Bayesian Calibration of Aneurysm Wall and Thrombus Material Properties in Patient-Specific Aortic Models

Gaia Caruso [1], Andrea Guala [3,4], Lydia Dux-Santoy [3], Sergi Bellmunt[5], Marvin García-Reyes[5], Miguel Ángel Martínez [1,2], Estefanía Peña Baquedano [1,2]

[1] Aragón Institute for Engineering Research (I3A), University of Zaragoza, Spain
[2] CIBER-BBN, Centro de Investigación en Red en Bioingeniería, Spain
[3] Vall d'Hebron Institut de Recerca, Barcelona, Spain
[4] Biomedical Research Networking Center on Cardiovascular Diseases, CIBER-CV, Instituto de Salud Carlos III, Madrid, Spain
[5] Department of Vascular Surgery, Hospital Universitari Vall d'Hebron, Barcelona, Spain

Abstract

This work introduces an inverse modeling approach tailored to individual patients for characterizing the biomechanical behavior of Abdominal Aortic Aneurysms. The method estimates the nonlinear, fibers' direction-dependent properties of the aneurysmal wall and of the intraluminal thrombus tissues. Patient-specific geometries and displacement fields, derived from magnetic resonance imaging scans spanning end-diastolic to late-systolic phases, serve as inputs for calibrating hyperelastic material models. A Bayesian optimization strategy is employed to reduce the mismatch between simulated displacements from finite element analysis and those obtained from image registration, yielding physiologically relevant mechanical models. This personalized framework provides a reliable means of identifying vascular tissue properties and represents a robust tool for enhancing aneurysm rupture risk prediction. The findings underscore the value of combining medical imaging, computational biomechanics, and probabilistic optimization to advance individualized biomechanical characterization of aneurysms.

1. Introduction

Abdominal aortic aneurysm (AAA) is a life-threatening vascular condition marked by a localized dilation of the abdominal aorta, often accompanied by a progressive weakening of the aortic wall and formation of an intraluminal thrombus (ILT). AAA rupture has a high mortality rate, yet current clinical decisions are still largely based on simple geometrical indicators, such as maximum diameter. However, diameter alone is an inadequate predictor of rupture risk, as it overlooks the complex interplay of factors affecting the aneurysm biomechanics [1–3]. Patient-specific finite element (FE) modeling offers a promising alternative for rupture risk assessment by simulating stress and strain distributions within the aneurysmal wall under physiological loading. This approach depends critically on accurate representation of tissue mechanical properties, which are nonlinear, heterogeneous, and patient-specific. Nonetheless, in vivo mechanical characterization remains elusive. The objective of this study is to develop a patient-specific inverse modeling framework for AAA that enables the estimation of nonlinear material properties of the aneurysmal aortic wall and the of ILT. The method is applied to a cohort of four patients with magnetic resonance imaging (MRI)-derived geometries and deformation data. The primary focus of the approach is the optimization of material parameters based on real, patient-specific deformation measurements, ensuring that the resulting biomechanical model reliably captures the actual mechanical behavior of the aneurysm. The model enables the identification of regions of elevated wall stress, which are key indicators for assessing rupture risk [4]. In parallel, it allows for the investigation of the mechanical influence of the ILT on aneurysm behavior.

2. Materials and Methods

2.1. Image Processing and Registration

Three-dimensional cine-MRI datasets were obtained from four patients diagnosed with AAAs, provided by the Vall d'Hebron Research Institute (Barcelona, Spain). The aortic wall and ILT were segmented to reconstruct patient-specific geometries throughout the cardiac cycle. Subsequently, the inner wall displacements between the end-diastolic and peak-systolic phases were registered using a non-rigid Iterative Closest Point (ICP) algorithm [5]. The study was approved by the local ethics committee (C.I. PI25/327) and written informed consent was obtained from each patient.

2.2. Finite Element Modeling and Simulation

FE models were constructed using quadratic tetrahedral meshes generated in the ANSA pre-processing environment. A uniform wall thickness (2 mm) was assigned to the segmented inner surface of the AAA, and the ILT volume was built adjacent to this surface. To ensure mechanical continuity, ILT elements in direct contact with the wall were shared with the corresponding wall elements, as shown in fig. 1. The aortic wall was modeled using the anisotropic Gasser-Holzapfel-Ogden constitutive formulation [6], characterized by five material parameters: C_{10} [kPa], k_1 [kPa], k_2 [-], γ [°], and κ [-]. The ILT was modeled as an isotropic, nearly incompressible neo-Hookean material [7], defined by a single stiffness parameter, c [kPa]. Parameter bounds for both materials were informed by previously reported experimental data [7, 8]. For each patient, 200 FE simulations were conducted in ABAQUS, by applying physiological loading conditions to the recovered zero-pressure configuration [9], ranging from average diastolic (80 mmHg) to systolic (120 mmHg) pressures. The material parameter space was systematically explored by sampling within the predefined bounds. To reduce computational cost, a surrogate model was built using Gaussian Process Regression (GPR). The model was trained using the simulation-derived displacements, where the inputs were the 6-dimensional material parameter vectors. The output was the root mean squared error (RMSE), derived from the discrepancy between the MRI-derived displacement field and the computationally obtained ones.

