Regional Heterogeneity in Aortic Aneurysms: A Method for Finite Element Analysis

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Keywords: aortic aneurysms, tissue biomechanics, regional heterogeneity, nonlinear biomechanics

An aortic aneurysm is characterized by a balloon-shape bulge that forms in the aorta due to significant degradation of the microstructure of the arterial wall material, affecting certain regions more prominently than others. Given that the mechanical behavior of the tissue is governed by its microstructure, the mechanical properties of the aortic aneurysms exhibit regional heterogeneity. Blood flow has the potential to separate the layers of the aortic wall in the weakened aneurysmal region, leading to blood leakage between them—this condition is known as dissection. Alternatively, the pressure of blood flow can rupture through all layers, resulting in severe internal bleeding—a state referred to as rupture. Both outcomes can be dangerous and potentially fatal. Currently, surgical intervention for aneurysms is often determined by criteria such as an aneurysm diameter greater than 5.5 cm or a growth rate exceeding 1 cm/year in diameter. However, these criteria do not always precisely indicate the risk of aortic rupture, making surgical decisions risky.

Efforts are underway to establish a more reliable and precise stress-based criterion for assessing rupture risk, aimed at enhancing aneurysm management and guiding surgical decisions. Finite element modeling (FEM), renowned for its capacity to simulate complex geometries, loading conditions, and material properties, serves as a powerful tool for more accurately evaluating aneurysm rupture risk by analyzing stress distribution caused by blood pressure. Despite substantial experimental and imaging evidence demonstrating the regional heterogeneity of aortic aneurysms, nearly all FEM simulations still treat the aortic wall as a spatially homogeneous matter.

Here, we propose a novel method to account for spatial material heterogeneity using 1) a realistic anisotropic nonlinear hyperelastic constitutive law, and 2) a continuously gradient material description of the regional variability. The latter will diminish the issue of stress discontinuity providing a more realistic stress distribution in the enlarged aorta. Recent studies indicate that the regional heterogeneity of the aneurysmal wall may serve as a biomarker, which could make our model relevant and timely. The results of FEM simulations for the idealized 3-dimensional aorta model with three different material definitions are compared and discussed: a) the idealized homogeneous model results in homogeneous stress mapping and identical stress across the circumference, b) the material with segmental heterogeneity proposed in the literature before leads to unrealistic stress discontinuities, while c) the material description based on a continuous gradient of material constants (which will converge to a continuous description as the mesh is refined) results in smoother and more realistic variability in the spatial stress distribution.