Influence of the pia mater modeling on the prediction of acute subdural hematoma

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I. INTRODUCTION

Traumatic brain injury (TBI) constitutes a leading global cause of mortality and morbidity, representing a profound public health burden. Subdural hematoma emerges as one of the most prevalent manifestations of TBI [1-4]. Specifically, acute subdural hematoma (ASDH) represents a catastrophic pathology, which is often associated with the disruption of bridging vein (BV) or BV-superior sagittal sinus (SSS) secondary to cortical displacement. Finite element (FE) models have been used to predict the ASDH risk. However, the mechanical role of the pia mater - a thin membrane enveloping the brain surface and anchoring BVs - has been largely overlooked. Despite not being universally agreed, a substantial body of experimental research indicates that the pia mater exhibits non-linear mechanical behavior [5, 6]. Nevertheless, the implementation of linear elastic material models remains the predominant strategy in FE head modeling [e.g., ref 7-9].

This study investigated how the pia mater modelling strategies influence cortical responses and the predicted risk of ASDH.

II. METHODS

Computational Modeling

The baseline FE head model was developed by Kleiven (2007) [7], including 11 pairs of major parasagittal BVs and considering sliding behavior on the brain-skull interface (Figure 1A, B). In the original model, the pia mater was approximated as a linear elastic membrane with a Young's Modulus of 11.5 MPa (Figure 1C). In this study, we modified the pia mater as a nonlinear simplified rubber, consistent with previous research [10], with the stress-strain curve derived from pial tension test (Figure 1C) [5].

Boundary conditions

To assess the biomechanical influence of the pia mater modeling, both models were subjected to impact kinematics obtained from published post-mortem human subject (PMHS) experiments. The applied boundary conditions comprised one loading known to induce ASDH (Case 21-2_2), with a translational acceleration peak of 450 g and a rotational acceleration peak of 26.2 krad/s^2. This was contrasted against two distinct profiles verified to not produce BV ruptured (Cases 25-2_1 and 25-2_2) [11].

III. INITIAL FINDINGS

Pia mater material modelling substantially affected the cortical displacements and BV responses. The application of a nonlinear pia mater with experimentally based properties significantly redistributed relative cortical displacements (Figure 2A). Under the ASDH-inducing impact, when using a linear pia mater model, the maximum cortical displacement and BV strain were predicted as 2.0 mm and 0.10, respectively. When using a nonlinear pia mater model, the cortical displacement increased to 8.8 mm and BV strain to 0.16. This trend was mirrored in the non-injurious impacts, where the transition to a nonlinear model elevated mean maximum cortical displacement from 0.7 mm to 3.4 mm and mean maximum BV strain from 0.04 to 0.07 (Figure 2B, C).

When compared with the BV-SSS ultimate strain range (0.29 ± 0.13) [12], a possible ASDH occurrence was only predicted when the pia mater was simulated as nonlinear material under the ASDH-inducing impact. None of the predicted BV strains fell within the range of the BV ultimate strain (0.50 ± 0.16) [13].

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IV. DISCUSSION

This study highlighted the mechanical role of pia mater on brain responses and the necessity of modelling pia mater with nonlinear material with experimentally based properties for reliable ASDH prediction. The majority of existing FE head models use a linear elastic material model, representing a higher stiffness than the nonlinear model adopted in this study (Figure 1C). Our results indicated that such an over-stiffening pia mater modelling approach constrained the brain cortical displacement and thereby underestimated the BV response and interpreted ASDH risk.

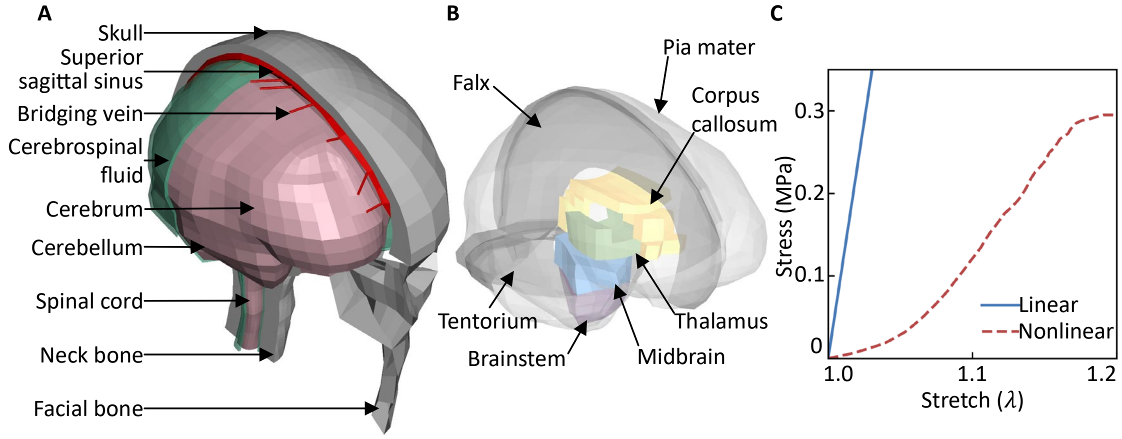

Figure 1. (A) Isometric view of the finite element model of human head with the skull open to expose the brain; (B) Isometric view of membranes and deep brain structures. (C) Stress-stretch response of pia mater: linear elastic and nonlinear model [5, 7, 10].

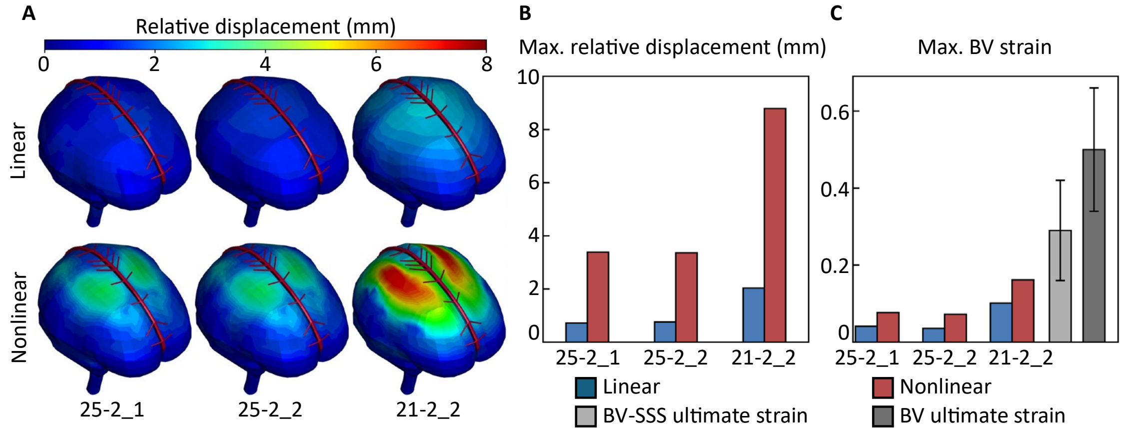

Figure 2. (A) Cortical relative displacement captured at the maximum value occurring time. (B) Maximum of the cortical relative displacement. (C) Maximum BV strain plotted together with the BV- superior sagittal sinus (SSS) ultimate strain and BV ultimate strain [12, 13].

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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