2.3. Bayesian Optimization and Biomechanical Analysis

An Automatic Relevance Determination Squared Exponential kernel was used with standardization and a constant basis function, allowing the GPR model to capture the anisotropic sensitivity of each parameter to the output error. The optimal parameter set was searched via Bayesian optimization, using the trained GPR as a probabilistic surrogate for the objective function. The optimization aimed to minimize RMSE. The acquisition function used was the Expected Improvement Plus (EI+), which balances exploration and exploitation in the parameter space [10]. Once the optimal material parameters were identified for each patient, they were employed in further FE simulations to compute biomechanical quantities of interest. In particular, the analysis focused on the inner surface of the aortic wall to evaluate the spatial distribution of mechanical indicators, such as peak wall stresses (PWSs) and logarithmic strains (PWLEs). These fields were used to identify localized regions of elevated mechanical loading, which are known to be clinically relevant for AAA rupture risk [11–13]. The influence of the ILT on stress shielding and stress redistribution was also examined by comparing FE simulations with and without the ILT component.

3. Results

For each patient, the optimized material parameters were assigned to the FE models. The resulting displacement fields were quantitatively compared to those obtained through image registration. The axial and circumferential stretch versus Cauchy stress curves corresponding to the optimal AAA material parameters for a representative patient (P2) are shown in fig. 2, together with a representative comparison of simulated and MRI-derived displacement fields. These results demonstrate that the model reliably reproduces both the deformation patterns and magnitude ranges observed in vivo. Furthermore, spatial distributions of maximum principal Cauchy stress and logarithmic strain were evaluated on the inner surface of the aortic wall using the calibrated material models. These maps revealed that PWSs and PWLEs consistently localized in regions of high curvature, particularly at the proximal and distal necks of the aneurysm (fig. 3 a, b). In contrast, the region underlying the ILT exhibited markedly lower stresses, supporting the hypothesis that the thrombus acts as a mechanical buffer. Additional simulations performed without the ILT showed a substantial increase in PWSs and PWLEs values, especially in the central bulging region of the AAA, where the ILT was originally located (fig. 3 c, d).

4. Discussion

This study presents a patient-specific inverse modeling framework for AAAs, designed to estimate individualized nonlinear properties of the AAA and the ILT. A central component of the framework is the calibration of the mechanical model against patient-specific imaging data. Simulated wall displacements between diastolic and systolic phases showed strong agreement with displacements extracted from MRI, confirming the physiological fidelity of the model. Inverse calibration of material parameters was performed using Bayesian optimization based on Gaussian Process Regression (GPR), which enabled efficient exploration of the high-dimensional parameter space with a reduced number of simulations. The optimization targeted the minimization of the error between FE-simulated and MRI-derived displacement fields. The resulting framework offers a robust, data-driven approach for patient-specific biomechanical modeling, contributing to more ac-

