The American Journal of Medical Sciences and Pharmaceutical Research
ISSN 2689-1026 | Open Access

TYPE Original Research
PAGE NO. 1-6

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Understanding abdominal aortic biomechanics: in vivo stress and load-bearing prediction

Prof. Alessandra Rossi

Department of Vascular Surgery and Biomechanics, University of Bologna, Italy

Dr. Kenji Nakamura

Department of Cardiovascular Surgery, Kyoto University, Japan

OPEN ACCESS

SUBMITTED 02 July 2025
ACCEPTED 03 August 2025
PUBLISHED 01 September 2025
VOLUME Vol.07 Issue09 2025

CITATION

Abstract: The abdominal aorta plays a critical role in blood circulation, and understanding its mechanical behavior is essential for the prevention and treatment of vascular diseases, such as aneurysms and atherosclerosis. This study aims to evaluate the stress state and load-bearing fraction in the abdominal aorta using an in vivo parameter identification method. This method combines medical imaging data with mechanical modeling to accurately estimate the mechanical properties of the aortic wall. The study employs finite element analysis (FEA) to model the abdominal aorta's stress distribution and load-bearing capacity under physiological conditions. Results indicate that this method provides a reliable estimate of the aorta's mechanical behavior and offers potential clinical applications in the personalized assessment of vascular health.

Keywords: Abdominal aorta, Stress state, Load-bearing fraction, In vivo parameter identification, Finite element analysis, Aortic aneurysm, Vascular biomechanics, Medical imaging, Aortic wall, Mechanical properties.

Introduction: The abdominal aorta is a central blood vessel in the body, transporting oxygen-rich blood from the heart to the lower parts of the bSody. The aorta's mechanical integrity is paramount for normal circulation, and any structural deformation or weakening can result in significant vascular diseases, such as abdominal aortic aneurysm (AAA) or atherosclerosis. Understanding the biomechanical behavior of the abdominal aorta, especially its stress distribution and ability to bear load under normal physiological conditions, is critical in predicting and managing these diseases.

Traditional methods for assessing the aortic wall's mechanical properties have largely been limited to ex vivo experiments or in vitro testing, which often fail to replicate the complex environment of the vessel within the living organism. Advances in in vivo imaging technologies, such as magnetic resonance imaging (MRI) and computed tomography (CT), have provided an opportunity to study the aorta under physiological conditions. This has led to the development of more sophisticated modeling techniques to predict the mechanical response of the aortic wall.

An emerging technique involves the use of parameter identification methods, which combine experimental data from medical imaging with computational models. These methods are used to estimate key mechanical properties of the aorta, such as elasticity, viscoelasticity, and stress distributions, under in vivo conditions. By integrating these methods into a computational framework, researchers can gain more accurate insights into the aortic wall's stress state and its ability to bear mechanical loads.

This article aims to evaluate the stress state and load-bearing fraction of the abdominal aorta as predicted by an in vivo parameter identification method. The study uses a finite element model (FEM), coupled with imaging data, to simulate the mechanical environment of the aorta under typical hemodynamic conditions. The goal is to assess the utility of this method in clinical applications, particularly for personalized diagnostics of vascular diseases.

The abdominal aorta is the largest and most important blood vessel in the body, responsible for delivering oxygenated blood from the heart to the lower parts of the body. Its mechanical integrity is vital for normal circulatory function, as it endures continuous blood flow under varying pressure and shear forces. As such, any changes in its structure or function can lead to significant clinical conditions such as abdominal aortic aneurysms (AAAs), atherosclerosis, or dissections. These conditions can be life-threatening and often go undiagnosed until advanced stages, emphasizing the need for early detection and monitoring of the aorta's mechanical behavior.

Abdominal aortic aneurysms (AAAs), for example, result from the abnormal dilation of the aortic wall, which increases the risk of rupture and can lead to catastrophic bleeding if not properly managed. Similarly, the development of atherosclerosis within the aorta causes the vessel to harden and lose its elasticity, making it more vulnerable to injury. The stress state within the aortic wall and its ability to bear mechanical loads are critical factors in the development and progression of these diseases. Excessive stress concentrations in specific regions of the aorta can lead to wall weakening and potentially to aneurysmal rupture.

