

Development of a Novel 3D Model to Investigate Prong-Induced Nasal Septum Injury In Preterm Infants

Biomedical Engineering Master's Thesis
Hamdan, R.

Mentors: Dr. Liping Tang, Dr. Shiyao Lin, Dr. Jun Liao

Background

Continuous positive airway pressure (CPAP) is a non-invasive ventilation method used to provide respiratory support for premature infants younger than 32 weeks of gestational age. However, 20-60% of these infants develop nasal deformities, such as columella erosion, due to CPAP nasal prongs. Current clinical practices prioritize prevention rather than addressing the root cause of these injuries. Strategies like alternating between prongs and masks, frequent monitoring every 4-6 hours, and using protective dressings help minimize damage but do not resolve the fundamental design issue.

Executive Summary

Due to the lack of suitable laboratory, animal, or human models, a 3D model was used to investigate how neonatal anatomy and CPAP prong design influence the mechanical interactions and resultant stress distribution across the nasal septum and columella.

Hypothesis: Nasal Prong misfit contributes to pressure buildup and injury in neonates.



Image of facial view of a preterm infant with nasal injury due to CPAP prongs.

Experimental Setup



3D Model Reconstruction:

MRI scans of neonates were processed in 3DSlicer to generate a detailed 3D model of an infant's head.



SolidWorks Design:

Replica models of various nasal prongs were created using SolidWorks.

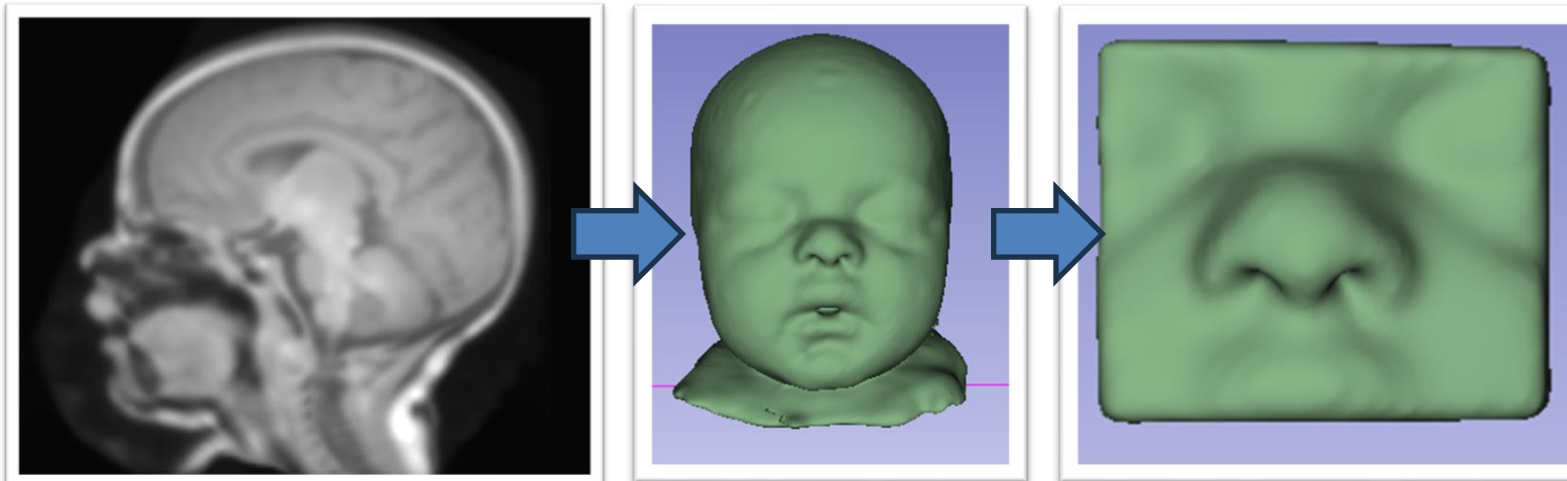


Simulation Setup in Abaqus:

The 3D head model and nasal prong model were assembled in Abaqus. Material properties, contact definitions, and boundary conditions were defined.

