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Review Article

Morphological Features of Abdominal Aortic Aneurysms and Association with Biomechanical Assessments of Aneurysm Wall Segments

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ABSTRACT

This study focuses on the impact of geometric factors such as asymmetry, irregularity and tortuosity on the progression and rupture of Abdominal Aortic Aneurysms (AAA). The current surgical threshold based on maximum transverse diameter lacks precision, underlining the importance of understanding the aneurysmal wall's intrinsic biomechanical properties through destructive testing.

We aimed to determine the influence of AAA morphology on its wall biomechanics by correlating preoperative tomographic geometries with uniaxial biomechanical test data of arterial fragments from open aneurysm repair.

It's an observational experimental and multicenter study, 47 individuals with AAA undergoing open repair had an anterior wall fragment tested uniaxially for load, stress, tension, strain energy, strain and thickness. Preoperative CT scans yielded 26 geometric indices, analyzed statistically using SPSS v28.0.1.

Results: Ruptured AAA fragments were significantly thinner ($p<0.05$). Positive correlations between the maximum Diameter (D_{max}) and biomechanical resistance parameters maximum load ($r=0.408$), failure tension ($r=0.372$) and failure stress ($r=0.360$) were observed. Diameter/Height ratio (DHr) also showed positive correlations with maximum load ($r=0.360$), failure tension ($r=0.354$) and failure stress ($r=0.289$). DHr was dependent on and correlated with Dmax, with simple regression analysis indicating significance ($p<0.05$). No statistical differences in biomechanical and geometric parameters were noted between ruptured and unruptured AAAs.

Conclusion: The maximum diameter and diameter/height ratio correlate linearly and positively with resistance parameters of AAA wall fragments. While DHr depends on D_{max}, other geometric indices show no correlation with biomechanical properties.

Key words: Biomechanics; Mechanical stress; Abdominal aortic aneurysm; Ruptured aortic aneurysm; Computed tomography; Computed tomography angiography

INTRODUCTION

In clinical practice, Abdominal Aortic Aneurysms (AAA) with asymmetric morphologies are frequently identified on CT scans, during surgical procedures and in autopsy studies. These AAAs often appear more fragile and prone to rupture, prompting questions about the progression of asymmetrically shaped aneurysms. Are they inherently weaker? Do they possess a higher potential for rupture?

Current surgical intervention criteria raise questions: How can the rupture of small AAAs be explained or conversely, why do some large, intact aneurysms remain unruptured (Figure 1). This leads to an investigation into characteristics beyond maximum diameter that may influence AAA growth and rupture. Do

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aneurysms with the same diameter but different shapes and geometries from different individuals share the same progression and rupture risk (Figure 2). Do they grow at the same rate? Do their walls share the same compositional, elastic and strength properties? [1].

Figure 1: Small aneurysm, collected at autopsy, showing a rupture in its wall.

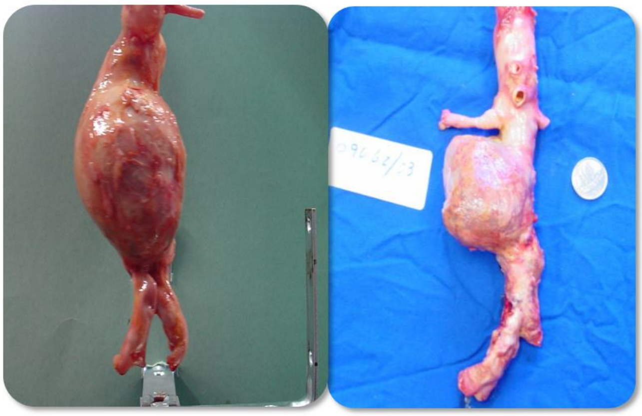

Figure 2: Aneurysms with similar diameters collected at autopsy, yet with different morphologies.

This research aims to understand if geometric characteristics of aneurysms influence the progression of these dilatations, such as asymmetries, arterial wall irregularities, curvatures, tortuosity, diameter asymmetry, neck angulations, aneurysmal sac length, the presence of luminal thrombus, among other aspects [2].

Given that AAA morphology and geometry seem to affect rupture risk, it is reasonable to consider that geometric characteristics also affect the intrinsic properties of the arterial wall, potentially altering AAA resistance and elasticity. Understanding arterial wall characteristics and their physiological biomechanics is crucial for comprehending this disease.

In solid biomechanics, one way to assess the arterial wall is through destructive uniaxial tensile testing. It is a practical method with established mathematical interpretation, extensively used in materials engineering.

Various factors contribute to AAA growth and predispose to rupture. The natural evolution of AAAs is dynamic, involving a living and active structure. This study aimed to uniquely evaluate how biomechanical properties of AAA walls interact with aneurysms' geometric aspects (one-dimensional, two-dimensional and three-dimensional) and correlate these factors [3].

LITERATURE REVIEW

In 2002 highlighted geometry as a key factor determining stress peaks in AAA. Their findings showed the highest stress topography coincided with rupture sites, typically at the posterolateral wall. Also noted how aneurysmal wall curvatures affect biomechanics, indicating that more elliptical shapes correlate with increased arterial wall stress [4].