Traditionally, methods to assess the aortic wall's mechanical properties and stress distribution have relied on invasive procedures or ex vivo experiments that do not account for the complex, real-time, in vivo environment of the aorta. However, recent advancements in medical imaging technologies, such as magnetic resonance imaging (MRI) and computed tomography (CT), have allowed for non-invasive and detailed analysis of aortic structure and function. These imaging techniques can generate high-resolution, three-dimensional (3D) models of the aorta, providing valuable data on its geometry and material properties.

Despite the advancements in imaging technology, quantitative assessment of the aorta's mechanical behavior remains a challenge. Finite element modeling (FEM) has emerged as a powerful computational tool that allows for the simulation of complex mechanical interactions within biological tissues. When combined with in vivo parameter identification methods, it offers a promising approach for accurately modeling the aorta's stress state and load-bearing capabilities based on patient-specific data.

In vivo parameter identification is a process in which computational models are adjusted to match real-world data, such as blood pressure and flow dynamics, obtained from imaging technologies. This method enables the estimation of critical mechanical parameters of the aortic wall, such as elasticity, stress distribution, and material stiffness, under normal physiological conditions. The combination of patient-specific models with biomechanical analysis provides more accurate assessments of the aorta's behavior compared to traditional methods. Importantly, these analyses can be performed without the need for invasive interventions, making it an ideal approach for early detection and personalized treatment of vascular conditions.

In particular, the stress state and load-bearing fraction of the aorta are two key indicators of its mechanical health. The stress state refers to the internal distribution of forces within the aortic wall, which influences the vessel's ability to withstand blood pressure and resist mechanical injury. The load-bearing fraction quantifies the portion of the aorta that contributes to carrying the total load exerted by blood flow and pressure. Understanding these factors is essential for identifying regions of the aorta that may be at increased risk of failure due to structural weaknesses or disease progression.

This study seeks to evaluate the stress state and load-bearing fraction of the abdominal aorta using an in vivo parameter identification method combined with finite element analysis (FEA). By integrating medical imaging data with computational modeling, we aim to assess the mechanical properties of the aorta under physiological conditions and explore the potential of this method for clinical applications. Specifically, we intend to determine whether this approach can provide reliable estimates of aortic mechanical behavior, which could be used for early diagnosis, personalized risk assessment, and tailored treatment of vascular diseases such as abdominal aortic aneurysms (AAAs) and atherosclerosis.

The main objective of this study is to assess whether in vivo parameter identification using imaging data and computational models can accurately predict the stress distribution and load-bearing fraction in the abdominal aorta. By doing so, we hope to provide insights into the potential for this method to enhance the clinical management of aortic diseases, ultimately improving patient outcomes through more precise and individualized treatment strategies.

METHODS

Study Design

This study utilizes computational biomechanics to evaluate the mechanical properties of the abdominal aorta in vivo. The methodology combines imaging data from MRI scans with a finite element model (FEM) to simulate the stress state and load-bearing fraction of the aorta. The primary objective is to determine whether this approach provides reliable and accurate estimates of the mechanical behavior of the abdominal aorta, as compared to traditional methods.

In Vivo Parameter Identification Method

The in vivo parameter identification method involves the following steps:

1. Medical Imaging: High-resolution MRI scans of the abdominal aorta are used to capture detailed images of the aortic wall’s geometry and structure. These images provide a three-dimensional (3D) representation of the aorta, which is used as input for the FEM.

2. Finite Element Model (FEM): The 3D geometry of the aorta obtained from MRI scans is imported into a FEM software. The aortic wall is modeled as an anisotropic, hyperelastic material, reflecting its complex mechanical properties. The model includes parameters such as wall thickness, material stiffness, and mechanical properties that are adjusted based on the in vivo data.

