Investigating Prong-Induced Nasal Septum Injury in Preterm Infants Using Novel 3D Modeling and Simulation

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INTRODUCTION

Why does continuous positive airway pressure (CPAP) prong cause nasal septum injuries only in preterm infants?

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.

Hypothesis: Poorly fitted prong design may exert excessive pressure on the columella. Preterm infants have narrower, softer nasal canals than full-term infants, making them more prone to tissue pinching and necrosis.

Objective: Due to the lack of suitable laboratory, animal or human models for testing, a 3D model of CPAP nasal prong and simulation has been used to examine the impact of CPAP nasal prongs on the nasal passage of infants, pinpoint the source of this issue, and assist the design of new prongs.

Image of facial view of a preterm infant shows nasal injury due to CPAP prong

MATERIALS AND METHODS

Neonate scans were obtained from the Neuroimaging Tools and Resources Collaboratory

3D Model Reconstruction:
- MRI scans of neonates were processed in 3D Slicer to generate a detailed 3D model of an infant's head. The nasal passageways were preserved, while the rest of the head was hollowed out.

SolidWorks Design:
- Replica models of various nasal prongs were created using SolidWorks.

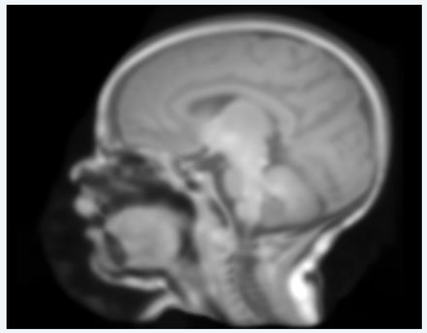
Autodesk Fusion:
- The mesh of the neonate model was simplified and converted into a STEP file

Simulation Setup in Abaqus:
- The 3D head model and nasal prong model were imported into the Abaqus software.
- Nasal prongs were inserted into the nasal passageways of the 3D head model.
- Poisson's ratio, Young's modulus, and density of both the prongs and infant skin were specified.

3D model of nasal structure

Process of 3D Model Creation:
- The MRI scan was imported into 3D Slicer, and the threshold tool under the segmentation tab was used to isolate relevant anatomical structures.
- The paintbrush threshold tool was applied to refine the nasal structures while ensuring the airways remained hollow for accurate modeling.
- The scissor tool was used to remove irrelevant structures and reduce the head model size for focused analysis.
- 3D model was saved as an STL file and converted to a STEP file using Autodesk Fusion. STEP file was then imported into Abaqus for simulation.

Sample Image (shown below) : MRI scan of 2-week-old neonate.

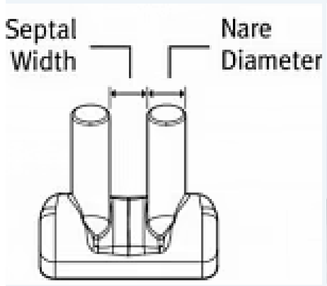


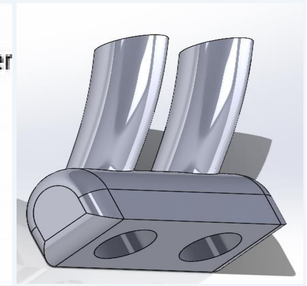
3D model of CPAP prongs

CPAP prong design: CPAP prongs were designed on SolidWorks based on the Fisher & Paykel Nasal CPAP Prongs

Dimensions: Designed based on neonatal anatomy, with a 3mm nare diameter and 2mm septal width to ensure proper fit and realistic interaction with nasal tissues.

Creation of 3D prong model:
- Created circular sketches based on neonatal nare diameter.
- Used the Loft tool to form the tapered structure.
- Applied the Shell tool to allow airflow.
- Extruded a base to connect the prongs.
- Used the Fillet tool to remove sharp corners.
- Saved as a SolidWorks file and imported directly into Abaqus.





