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C2B2: A Phenomenological Model for Cavitation

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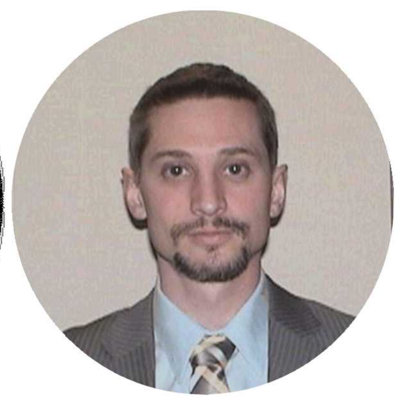

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Background

- The Sandia Injury Biomechanics Laboratory (SIBL) contributes to the understanding of the potential of injury from **intracranial cavitation** in the human head, secondary to blast exposure.

- **Intracranial cavitation** is believed to be a multi-scale problem, wherein the bulk response is on the order of centimeters, but the bubbles are believed to be on the order of micrometers or nanometers.

- The simulation of cavitation can lead to **mesh-dependent results**, which is an impediment.

OBJECTIVE

- Create a phenomenological model for cavitation that avoids mesh-dependence, is easy-to-use, and replicates experimental results.
- Apply the model to Sandia's human digital twin to predict intracranial cavitation, secondary to blast exposure, for an unhelmeted and helmeted case.
- Quantify the injury risk to the brain by volume and anatomical location.

TECHNICAL APPROACH

- We leveraged the PANTHER development work
  - high-fidelity geometric model of the human head and neck, consisting of 5.7M hexahedral finite elements at a nominal resolution of 1-mm3,
  - high-fidelity material models for the human tissues and helmet constituents.

- We calibrated our cavitation model based on results from an experimental drop test and an experimental blast.

- We then applied our calibrated model to a numerical blast exposure of our human digital twin, comparing unhelmeted and helmeted cavitation outcomes.

ACCOMPLISHMENTS

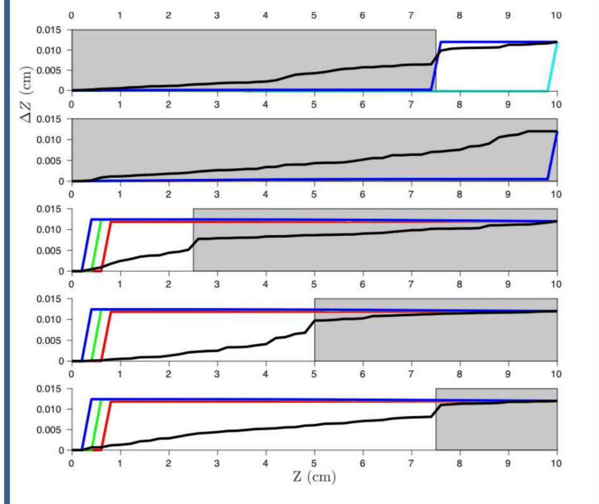
- Demonstration of shortcomings of existing approaches, showing mesh dependency, and motivation for an alternative approach.

- Development of a phenomenological model for cavitation based on high relative negative pressure and high relative negative time derivatives.

- Verification of the phenomenological model based on drop test and blast experiments.

- Application of model to human digital twin to quantify brain exposure to cavitation by volume and anatomical region.

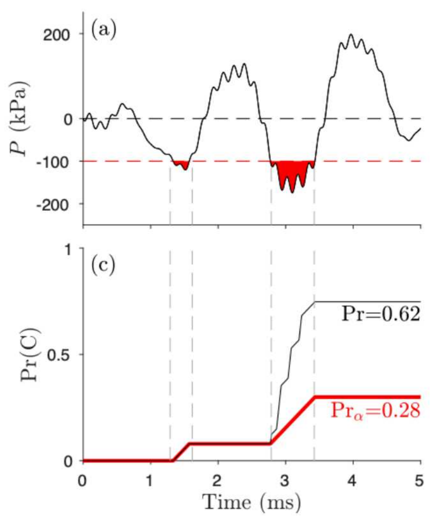
Success Stories



Mesh Dependence

Existing models for cavitation have inherent mesh dependence, making their results challenging to interpret: Did the physics cause the cavitation, or did the mesh cause the cavitation?

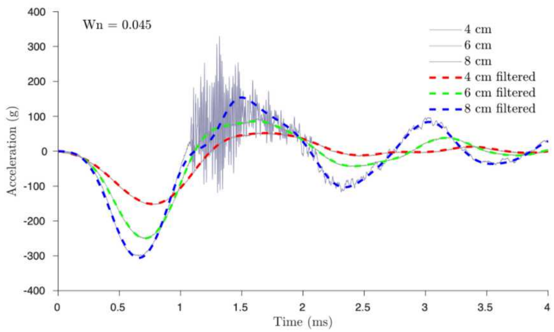
We demonstrated a one-dimensional example problem, composed of gray matter and white matter, at varying proportions. The results showed mesh dependence, with no reliable way to ascertain where cavitation likely occurred.



Phenomenological Model

We formulated a new and simple phenom-enological model for cavitation, based on the the observations that both high relative negative pressure and high relative negative time derivatives of pressure are required for cavitation onset.

We posited an additive decomposition of these two effects, allowing for high negative pressures to be calibrated independent from high negative time derivatives.