Through tomographic imaging and geometric reconstructions using Finite Element Analysis (FEA), it is possible to estimate stress on AAA walls. Stringfellow et al., in 1987 utilized FEA to deduce that spherical and cylindrical aneurysms experience stress peaks at different topographies based on their anatomy. Vorp et al., modeled three-dimensional aortas, calculating stress through FEA and concluded that both asymmetry and diameter significantly increase stress within the aortic aneurysm wall. In 2009 Martufi et al., proposed morphological assessment of AAAs using specific geometric indices, defining One-Dimensional (1D), Two-Dimensional (2D) and Three Dimensional (3D) indices to quantify AAA geometry and morphology. Subsequent research, including Shum et al., in 2011, correlated various geometric characteristics observed in tomographic images with rupture, such as aneurysmal sac length, height, volume, surface area, protrusion height and intraluminal thrombus volume [5].

Tang, et al., compared 27 geometric indices between ruptured and unruptured AAAs, finding correlations between the height of the largest sac protrusion, smaller mean curvatures and AAA rupture. Similarly Parikh, et al., identified three geometric indices more prevalent in ruptures: Total centerline length, total AAA wall surface area and the norm of Gaussian curvatures [6].

The largest known case series of uniaxial biomechanical aneurysm tests is by Tavares Monteiro, et al., who conducted uniaxial tensile testing on the anterior wall of 90 patients with AAA. They found that resistance parameters are greater in AAAs larger than 5.5 cm in diameter, with larger aneurysms showing fewer elastic fibers and more inflammatory cells. This suggests that larger AAAs undergo intense remodeling with increased collagen deposition in the media and adventitia layers to withstand stress [7].

Raghavan, et al., assessed four aneurysms from autopsies and observed a significant thinning of tissue around the rupture sites, suggesting that tissue degradation at the site is a localized and not uniform process a finding that documents the heterogeneity of the AAA wall [8].

da Silva, et al., noted that fusiform aneurysms, which were more frequent and had smaller diameters upon rupture compared to spheric aneurysms, indicated that morphology and geometry might be associated with aneurysmal rupture [9].

This abstract underscores the importance of geometric and biomechanical factors in the pathophysiology of AAAs, suggesting that a comprehensive assessment of these parameters is essential for advancing the understanding and management of aneurysm risk [10].

DISCUSSION

Our study correlated geometric measurements of AAA, derived from tomographic images, with uniaxial biomechanical test values of aortic aneurysm fragments obtained during open surgical repairs. It's an observational experimental and multicenter study, 47 individuals with AAA undergoing open repair had an anterior wall fragment tested uniaxially for load, stress, tension, strain energy, strain and thickness. Preoperative CT scans yielded 26 geometric indices. Positive linear correlations emerged between two geometric indices, the maximum Diameter (D_{max}) and the Diameter/Height ratio (DHr), with biomechanical indices of resistance including maximum failure strength, failure tension and failure stress. Correlations were as follows: D_{max} with maximum failure strength (P=0.04, r=0.408), failure tension (P=0.01, r=0.372) and failure stress (P=0.013, r=0.360); DHr with maximum failure strength (P=0.013, r=0.360), failure tension (P=0.015, r=0.354) and failure stress (P=0.049, r=0.289). No correlations were observed with other geometric indices or with the failure strain, failure strain energy and thickness of the aortic fragments [11].

The rupture of an AAA biomechanically signifies the failure of the diseased aortic wall due to its inability to withstand stress. The mechanical properties of the aortic wall are thus crucial in understanding AAA pathogenesis and rupture. The value of such research is underscored by the wealth of information gleanable from aortic tissue fragments [12].

This study focused on two spheres relevant to AAA knowledge: Morphology/geometry and the biomechanical parameters of the AAA wall, investigating their correlation. Clinical observations suggest that asymmetrically shaped aneurysms are more susceptible to rupture [13].

It is well-established that AAAs with larger diameters rupture more frequently than those with a smaller maximum transverse diameter. However, our findings challenge the assumption of uniform wall weakening with increasing AAA diameter. Instead, larger AAAs in our sample demonstrated stronger anterior walls than smaller AAAs, as indicated by the positive correlation between D_{max} and the resistance parameters [14].

The initial events of aneurysmal formation are thought to include the loss of elastic fibers leading to arterial dilation. Accompanied by mechanical stimuli due to changes in diameter and shape, remodeling ensues, involving collagen fiber deposition in the arterial wall, increasing its absolute quantity. Thus, there is an active, heterogeneous compensatory remodeling process with collagen deposition varying by arterial wall topography [15].

Rupture depends on a localized region where stress exceeds the arterial wall strength. Given the non-linear and non-homogeneous nature of aneurysmal wall remodeling, it is presumed that areas of greater wall weakness may be responsible for aneurysmal rupture [16].

While this study's destructive testing methodology is limited to anterior wall fragments, ideally, samples would be sourced from various topographies due to compositional variations. Nevertheless, removal of additional wall fragments from living patients presents challenges. Cadaveric studies are an alternative, offering the ability to collect from multiple AAA locations [17].

This underscores the necessity for more individualized AAA assessments, balancing this against the universal appraisal. Diameter remains a primary parameter in surgical treatment decisions, significantly influencing AAA natural history, stress experience and intrinsic wall characteristics [18].

CONCLUSION

The maximum transverse diameter of AAA and the Diameter/Height ratio of the aneurysmal sac are linearly and positively correlated with biomechanical resistance parameters of fragments from the anterior wall of the AAA. There was no correlation found between the other geometric indices and the biomechanical parameters located in the anterior wall of the AAA.

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