Mises stress state (peeled muscular and (sub)mucosal layer representation)

A subsequent spatiotemporal activation of the muscular layers' myosin heads leads to a relative sliding between the actin and myosin filaments which results in the peristaltic contraction of the patient's esophagus. The mucosa and submucosa both buckle as a response to the compressive forces exerted by the outer muscularis externa, which leads to the full occlusion of the esophageal lumen needed to push the food or fluid bolus down (peak contact pressures on the inner mucosal layers of 3.496 ± 0.7873 kPa at 100% lumen occlusion). Local compression and extension, as well as local stress states can be found in Fig. 3. The stent model was virtually implanted following the procedure described in the stent's Instructions For Use and is depicted in Fig. 4. The combination of the stent model's validated mechanical dilating behavior and the complex (patho)physiological patient-specific model leads to interesting insights on the stent's capability to open up the constricted lumen (see Fig. 4), the contact pressures between stent and esophagus (varying locally from 0.522 to 2.089 kPa) and the stress state the device induces in the esophageal wall.

DISCUSSION

Finite element analysis (FEA) has the potential to expand our knowledge on the esophagus' functioning and disease states [1], however some shortcoming, such as the absence of active constitutive models, three-dimensional geometries and the incorporation of in-vivo stresses were still impeding the use of FEA to study the relationship between stress, remodeling and mechanosensory function. To our knowledge, this computational framework is the first of its kind to overcome these deficiencies. The framework proved capable to simulate the active peristaltic contraction of the esophageal muscle tissue and the buckling of the (sub)mucosal layers in a pathophysiological state. The computed stress and strain states of the esophageal wall allow us to assess the remodeling processes of esophageal tissue in diseased states [1], to get more insight in the physiological process of food swallowing and to perform virtual device (e.g. stent) implantation or surgery, as shown during the virtual stent implantation.

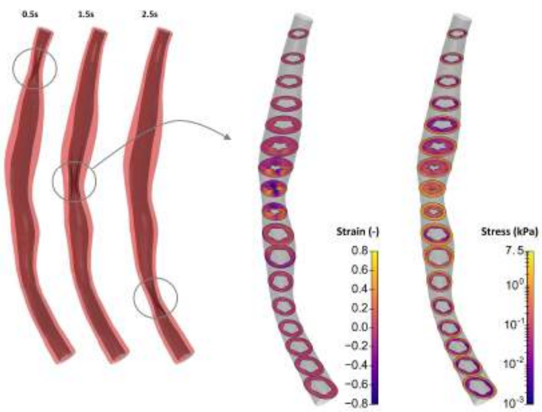

Figure 3: Peristaltic contraction

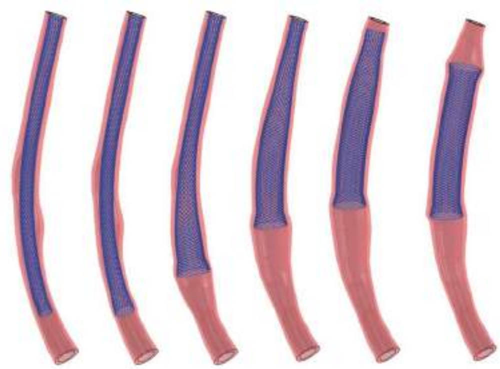

Figure 4: Virtual Stent Implantation procedure

ACKNOWLEDGEMENTS

This work was supported by a Strategic Research grant from the Flemish government's Department for Innovation and Entrepreneurship (VLAIO).

REFERENCES

1. Gregersen, H., *Biomechanics of the gastrointestinal tract: new perspectives in motility research and diagnostics*. 2003: Springer Science & Business Media.
2. Sommer, G., et al., *Multiaxial mechanical response and constitutive modeling of esophageal tissues: Impact on esophageal tissue engineering.* Acta Biomater, 2013. **9**(12): p. 9379-91.
3. Liao, D., et al., *Two-layered quasi-3D finite element model of the oesophagus.* Med Eng Phys, 2004. **26**(7): p. 535-43.
4. De Putter, S., et al., *Patient-specific initial wall stress in abdominal aortic aneurysms with a backward incremental method.* Journal of biomechanics, 2007. **40**(5): p. 1081-1090.
5. Peirlinck, M., et al. *An in silico biomechanical analysis of the stent-esophagus interaction.* in *2015 Summer Biomechanics, Bioengineering and Biotransport Conference*.