3D Model of Infant Anatomy

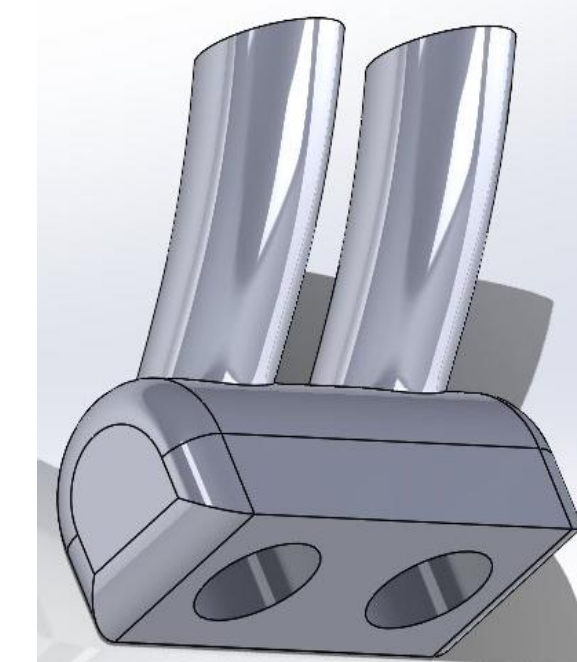
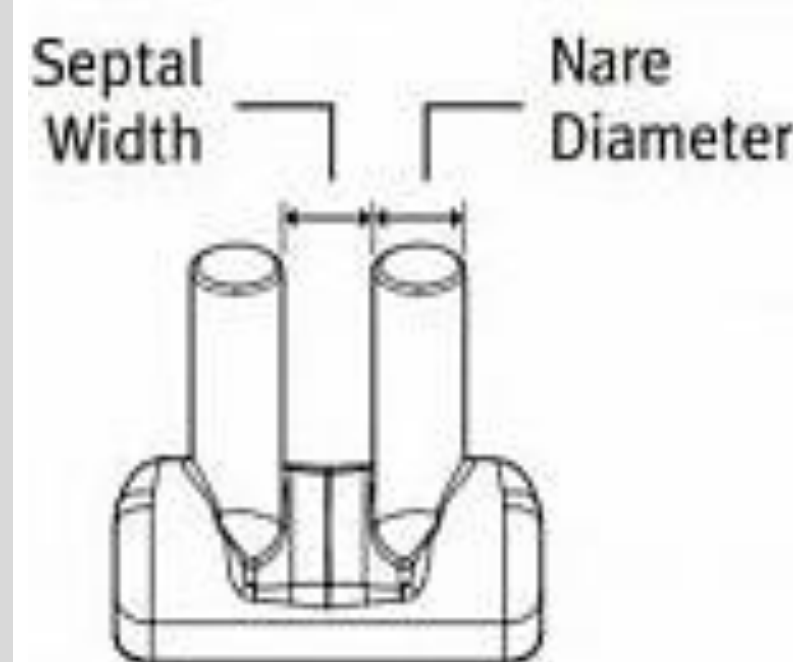
Neonate scans were obtained from the Neuroimaging Tools and Resources Collaboratory



MRI scans were used to create 3D models of infant nasal anatomy.

Models representing 2-wk-old and a 4.5-mo-old infant were developed to capture age-related differences in nasal size and structure. This approach allows comparison of how CPAP prongs interact with smaller, more fragile neonatal anatomy versus more developed infant anatomy.

