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The Effect of Computational Methods on Abdominal Aortic Aneurysm Stresses

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ABSTRACT

Rupture of abdominal aortic aneurysms (AAA) remains a critical clinical concern, for which biomechanical metrics, particularly peak wall stress (PWS), are increasingly recognized as essential adjuncts to conventional diameter-based rupture risk criteria. Finite element analysis (FEA) provides a rigorous framework for estimating patient specific wall stresses, yet the fidelity and reproducibility of these estimates depend strongly on mesh design. This study systematically evaluates the influence of tetrahedral versus hexahedral elements on AAA wall stress using two patient-specific models implemented in ANSYS, with both configurations subjected to graded mesh refinement, identical boundary conditions, and uniform constitutive parameters to isolate element type effects. Tetrahedral meshes produced stable, repeatable PWS estimates with smooth numerical convergence across a wide range of element densities, whereas

hexahedral meshes exhibited larger stress variability and stronger dependence on mesh resolution. Although hexahedral elements achieved superior geometric quality indices, they required substantially greater computational cost and showed less consistent stress convergence. Both formulations yielded comparable spatial patterns of wall stress, but tetrahedral meshes offered improved numerical robustness and computational efficiency. Overall, these findings support tetrahedral meshing as the more practical and reliable option for patient-specific AAA biomechanical workflows, particularly those prioritizing speed, automation, and clinical integration.

Keywords: Abdominal Aortic Aneurysm, Finite Element Analysis, Mesh Topology, Peak Wall Stress.

INTRODUCTION

The Abdominal Aortic Aneurysm (AAA) constitutes a progressive and life-threatening vascular pathology characterized by permanent enlargement of the abdominal aorta to minimally 150% of its reference diameter. Although commonly asymptomatic untreated AAA progressively expands until rupture, producing catastrophic internal hemorrhage with mortality rates exceeding 80% [1]. Diameters surpassing 3 cm are clinically designated as aneurysmal, with elective surgical repair typically recommended at or above 5.5 cm due to sharply escalating rupture probability. Nevertheless, accumulating evidence demonstrates that rupture can occur at smaller diameters, underscoring the limitation of diameter alone as a rupture risk predictor [2].

Subsequently, interest has intensified in biomechanical metrics that more directly represent the mechanical competence of the aneurysm wall. Among these, peak wall stress, commonly expressed as maximum principal stress (MPS), is a powerful predictor, since rupture represents a mechanical failure where localized stress exceeds tissue strength. Ongoing research underscores the importance of integrating biomechanical assessment into clinical AAA evaluation, demonstrating that patient-specific stress distributions provide information beyond purely geometric parameters [3].

With the help of using Finite element analysis (FEA) which is the predominant computational approach for estimating wall stresses in patient-specific AAA models. Its capability to simulate the mechanical response of complex vascular geometries under physiological pressure renders it indispensable for assessing rupture potential. Advances in computational biomechanics, particularly in meshing techniques, material modeling, and solver efficacy, continually enhance the reliability of the AAA stress predictions [4, 5].

The reliability of the FEA results, however, is profoundly influenced by the computational mesh. The Mesh configuration, resolution, and element quality dictate numerical precision, stability, and convergence. A critical consideration is the choice between tetrahedral and hexahedral elements, each possessing distinct advantages and limitations. Tetrahedral meshes offer great flexibility and are simpler to generate for complex anatomies, whereas hexahedral meshes typically provide superior numerical performance and lower quantization error, despite being more challenging to generate [6]. Recent comparative investigations in vascular biomechanics emphasize that mesh choice can substantially influence peak stress calculations and computational expense, and thus must be carefully optimized in patient-specific studies [4, 7].

In the present study, a need exists to better characterize how mesh formulation affects AAA stress predictions. The investigation synthesizes computational results from two independent FEA models utilizing ANSYS to evaluate the impacts of tetrahedral and hexahedral mesh types on the precision, stability, and computational efficacy of AAA stress analysis. By systematically comparing stress results and computational requirements, this work offers contemporary recommendations for selecting appropriate meshing strategies in modern AAA biomechanics.