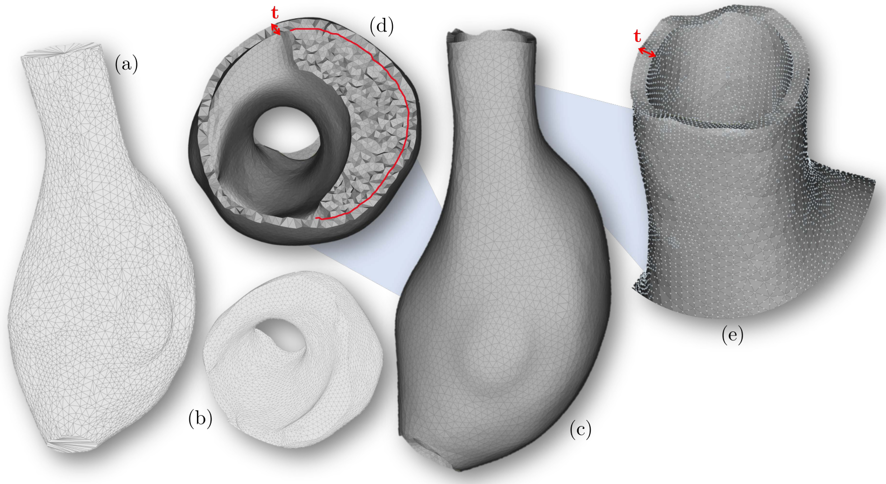

Figure 1. Representative patient's AAA lumen (a) and ILT (b) segmented and meshed surfaces and ANSA pre-processing 3D FE whole model (c), with a closer look to the cross section including the ILT (d), where the contact surface between the aortic wall and the ILT is highlighted, and to the proximal end (e), where the thickness (t) of the aortic wall is shown and the nodes belonging to the quadratic elements are highlighted.

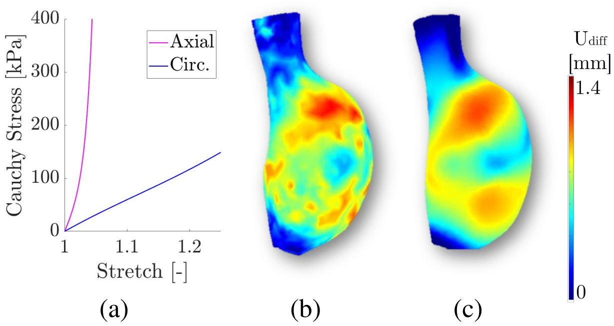

Figure 2. Axial and circunferential stretch [-] - Cauchy stress [kPa] curves of the optimal AAA material (a) and displacements' difference between systolic and diastolic phase (U_{diff} [mm]) distribution maps on the inner AAA wall of P2 for FE model (b) and MRI-derived (c).

curate rupture risk assessment through realistic geometry, boundary conditions, and tissue heterogeneity. The spatial distribution of maximum principal stress and logarithmic strain across the inner aortic wall revealed PWSs associated with high curvature regions, while lower stresses were related to ILT deposition [14]. Maximum wall stress values fell within clinically expected ranges [4]. Comparative simulations with and without the ILT clearly illustrated its biomechanical impact: the ILT not only attenuated peak stress magnitudes but also altered their spatial distribution. These findings support the hypothesis that the ILT functions as a mechanical buffer, reducing localized wall loading while redistributing stresses across the aneurysmal region [4]. Nonetheless, the framework is subject to some limitations: the mechanical model assumes uniform wall thickness and homogeneous ILT properties. While these assumptions were addressed through sensitivity analyses and Bayesian calibration, further refinement may be achieved by integrating diffusion tensor imaging (DTI) to capture spatially varying mechanical characteristics. However, by incorporating inverse-calibrated material properties, patient-specific geometries, and the mechanical contribution of the ILT, this study advances the development of personalized AAA rupture risk models grounded in biomechanics and data. The proposed framework lays the foundation for future integration into clinical imaging workflows, enabling non-invasive, simulation-based risk stratification in AAA management.

5. Conclusion

This work presents a patient-specific inverse modeling framework that integrates imaging and biomechanics to estimate aortic wall and ILT material properties in AAAs. The proposed methodology accurately reproduces physiological deformation patterns and highlights the biomechanical role of ILT in modulating stress distribution. By enabling image-based calibration of material models, the framework supports the development of personalized rupture risk assessment tools. Future efforts will focus on accelerating computation and integrating additional imaging

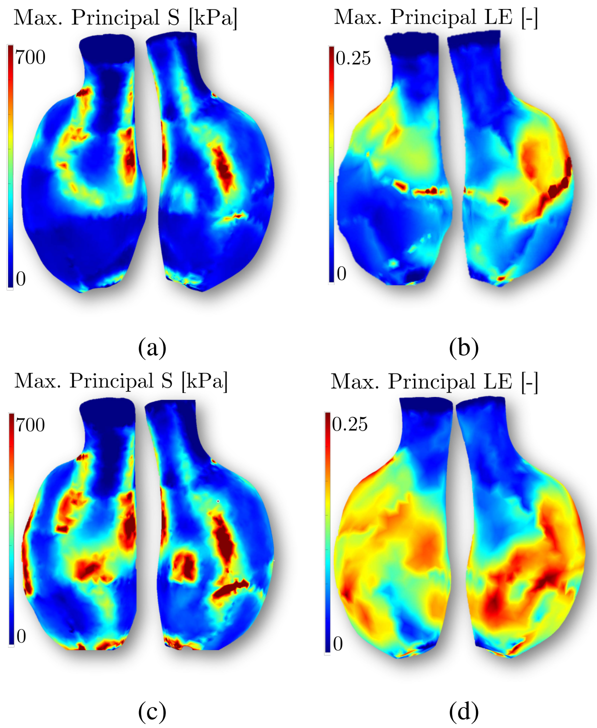

Figure 3. Maximum principal stress [kPa] and Maximum principal logarithmic strain [-] maps in the inner AAA wall of P2 (two different views each), obtained with optimized material properties, including ILT (a,b) and omitting ILT (c,d).

modalities for enhanced clinical applicability.