3D Model of CPAP Nasal Prongs



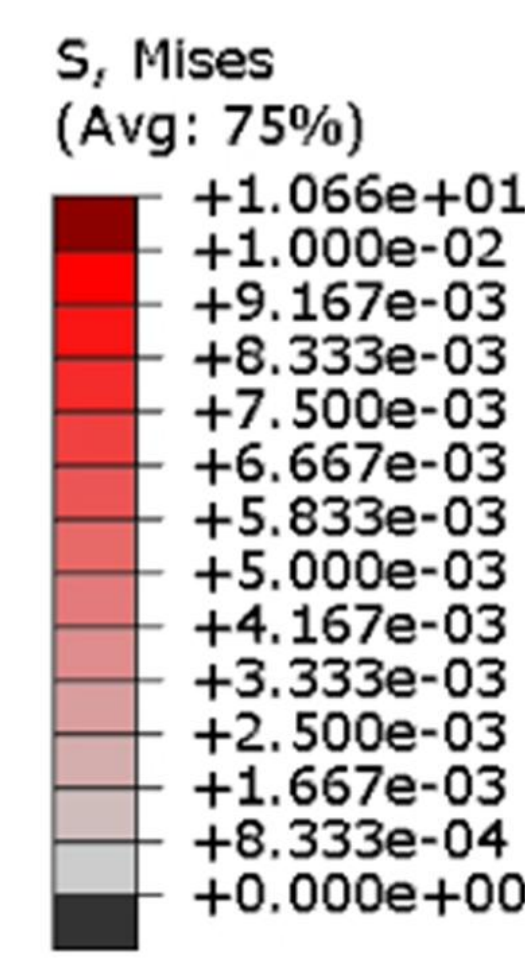
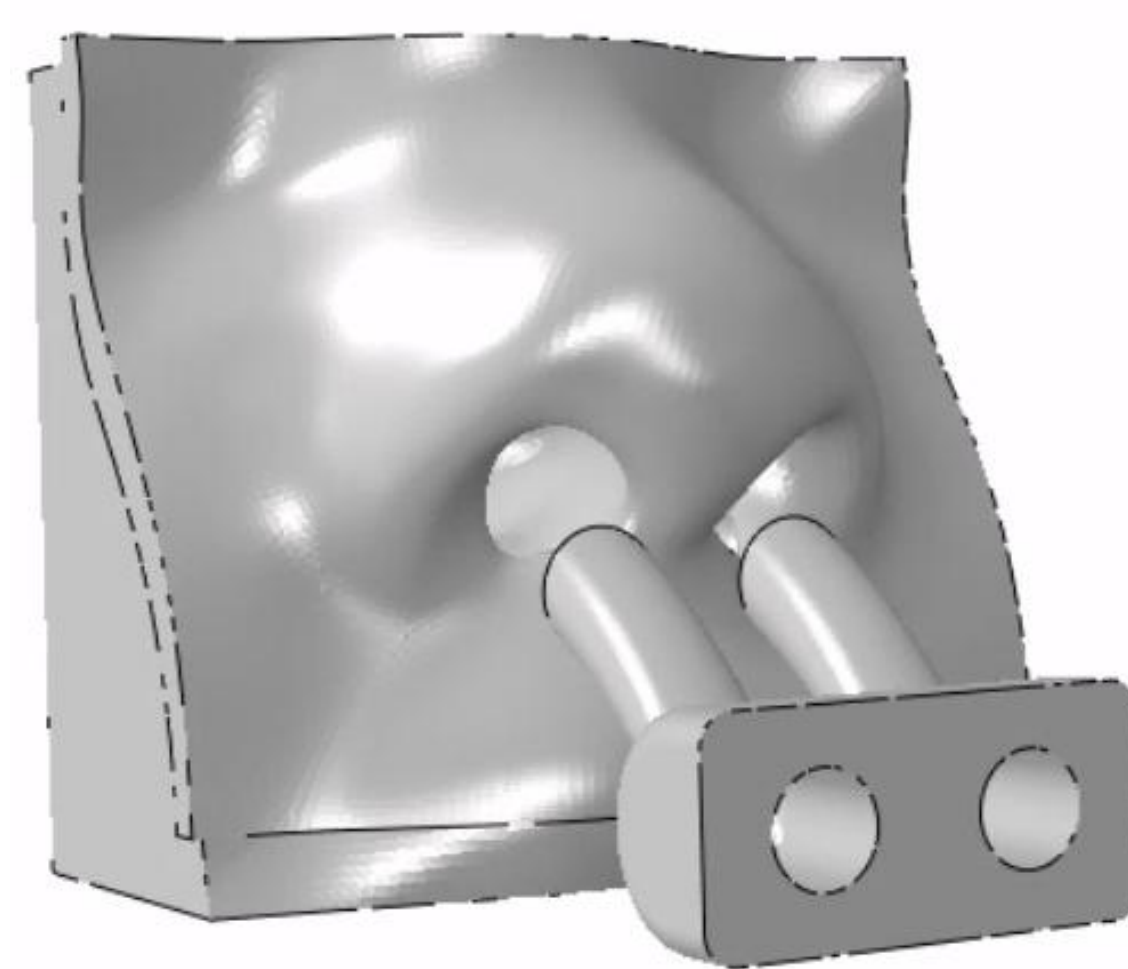
CPAP prongs were designed on SolidWorks based on the Fisher & Paykel Nasal CPAP Prongs.

Dimensions: Designed based on septal width and nare diameter of neonate.

Finite Element Analysis on Abaqus

Finite element analysis (FEA) Simulations: computer modeling technique that mathematically divides a structure into many small regions with assigned material properties, allowing forces and pressures to be calculated.

Simulations began with the nasal prongs positioned just outside the nostrils, allowing controlled insertion and realistic interaction with nasal tissue during the analysis.