MATERIALS AND METHODS

Model Preparation

A patient-specific, three-dimensional infrarenal AAA configuration was employed as the geometric basis for all computational assessments. The anatomy was reconstructed from contrast-enhanced CT angiographic images and subsequently processed to obtain a watertight surface defining the luminal boundary, intraluminal thrombus (ILT) was excluded from primary comparisons to isolate the influence of element topology. The surface geometry was imported into ANSYS Workbench software and transformed into a solid volume for FEA. Utilizing patient-specific CT datasets and semi-automated segmentation is consistent with contemporary computational pipelines and supports clinically relevant, patient-derived inferences [7].

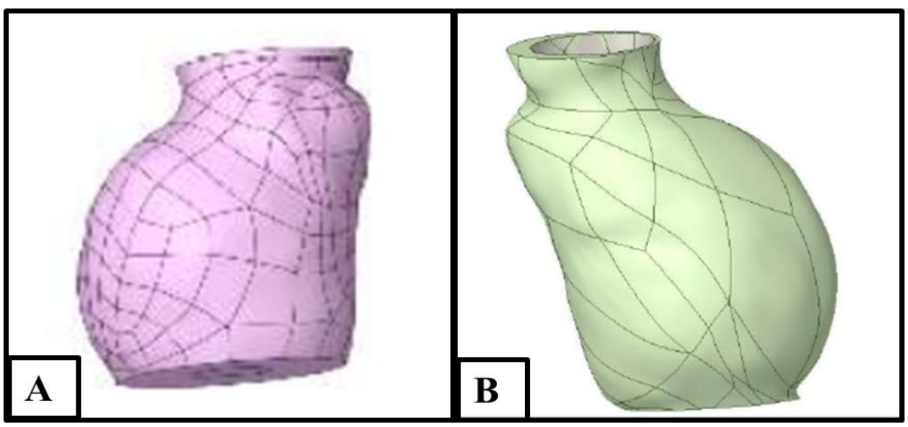

Figure 1 3D AAA of patients (A) Model 1 and (B) Model 2

Material Models and Properties

For initial comparisons between meshing schemes, the aneurysm wall was modeled as a homogeneous, isotropic, linear-elastic continuum. The principal material parameters were specified as Young's modulus = 2.7 MPa and Poisson's ratio = 0.45, corresponding to values from prior AAA FEA benchmark investigations to decouple mesh effects from fundamental complexity. An additional, high-stiffness case (Young's modulus ≈ 100 MPa) was also examined to approximate morphological stress distributions with minimal wall deformation. Implementing a simplified linear-elastic formulation enables a controlled evaluation of quantization influences, an approach supported by earlier study assessing mesh topology under constant material properties [8].

Meshing Strategy and Element Types

Two distinct finite element topologies were generated for comparative evaluation. Firstly, quadratic tetrahedral Meshes were produced using ANSYS automated meshing tools with progression controls to preserve acceptable element aspect ratios in regions of elevated curvature. The tetrahedral quantization was selected for its automation and capability to conform to complex AAA geometries with limited operator intervention, element density was systematically varied for convergence assessment (typical range: 24,000 - 115,000 elements) [8]. Secondly, quadratic hexahedral / hexa-dominant meshes were created where structured or hexa-dominant quantization were obtained using a multizone sweeping strategy and automated patching to realize high-quality brick elements across the wall thickness. Although constructing high reliability hexahedral meshes for complicated anatomies generally requires substantial analyst input, Thus, a standardized workflow was applied to keep generation times compatible with clinical research constraints. The hexahedral element counts were matched to tetrahedral counterparts which were feasible to separate topological effects from element number [8]. For both the mesh families, conventional quality indices were calculated and archived to quantify geometric distortion and expected numerical performance such as element skewness, aspect ratio, and minimum/maximum element size. The mesh refinement analyses were performed by progressively increasing element density until principal output metrics (peak principal stress and total deformation) exhibited asymptotic convergence. The requirement for mesh convergence and grid independence, emphasized in recent study literature [8].

