Modeling Brain Atrophy with Region-Specific Material Properties

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Summary

This study investigates cerebral atrophy using 3D brain models with varying regional heterogeneity to simulate normal and accelerated cerebral atrophy. Results show that increased heterogeneity improves accuracy in stress distribution. Findings highlight the importance of regional material properties for realistic simulations under various physiological and pathological conditions.

Introduction

Understanding the mechanical activity of the brain, one of the most complex organs in the human body, is crucial for elucidating its function in both health and disease. This paper explores the significance of investigating cerebral atrophy—a condition characterized by a reduction in brain volume, often pathologically accelerated by the accumulation of misfolded neurotoxic proteins [1]—through the use of heterogeneous brain models in full-scale simulations.

Methods

3D brain models were generated from images in the OASIS dataset, utilizing *FreeSurfer* for image processing and segmentation. A custom Python script was developed to create a mesh of 2×2×2 mm hexahedral elements, partitioning the brain into 17 regions, as illustrated in Figure 1. To facilitate comparative analysis, simplified models with increasing homogeneity (9, 4, 2, and 1 region) were also constructed. Region-specific material properties were incorporated [2], and brain tissue behavior was represented using a one-term Ogden model. Cerebral atrophy was simulated using the *deal.II* finite element library, with distinct atrophy rates assigned to normal and accelerated atrophy. A normal atrophy rate was applied to healthy aging, while accelerated atrophy—induced by a high concentration of misfolded proteins—led to increased volume loss [3].

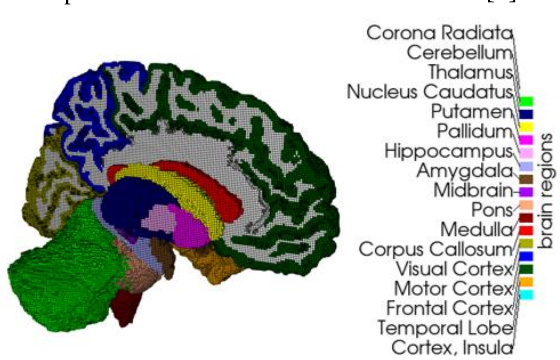

Figure 1: Brain model with regional segmentation.

Results and Discussion

Simulations of cerebral atrophy on 6 brains showed a 20-25% decrease in global brain volume and a 20% reduction in hippocampal volume, with the ventricles enlarging by 2.2-5%. Moreover, compressive hydrostatic stress in the brain tissue increased as atrophy progressed.

The comparison of models with varying levels of heterogeneity (1R, 2R, 4R, and 9R) against the fully heterogeneous 17R model revealed that the 1R model, assuming homogeneity, exhibited the largest deviations in regional stress and deformation patterns. As heterogeneity increased, these deviations decreased, with the 2R, 4R, and 9R models aligning progressively better with the 17R model. Notable improvements were observed in specific regions, such as the corpus callosum and corona radiata starting with the 4R model, and the hippocampus and amygdala from the 9R model, as shown in Figure 2, illustrating the absolute difference in hydrostatic stress between the 17R model and the four simplified regional models.

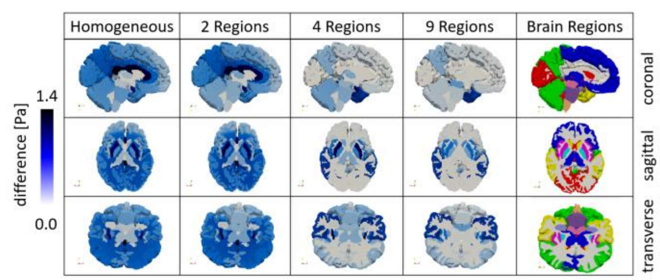

Figure 2: Absolute difference in hydrostatic stress between the fully heterogeneous model and the four simplified regional models.

Conclusions

Region-specific material properties play a crucial role in developing accurate brain models, with increased heterogeneity enhancing precision, particularly in key brain regions. Therefore, additional experimental data is required to further characterize regional differences, enhance model reliability, and accurately capture the complex mechanical behavior of brain tissue under various physiological and pathological conditions.

References

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