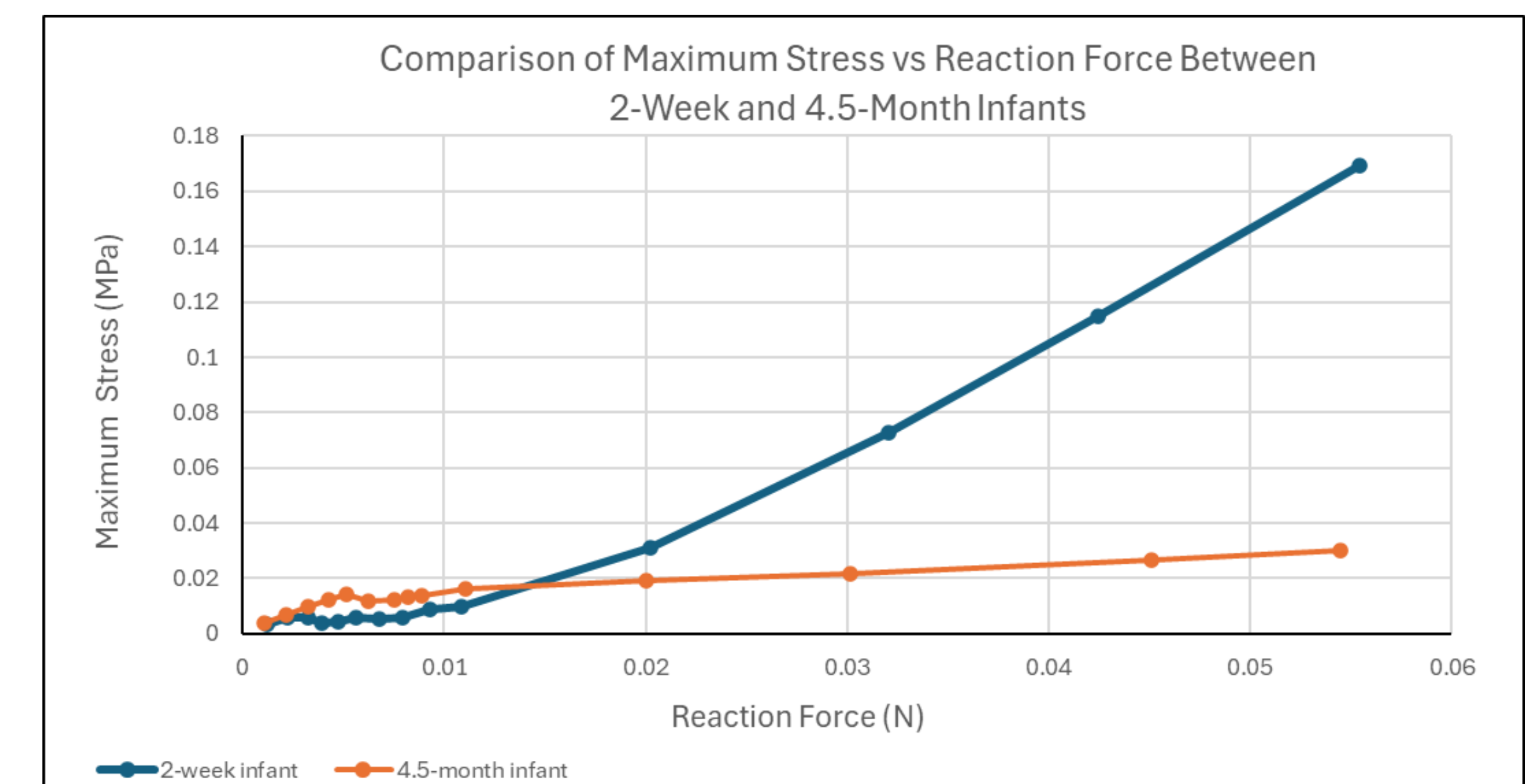
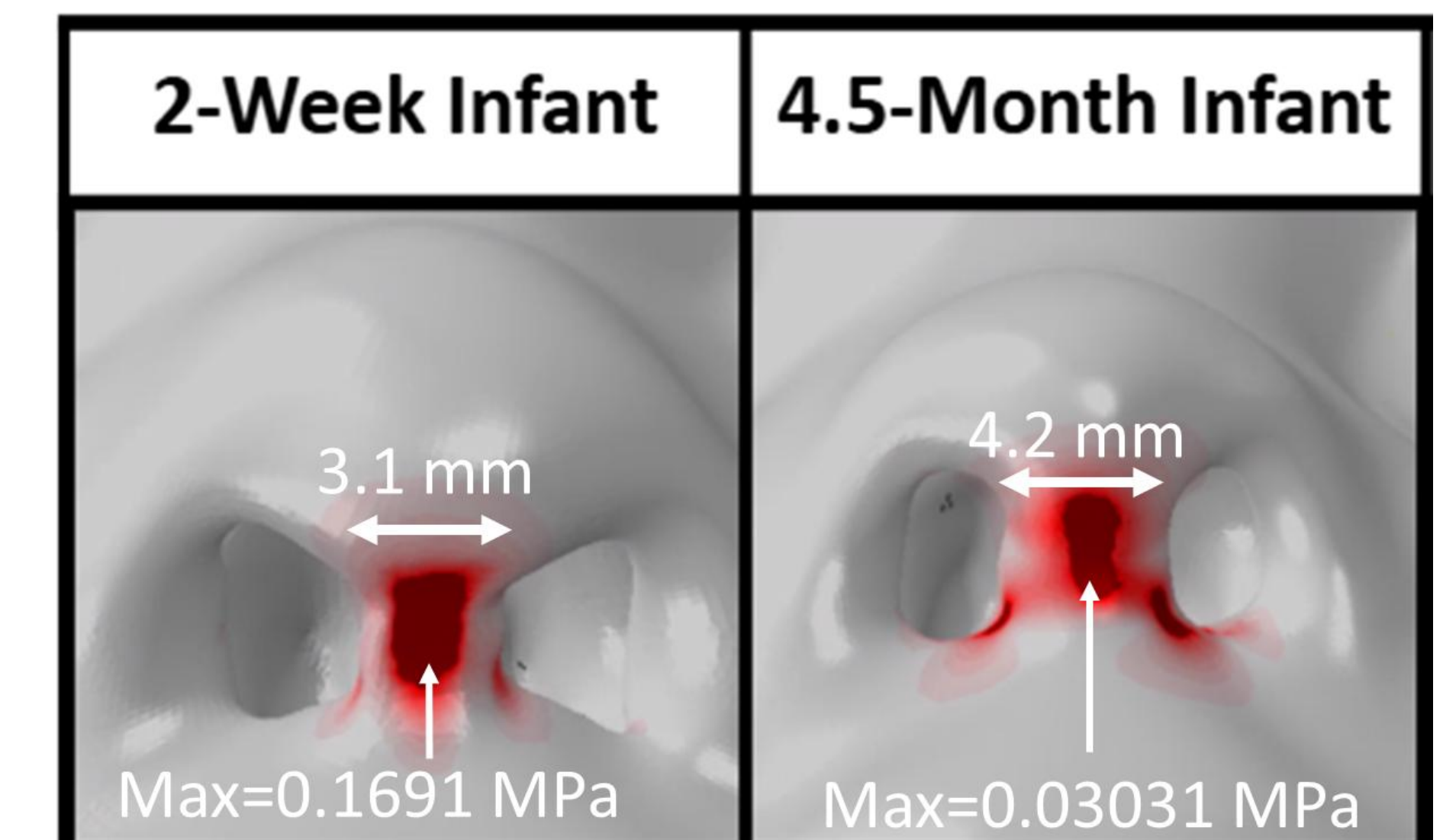
- Hyperelastic silicone was assigned to the prongs.
- Cartilage was modeled as a linear elastic material ($E = 0.44 \text{ MPa}$, $\nu = 0.32$).
- Infant skin was modeled as hyperelastic. The 2wk model was assigned softer skin, while the 4.5mo model was assigned stiffer skin.