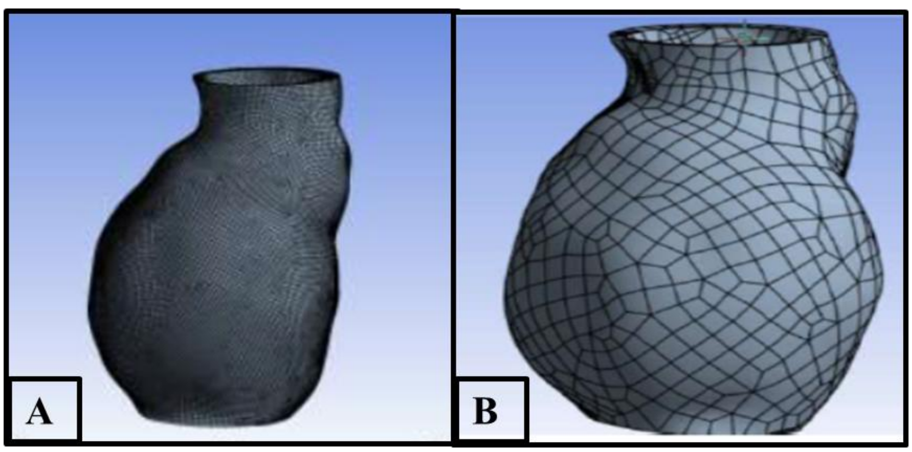

Figure 2: Finite element meshes (A) Model 1 and (B) Model 2

Boundary Conditions and Load

To represent physiological constraints while isolating meshing behavior, the proximal and distal boundaries of the AAA models were prescribed fixed supports (zero translational motion), consistent with established AAA FEA protocols that neglect respiratory-induced movement. A spatially uniform intraluminal pressure corresponding to mean systolic loading was applied to the luminal surface to generate wall stresses. It was reassigned as a global force for documentation which corresponds to a mid-descending aorta displacement load reported in analogous studies (21.7 N as a representative magnitude). Additionally, simulations with varied intraluminal pressures were performed to verify that relative discrepancies between mesh types persisted throughout physiologically relevant pressure ranges [7].

Finite Element Formulation

All the finite element computations were carried out in ANSYS Mechanical using a static, small-strain, displacement-based formulation to preserve direct comparability among cases. For

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quadratic element formulations, appropriate numerical integration schemes and anti-locking controls were activated to mitigate volumetric locking, particularly under near-incompressible conditions (Poisson's ratio ≈ 0.45). Where relevant, hybrid formulations or reduced integration options were explored to ensure that observed disparities reflected mesh topology rather than integration artifacts. The convergence thresholds were tightened until residual force norms satisfied conventional engineering criteria, thereby supporting solution robustness [4].

RESULTS

The analysis of material behaviour identified clear differences between the two mesh families. Both models reported that tetrahedral meshes produced stable and repeatable maximum principal stress (MPS) estimates, with negligible variation over a range of element sizes or counts, exemplified by values spanning 0.339–0.351 MPa. In contrast, hexahedral meshes showed larger MPS fluctuations dependent on element refinement, with an illustrative range of 0.253–0.361 MPa, reflecting increased susceptibility to quantization settings.

Table 1: MPS Results (MPa) according to parameters (Mesh type, Element size).

Mesh Type	Young's Module (MPa)	Poisson's Ratio	Element Size (mm)							
			2.5	3	3.5	4	4.5	5	5.5	6
Tetrahedral	2.7	0.45	0.34569 MPa	0.34912 MPa	0.34454 MPa	0.3506 MPa	0.33962 MPa	0.3441 MPa	0.3505 MPa	0.35134 MPa
Hexahedral			0.34118MPa	0.6141 MPa	0.29359 MPa	0.27688 MPa	0.3007 MPa	0.28092 MPa	0.31184 MPa	0.25356 MPa

For convergence, both topologies produced similar total deformation, but hexahedral stress predictions oscillated markedly with refinement, whereas tetrahedral stresses approached convergence monotonically. From a computational standpoint, hexahedral meshes required substantially longer solution times and exhibited nonlinear growth in memory demand. Tetrahedral meshes displayed approximately linear scaling of computational cost, were generated automatically, and required considerably fewer computational resources.