3. Parameter Identification: A nonlinear optimization technique is applied to the FEM to identify the mechanical properties of the aorta that best match the observed blood pressure and flow dynamics within the aorta, as captured through imaging. This approach is based on matching computational results with real-time physiological data, such as pressure distributions within the aorta, allowing for accurate parameter identification.

4. Stress and Load-Bearing Fraction Calculation: Once the optimal parameters are identified, the FEM simulation is used to calculate the stress state and load-bearing fraction of the aorta. The stress state refers to the distribution of forces within the aortic wall, while the load-bearing fraction quantifies the portion of the aorta that contributes to carrying the overall load, both of which are crucial for understanding the aorta’s mechanical function.

Data Collection

- Participants: The study uses imaging data from a cohort of healthy volunteers and patients diagnosed with mild to moderate aortic conditions. For control purposes, healthy participants' data were used to establish baseline values for comparison.
- Imaging Protocols: Participants underwent MRI of the abdomen with a focus on obtaining high-resolution images of the abdominal aorta. MRI scans were performed at rest to capture baseline data of the aorta’s geometry and structure. Blood pressure measurements were also taken to inform the FEM simulations.

Simulation and Analysis

The collected imaging data and physiological measurements were input into the FEM to simulate the stress distribution and load-bearing fraction across different segments of the abdominal aorta. The simulation accounts for both static and dynamic blood flow conditions, replicating the natural hemodynamic forces exerted on the aorta during the cardiac cycle.

Stress distribution was calculated at multiple points along the aorta to identify areas of high and low stress. These data were used to assess potential areas of vulnerability, which could be indicative of risk for disease progression. The load-bearing fraction was calculated by determining the proportion of the aortic wall that contributed most significantly to the resistance against blood flow and pressure.

RESULTS

Stress State of the Abdominal Aorta

The simulation results revealed significant variations in stress distribution across different segments of the abdominal aorta. The proximal portions of the aorta (near the diaphragm) exhibited the highest stress, likely due to the higher blood pressure and flow velocity at these locations. In contrast, the distal segments of the aorta (closer to the iliac arteries) showed lower stress levels, consistent with the gradual decrease in blood pressure downstream.

These findings were consistent across both the healthy and patient cohorts, although individuals with pre-existing vascular conditions showed increased localized stress in specific regions, particularly in the presence of atherosclerotic plaques or aneurysmal dilation. The stress concentration in these regions may suggest areas at increased risk of rupture or other complications.

Load-Bearing Fraction

The load-bearing fraction was found to be highest in the thoracoabdominal junction, where the aorta must bear the greatest hemodynamic load. The FEM simulations revealed that a significant proportion of the total load was carried by the outer layers of the aortic wall, particularly in regions that were under the highest stress.

In patients with abdominal aortic aneurysms (AAAs), the load-bearing fraction was altered, with a reduction in the aortic wall's load-bearing capacity at the site of dilation. This reduction in the load-bearing fraction could be an early indicator of impending aortic rupture, providing valuable clinical insights for monitoring at-risk patients.

DISCUSSION

The findings from this study highlight the utility of an in vivo parameter identification method for accurately predicting the stress state and load-bearing fraction in the abdominal aorta. By combining medical imaging with computational models, this approach provides a detailed and non-invasive way to assess the mechanical properties of the aorta under real-life conditions.

One of the key advantages of this method is its ability to provide patient-specific models, which can be used to guide clinical decision-making, particularly in the management of abdominal aortic aneurysms (AAAs). By identifying regions of high stress and low load-bearing capacity, clinicians can better predict the risk of rupture and tailor treatment strategies accordingly.

However, there are several limitations to the study. First, the model assumes an idealized representation of the aortic wall and does not fully account for complex factors such as inflammatory responses or viscoelastic properties of the tissue. Additionally, the precision of MRI data, although high, is still subject to certain limitations, such as the inability to capture tissue heterogeneity in real-time.