Post-simulation visualization. After the simulation is completed, the nasal prongs are inserted into the anatomy and deform under contact. Red regions indicate areas of higher mechanical stress in both the prongs and surrounding nasal tissue.

Experimental Results

Both models were compared at a reaction force of 0.05 N. The 2-week infant experienced higher stress than the 4.5-month infant, with peak stress consistently localized at the columella, indicating this region as the most vulnerable to prong-induced injury.

Representative von Mises stress distributions at a reaction force of 0.05 N for the 2-week and 4.5-month infant models. Warmer colors (red) indicate higher tissue loading.



Maximum stress versus reaction force for the 2-week and 4.5-month infant models, with higher stress observed in the 2-week model.

Conclusions

Peak tissue stress consistently localized to the columella, identifying it as the most vulnerable region to prong-related injury. Overall, this work provides a mechanistic explanation for columella-focused nasal injury during CPAP therapy and highlights computational modeling as a safe, ethical tool for studying device-tissue interactions in neonates.

Future Directions:

- Expand simulations across a wider range of infant anatomies.
- Apply modeling insights to improve prong sizing and CPAP interface design.

References

- Maruccia, M., Fanelli, B., Ruggieri, M., & Onesti, M. G. (2014). Necrosis of the columella associated with nasal continuous positive airway pressure in a preterm infant. *International wound journal*, 11(3), 335–336.
- Fu, Y., Li, X., Yu, Y., Li, R., & Shi, T. (2024). Summary of the best evidence for the prevention of nasal injury in preterm infants with nasal noninvasive ventilation. *Translational pediatrics*, 13(2), 224–235. 23-465.