Acknowledgments

This work was supported by project PID2022-140219OB-I00 funded by MICIU/AEI/10.13039/5011000 11033, the “European Union NextGenerationEU/PRTR,” and the Government of Aragón (project T24-20R). Additional support was provided by FSE+PRE2023 UZ-18 (MICIU/AEI/10.13039/501100011033) and “ESF Investing in your future” / “ESF+” and by the project ”Instituto Carlos III PI19/01480”. CIBER Actions are financed by the Instituto de Salud Carlos III with co-funding from the European Regional Development Fund.

References

[1] Holzapfel GA, Tong J, Regitnig P. Recent advances in the biomechanics of abdominal aortic aneurysms. Strasbourg, France: Europrot, 2002.

[2] Boniforti MA, Cesaroni MC, Magini R, Pasqui E, de Donato G. Image-based numerical investigation in an impending abdominal aneurysm rupture. Fluids 2022;7:269.

[3] Maier A, Gee MW, Reeps C, Pongratz J, Eckstein HH, Wall WA. A comparison of diameter, wall stress, and rupture potential index for abdominal aortic aneurysm rupture risk prediction. Ann Biomed Eng 2010;38(10):3124–3134.

[4] Wang X, Ghayesh MH, Li J, Kotousov A, Zander AC, Dawson JA, Psaltis PJ. Impact of geometric attributes on abdominal aortic aneurysm rupture risk: an in vivo fsi-based study. Int J Numer Methods Biomed Eng 2024;.

[5] Audenaert EA, Van Houcke J, Almeida DF, Paelinck L, Peiffer M, Steenackers G, Vandermeulen D. Cascaded statistical shape model based segmentation of the full lower limb in ct. Comput Methods Biomech Biomed Eng 2019; 22(6):644–657.

[6] Gasser TC, Ogden RW, Holzapfel GA. Hyperelastic modelling of arterial layers with distributed collagen fibre orientations. J R Soc Interface 2006;3(6):15–35.

[7] Vande Geest JP, Sacks MS, Vorp DA. A planar biaxial constitutive relation for the luminal layer of intra-luminal thrombus in abdominal aortic aneurysms. J Biomech 2006; 39(13):2347–2354.

[8] Niestrawska JA, Viertler C, Regitnig P, Cohnert TU, Sommer G, Holzapfel GA. Microstructure and mechanics of healthy and aneurysmatic abdominal aortas: experimental analysis and modelling. J R Soc Interface 2016;13.

[9] Raghavan ML, Ma B, Fillinger MF. Non-invasive determination of zero-pressure geometry of arterial aneurysms. Ann Biomed Eng 2006;34(9):1414–1419.

[10] Shahriari B, Swersky K, Wang Z, Adams RP, de Freitas N. Taking the human out of the loop: a review of bayesian optimization. Proc IEEE 2016;104(1):148–175.

[11] Gasser TC, Görgülü G, Folkesson M, Swedenborg J. Failure properties of intraluminal thrombus in abdominal aortic aneurysm under static and pulsating mechanical loads. J Vasc Surg 2008;48(1):179–188.

[12] Chocke E, Cockerill G, Wilson WRW, Sayed S, Dawson J, Loftus I, Thompson MM. A review of biological factors implicated in abdominal aortic aneurysm rupture. Eur J Vasc Endovasc Surg 2005;30:277–284.

[13] Humphrey JD, Holzapfel GA. Mechanics, mechanobiology, and modeling of human abdominal aorta and aneurysms. J Biomech 2012;45:805–814.

[14] Caruso G, Martínez MA, Peña E. Impact of mechanical properties of aneurysms and intraluminal thrombus on abdominal aortic aneurysm outcomes. Meccanica 2025; 60:475–495.

Address for correspondence:

Gaia Caruso
Mechanical Engineering Dept. School of Engineering and Architecture. Bioengineering Division. Aragón Institute of Engineering Research (I3A). Agustín de Betancourt Building. University of Zaragoza María de Luna, s/n. 50018 Zaragoza (Spain)
gcaruso@unizar.es