Future studies should aim to refine the model by incorporating more advanced imaging techniques, such as contrast-enhanced MRI or CT angiography, and biomechanical data from other imaging modalities. Furthermore, longitudinal studies could help assess how changes in the mechanical properties of the aorta correlate with the progression of vascular diseases and their clinical outcomes.

The findings from this study present significant insights into the mechanical properties of the abdominal aorta, specifically focusing on the stress state and load-bearing fraction using in vivo parameter identification and finite element analysis (FEA). The primary goal of this research was to assess the utility of computational models, driven by real-time physiological data, in predicting the mechanical behavior of the aorta under typical conditions. The results support the hypothesis that this approach offers a powerful tool for predicting vascular behavior, which could have major implications for clinical management, particularly in the prevention and treatment of aortic diseases such as abdominal aortic aneurysms (AAAs) and atherosclerosis.

1. Stress State and Load-Bearing Fraction in Healthy Aorta

The stress state analysis revealed that the abdominal aorta experiences significant variations in stress distribution, with the highest concentrations typically located in the proximal regions (closer to the diaphragm) and lower concentrations in the distal regions (near the iliac arteries). This is consistent with what is known about the hemodynamics of the aorta; the blood flow and pressure are highest near the origin of the aorta and decrease as blood moves downstream. The proximal aorta is subjected to higher hemodynamic stress due to the higher velocity and pressure of the blood flow coming directly from the heart. These regions have evolved to withstand these forces, which explains the observed higher load-bearing fraction and stress tolerance.

The load-bearing fraction analysis also demonstrated that the outer layers of the aortic wall in healthy individuals carry a significant proportion of the total mechanical load. This finding aligns with prior research suggesting that the external layers, which are primarily composed of collagen and elastin fibers, provide structural support and elastic recoil necessary for normal aortic function. These fibers are critical for maintaining the vessel's elasticity, allowing it to expand and contract in response to pulsatile blood flow. The results from the model suggest that these outer layers are the primary contributors to the aorta's ability to withstand pressure fluctuations and ensure stable blood flow through the body.

2. Stress Distribution and Load-Bearing Fraction in Aortic Pathologies

For patients with abdominal aortic aneurysms (AAAs) or atherosclerosis, the results highlighted distinct changes in both the stress distribution and load-bearing fraction. Aneurysmal dilation of the abdominal aorta was associated with localized stress concentrations in the regions of the vessel that had undergone structural changes. These stress concentrations, often located at the point of dilation, reflect the weakening of the aortic wall in these areas, suggesting that the tissue is less capable of withstanding normal hemodynamic forces. This finding is particularly important for clinical management, as it identifies regions at high risk for further damage or rupture.

Moreover, the load-bearing fraction in patients with AAAs was found to be significantly lower compared to healthy controls. The aortic wall's reduced ability to bear the mechanical load is a direct consequence of the weakening of the vessel due to aneurysmal dilation. This reduction in the load-bearing capacity could be an early predictor of aneurysmal rupture and serves as an important clinical marker for determining treatment strategies.

Similarly, in patients with atherosclerosis, regions of the abdominal aorta where plaques had formed exhibited lower load-bearing capacities. These plaques, which consist of fatty deposits and calcified tissue, not only obstruct the flow of blood but also alter the mechanical properties of the aortic wall. The stiffening of the vessel wall due to atherosclerotic plaque deposition results in a reduced ability to accommodate changes in blood pressure. The computational model was able to reflect these changes, providing an important tool for assessing the progression of atherosclerosis and identifying high-risk areas for cardiovascular events such as rupture or dissection.

3. In Vivo Parameter Identification and Personalized Assessment

One of the most important aspects of this study is the use of in vivo parameter identification for personalized diagnostics. The ability to use real-time imaging data and physiological parameters from individual patients to construct computational models allows for the creation of highly accurate and patient-specific simulations. This approach stands in stark contrast to traditional, one-size-fits-all methods that rely on generalized assumptions about the mechanical properties of the aorta.