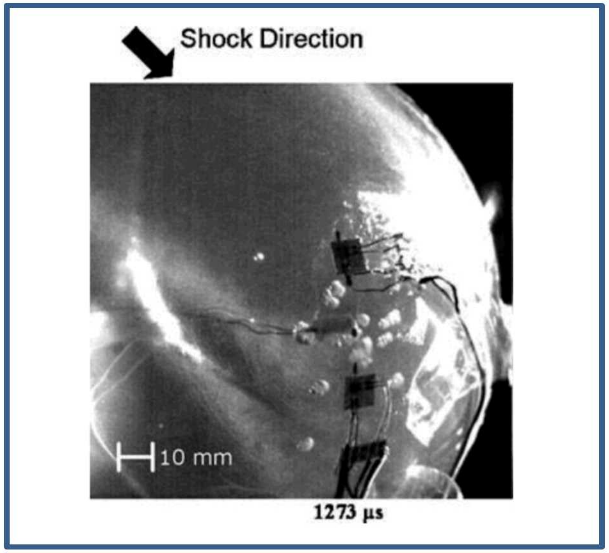


Kang Experiments

Kang and coworkers demonstrated the necessary drop height threshold required to produced acceleration-induced cavitation in a cuvette.

We reproduced the drop table experiments. We found that cavitation likely occurred for the 8-cm drop height case, but not for the 4- and 6-cm drop height cases, the same results as in Kang’s experiments.

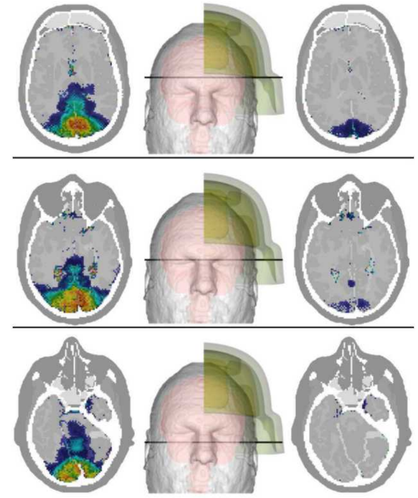
Success Stories



Goeller Experiments

Goeller and coworkers demonstrated coup and contrecoup cavitation in an ellipsoid test object, scaled to dimensions of the human head, exposed to blast overpressure.

We reproduced these blast experiments. We found high probabilities of cavitation at the coup and contrecoup locations of the head, similar in magnitude, timing, and location as in the Goeller experiments.

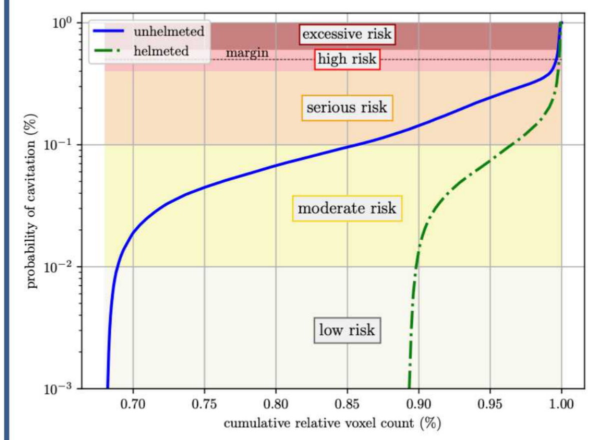


Intracranial Cavitation Prediction

We applied our calibrated phenomenological model of cavitation to a numerical blast exposure of our human digital twin, comparing unhelmeted and helmeted scenarios.

In the image above, axial images on the left are the unhelmeted case, axial images on the right are the helmeted case. The horizontal black line in the center images indicate the elevation of the axial slice.

Results show cavitation probabilities for the unhelmeted case exceed the helmeted case.



Injury Risk

In addition to quantify where cavitation occurred in the brain, we quantified the probability of cavitation based as a function of cumulative brain volume.

We segmented the cavitation probabilities into more-likely-than-not and less-like-than-not categories. Thereafter, we proposed refined segmentation to develop categories of low, moderate, serious, high, and excessive risk.

The helmet helped to reduce risk but did not eliminate all risk.

ISSUES

- No issues.

CONCLUSIONS

- The Navy and Traumatic Brain Injury Community now have a phenomenological model for cavitation that
  - avoids mesh dependency,
  - is simple and easy-to-use,
  - reproduces two genres of experimentally produced cavitation: acceleration and blast
  - can be used to evaluate the relative merits of personal protective equipment (PPE) designs.

PATH FORWARD

Activities Schedule	FY17	FY18	FY19	FY20	FY21	FY22	FY23
Objective 1							
Overpressure and standoff parameterization					◆ ●		
Geometry enhancements						● — ▲	

◆ Start ◆ Tests, Demos, & Key Events ● Milestone ▲ S&T Delivery

PUBLICATIONS, PATENTS, PRESENTATIONS, & AWARDS

- Work in progress: SAND report.

COOPERATIVE DEVELOPMENT

- The current work builds on previous developments:

  - Head/Neck model supported by James Mackiewicz ONR Code 30.

  - The PANTHER development work
    - high-fidelity geometric model of the human head and neck, consisting of 5.7M hexahedral finite elements at a nominal resolution of 1-mm^3,
    - high-fidelity material models for the human tissues and helmet constituents.

COLLABORATION & DISCUSSION

- There is potential for further collaboration with Kang, *et al.*, to continue verification and validation of the cavitation model.