Simulation of Nasal Prong-Induced Nasal Septum injury

Abaqus was used for contact simulation
- The nasal prongs and neonatal model were imported into Abaqus.
- The neonate model had a mesh element size set to 3. The prongs had mesh element size set to 1.
- Mesh sizes were determined through trial and error to ensure a coarse but stable simulation.

Material: Prongs were assigned silicone properties. Neonate model was assigned a density of 1200 kg/m³, Poisson's ratio of 0.42, and a Young's modulus of 16.7 MPa.

Assembly: The nasal prongs were positioned within the neonatal nasal model.

Interaction Definition: Explicit analysis was used to simulate contact between the prongs and nasal tissues.

Boundary Conditions: The back of the prongs and the back of the neonate's head were fixed for stability.

Run Analysis: The job was submitted for simulation, and results were analyzed.

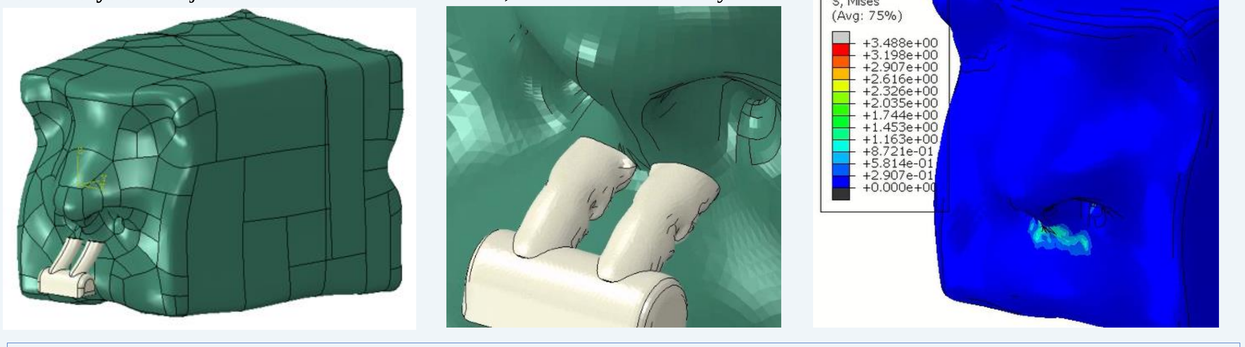


Image of the updated solid 3D head model of a neonate, and replica of nasal prongs designed in SolidWorks.

Significant Findings:
- Finite element analysis in Abaqus revealed significant stress distribution and deformation in preterm infant nasal anatomy due to CPAP nasal prongs.
- The von Mises stress map highlights concentrated stress at the columella, showing a potential risk for pressure-induced injury.
- The deformation analysis shows the nasal prongs being altered as they are inserted into the nasal passage, demonstrating how contact pressure affects both the prongs and surrounding tissue.
- These results emphasize the role of anatomical differences in preterm infants and the need for improved prong design to minimize injury risk.
- The results suggest that a new CPAP prong design for preterm infants may be developed to significantly reduce nasal injuries.

CONCLUSION

This study demonstrates the impact of CPAP nasal prongs on preterm infant anatomy, highlighting regions of high stress concentration, particularly around the columella. The deformation results further indicate that nasal prongs experience structural changes upon insertion, reinforcing the need to consider both external and internal anatomical factors in design evaluations.

For future work, the initial positioning and angling of the prongs should be refined to better replicate clinical practice. The material properties of both the nasal prongs and infant skin should be adjusted to include viscoelastic characteristics for a more accurate representation of real-life interactions. 3D scans of younger neonates' nasal structure may also be incorporated, along with simulations across different gestational ages, to better capture anatomical variations. Lastly, making the model translucent after simulation would allow for better visualization of the prongs' effects on the internal nasal passageways, providing further insights into potential areas of injury.

REFERENCES

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