Assessing the Role of Intraluminal Thrombus in Abdominal Aortic Aneurysm Biomechanics through Patient-Specific Bayesian Material Calibration

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Introduction

This study proposes a patient-specific material calibration framework to accurately characterize both aortic wall and intraluminal thrombus (ILT) properties. By integrating imaging and biomechanics, it enables reliable assessment of ILT's mechanical role—often neglected in literature—thus avoiding stress overestimation and improving rupture risk evaluation in abdominal aortic aneurysm (AAA) models.

Materials and Methods

3D cine-magnetic resonance imaging (MRI) acquisitions from four patients with AAAs were provided by the Vall d'Hebron Research Institute (Barcelona, Spain). The aortic wall and the ILT were segmented to reconstruct patient-specific geometries across the cardiac cycle, focusing on end-diastolic and peak systolic phases. Finite element (FE) models were built using quadratic tetrahedral meshes (Fig. 1) in ANSA pre-processor. The aortic wall was modeled with an anisotropic Gasser-Holzapfel formulation [1], whose strain energy function is governed by five parameters: C_{10} [kPa], k_1 [kPa], k_2 [-], γ [°], κ [-], and the ILT as an isotropic, nearly incompressible neo-Hookean material [2], described by a single material parameter: c [kPa]. The parameter ranges for both models were derived from experimental data [2,3]. For each patient, 200 FE simulations of diastolic (80 mmHg) and systolic pressure (120 mmHg) on a recovered zero-pressure configuration [4] were performed in ABAQUS FEA, by sampling the material parameters' space. A Gaussian process surrogate model was trained to approximate simulation outcomes, and Bayesian optimization was used to identify the parameter set that minimized the root mean squared error (RMSE) between simulated and MRI-derived wall displacements between diastolic and systolic phases. Additional simulations excluding the ILT were conducted, employing the previously optimized material parameters.

Results

The Bayesian-calibrated material parameters for the four patients are reported in Tab. 1. The optimized material models were applied to the patient-specific FEMs, which achieved good agreement with MRI-based displacement data (RMSE < 10%) in all four patients (Patient 1 in Fig.2a,b for reference). Including the ILT in the models consistently led to lower peak wall stresses (PWS) and deformations, particularly in regions covered by thrombus. Stress concentration zones shifted toward uncovered regions or the aneurysm necks when ILT was present (Fig.2c,d). Comparisons between models with and without ILT showed significant differences in predicted wall stress distributions and PWSs, with up to 90% overestimation of wall stress when ILT was excluded. Notably, sensitivity analyses showed that the presence of ILT has a much stronger mechanical impact than the specific choice of ILT material parameters [5]. While varying ILT material properties produced minor changes in stress and strain patterns, omitting the ILT entirely led to pronounced overestimations, underlining the importance of its inclusion in biomechanical models.

Discussion

This framework enables the definition of AAA material properties and the integration of ILT in a patient-specific, data-driven manner. The results support the hypothesis that the ILT serves a mechanically protective function by reducing wall stress and redistributing mechanical load across the aneurysm. This aligns with previous experimental and computational studies that describe the ILT as a stress-shielding layer [6]. Moreover, the relatively low sensitivity of wall stress to variations in ILT material properties—compared to the pronounced influence of ILT geometry and presence—suggests that simplified constitutive models may suffice, provided that the ILT is properly represented in the geometry.

Conclusions

This study assesses the value of a Bayesian, imaging-based approach for calibrating patient-specific material properties in AAA modeling. The findings underscore the crucial role of ILT presence in accurately capturing PWSs, with its geometric inclusion proving significantly influential. These insights support the integration of ILT in computational workflows and reinforce the potential of personalized, non-invasive biomechanical analyses for improved rupture risk prediction.

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Tab. 1. optimized material parameters for the four patients.

C_{10} [kPa]	*k1* [kPa]	*k2* [-]	γ [°]	κ [-]	*c* [kPa]
118	64.0	53.1	20.8	0.27	17.0
98.0	848	416	30.5	0.02	31.3
120	704	403	41.1	0.05	39.6
94.0	57.0	426	7.95	0.17	33.3

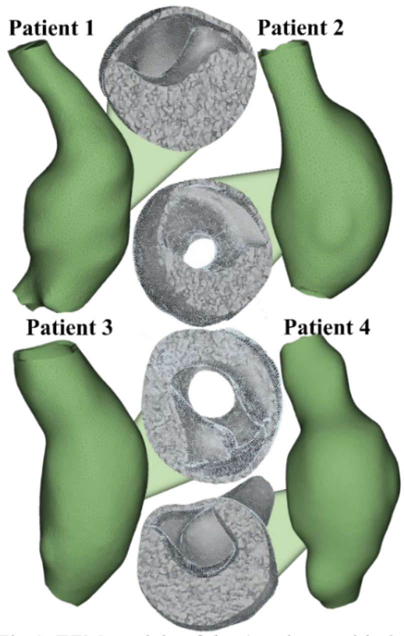

Fig.1. FEM models of the 4 patients with the respective cross sections showing the ILTs.

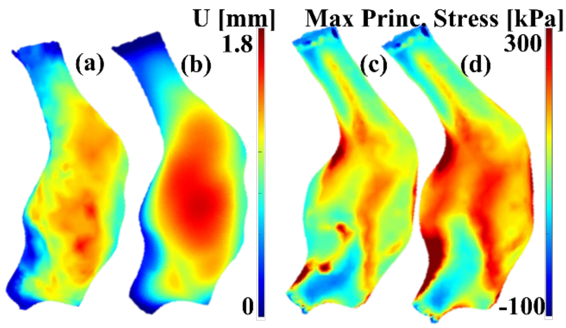

Fig.2. Segmented (a) and computationally modeled (b) displacements with optimized material parameters of Patient 1. Max principal stress distributions for the FEM including (c) and omitting (d) the ILT.