The mesh quality indicators revealed that tetrahedral meshes had higher skewness values (0.79–0.82) yet remained within acceptable limits, while hexahedral meshes achieved better geometric metrics (skewness 0.52–0.63) but still manifested numerical instability. The stress contour plots verified that both mesh types reproduced the characteristic posterior stress concentration, though differences in absolute peak MPS remained below statistical significance.

DISCUSSION

In the present study the analysis demonstrates that computational mesh configuration critically governs the accuracy, stability, and efficiency of AAA stress predictions, substantiating recent findings from computational biomechanics. As FEA becomes progressively adopted for patient-specific rupture-risk assessment, understanding mesh topology's influence is essential for interpreting wall stress outcomes and ensuring reliable biomechanical indicators.

The concerning accuracy and reliability, the findings demonstrate that tetrahedral elements consistently produce robust and predictable convergence across a broad spectrum of element densities. Their geometric flexibility enables them to conform naturally to patient-specific aneurysm morphologies, which commonly exhibit tortuous configurations, asymmetric expansions, and localized curvature variations. This conformability permits tetrahedral meshes to generate stable peak-stress estimates without requiring extensive manual intervention. The observation aligns with recent investigations emphasizing tetrahedral quantization's appropriateness for automated vascular modeling and clinical workflows requiring rapid processing. Moreover, the refinement protocol is straightforward, enabling efficient mesh-convergence studies, a component proven as fundamental for minimizing numerical uncertainty in AAA biomechanics [4, 9].

The hexahedral elements despite theoretical advantages in structured topology and element quality, exhibit inconsistent performance when deployed on intricate vascular geometries. The multiple investigations observe that hexahedral meshes demonstrate increased sensitivity to element size and quality irregularities, potentially inducing localized stress oscillations, particularly near sharp geometric transitions or bifurcations [10]. The dependence on meticulously controlled mesh topology frequently demands labor-intensive manual modeling or advanced semi-automatic block-structured methods, which can be impractical for large patient cohorts.

From a computational efficiency standpoint, tetrahedral meshes provide substantial advantages. They are faster to generate, scale more predictably with increasing mesh density, and require significantly less user effort. These characteristics render them highly appropriate for clinical settings where processing speed is paramount. Conversely, hexahedral meshes, while yielding high-quality elements, necessitate longer computation times, greater memory consumption, and demonstrate more nonlinear performance scaling with rising complexity. This corroborates recent observations that the computational overhead for generating high-quality hexahedral meshes frequently exceeds their theoretical accuracy advantages in routine clinical simulations [11].

The clinical implications of these findings are significant. The stress-based rupture guides particularly maximum principal stress gain acceptance as supplementary metrics to maximum diameter, computational prediction fidelity directly influences clinical interpretation and management decisions. Given their balance of reliability, automation compatibility, and computational economy, tetrahedral meshes are generally more practical for standard AAA biomechanical assessments, especially in time-critical contexts like screening or pre-operative planning. Although hexahedral meshes may be preferable in controlled research settings prioritizing accuracy optimization where computation time is less constrained, their integration into clinical practice remains challenging. Both the mesh types produced similar qualitative MPS distributions, indicating either can be suitable following careful validation. Nevertheless, the cumulative evidence supports tetrahedral elements as the most efficient and clinically scalable option for patient-specific AAA stress analysis [4, 12, 13].

CONCLUSION

The study concludes that the selection of computational meshing strategy markedly affects AAA wall stress evaluation. Although hexahedral elements can produce high-quality, structured meshes, they require substantial computational effort and exhibit greater variability in stress outcomes. The tetrahedral elements contrast consistently deliver stable stress estimates, capture complex AAA geometries effectively, and demand considerably fewer computational resources.

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Taken together tetrahedral meshing constitutes the preferred option for practical and reliable biomechanical characterization of AAA wall stresses, particularly in patient-specific simulations and clinical applications. Nonetheless, both mesh families remain appropriate when sufficiently refined and validated, emphasizing the ongoing need for optimized meshing standards and improved automated hexahedral meshing tools.

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