For instance, the blood pressure and flow dynamics measured in each individual are used to customize the model to accurately reflect the mechanical behavior of that patient’s aorta. This leads to a more personalized risk assessment and enables clinicians to make more informed decisions about treatment options. Whether the patient is at risk for developing an aneurysm, suffering from atherosclerosis, or dealing with other vascular conditions, this personalized approach allows for more tailored management plans. The ability to simulate how different interventions (e.g., medication, surgical repair) may impact the aorta’s stress state and load-bearing fraction could lead to better clinical outcomes.

4. Limitations and Challenges

While the study provides valuable insights, there are several limitations that must be addressed in future research.

- Model Assumptions: One of the major limitations of the current model is that it assumes the aortic wall to be a hyperelastic material, which may not fully capture the complex viscoelastic behavior of the tissue. In reality, the aortic wall exhibits time-dependent behavior, especially under conditions of high strain or when exposed to pathological conditions. Future studies could benefit from incorporating viscoelastic models to better simulate the mechanical response of the aorta under varying conditions.

- Imaging Resolution: Although MRI provides high-resolution images, it still has limitations in capturing tissue heterogeneity at the microscale level. The ability to model fine details, such as the distribution of collagen fibers and elastin in the aortic wall, would enhance the accuracy of the simulations. Advanced imaging techniques, such as contrast-enhanced MRI or 3D ultrasound, could help overcome some of these limitations.

- Longitudinal Data: This study focused on cross-sectional data, and future studies would benefit from longitudinal research that tracks changes in the aorta’s mechanical properties over time. This would allow for better predictions of disease progression and provide insights into how the mechanical behavior of the aorta changes in response to treatment interventions.

- Multi-Modality Data: The use of multimodal imaging techniques, such as combining MRI with CT angiography or ultrasound, could provide more comprehensive datasets for parameter identification. Multi-modality imaging could also help overcome the resolution limitations inherent in each individual imaging technique, providing a more complete picture of the aorta's mechanical environment.

5. Clinical Implications and Future Directions

The clinical implications of this study are profound. By incorporating in vivo parameter identification into the clinical workflow, clinicians can better predict the risk of vascular events such as rupture, dissection, or aneurysm formation. This personalized approach allows for earlier intervention and more tailored treatment strategies, which could ultimately improve patient outcomes.

Moving forward, it is essential to refine the modeling techniques and incorporate more patient-specific data to enhance the predictive power of the models. Additionally, as biomechanics continues to evolve, there is a growing opportunity to integrate machine learning algorithms into these computational frameworks. Machine learning could be used to identify subtle patterns in the data that might not be easily detectable through traditional methods.

Lastly, as the field progresses, there will be a need for clinical trials that assess the efficacy of model-guided treatments. These trials could determine whether personalized simulations lead to better clinical outcomes in patients with aortic diseases. If successful, this approach could become a standard part of clinical practice, transforming how vascular diseases are diagnosed and treated.

This study demonstrates the potential of in vivo parameter identification combined with finite element analysis (FEA) in assessing the mechanical behavior of the abdominal aorta. By simulating the stress state and load-bearing fraction of the aorta in real-time, this approach offers a non-invasive, patient-specific method for understanding the biomechanical properties of the vessel. The results provide valuable insights into the early detection and management of abdominal aortic aneurysms (AAAs) and atherosclerosis, and the approach may eventually play a crucial role in improving clinical outcomes for patients with vascular diseases. However, further refinement of modeling techniques and clinical validation are needed before this method can be fully integrated into routine clinical practice.

CONCLUSION

This study demonstrates that an in vivo parameter identification method, combined with finite element modeling, offers a promising tool for evaluating the stress state and load-bearing fraction of the abdominal aorta. The findings suggest that this approach could enhance the precision of vascular diagnostics and provide critical insights into the pathophysiology of aortic diseases. While promising, further refinement of the technique and its integration with clinical practice will be necessary to optimize its utility in patient care.

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