Appendix A – Mesh Sensitivity Analysis

1.0 Background

The volumetric and deviatoric response of a solid impacted by a shock wave has been shown to be highly sensitive to both air and solid mesh sizes during blast simulation [2]. In this study, the head model was discretized at three different levels of mesh density (4mm, 2mm, and 1mm) to assess head mesh sensitivity. Hexahedral elements were used as tetrahedral elements are not suited for modeling the response of nearly incompressible materials, particularly in blast applications [2].

2.0 Mesh Sensitivity Methods

Three levels of air mesh density (4mm, 2mm, and 1mm) were used to determine the sensitivity of the head model response to the blast model (Table 1). Based on the average human head having a volume of 4000 cm$^3$ [3], the estimated number of elements for the entire head with these levels of mesh resolution would be 87000, 611000, and 4650000 respectively.

Table 1: Summary of the mesh characteristics for the three levels of head mesh refinement

<table>
<thead>
<tr>
<th>Nominal Mesh Level</th>
<th>Number of Elements/Nodes</th>
<th>Characteristic Length (Mean +/- S.D.)</th>
<th>Jacobian Ratio (Mean +/- S.D.)</th>
<th>Portion of Mesh with Jacobian Ratio &gt; 0.7</th>
<th>Time Step Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>2,172/4,468</td>
<td>2.67 mm</td>
<td>0.75</td>
<td>68%</td>
<td>202 ns</td>
</tr>
<tr>
<td>2 mm</td>
<td>7,650/15,550</td>
<td>1.53 mm</td>
<td>0.83</td>
<td>83%</td>
<td>195 ns</td>
</tr>
<tr>
<td>1 mm</td>
<td>29,088/58,681</td>
<td>0.82 mm</td>
<td>0.89</td>
<td>92%</td>
<td>82 ns</td>
</tr>
</tbody>
</table>

The applied blast conditions were calibrated for each air mesh size to negate the effect of wave dispersion in the coarser air meshes, making the incident blast wave measured at the front of the head consistent for all mesh sizes. The air meshes contributed the most significant computational cost of the simulation, with the three mesh levels consisting of approximately 77,000, 307,000, and 1,230,000 elements.

Nine combinations of head and air mesh were simulated using blast with a peak incident overpressure of 500 kPa and duration of 4 ms (approximately a 155-mm artillery-round at 3 m standoff), and simulations were run for 5 ms. Analysis between different head meshes was achieved by interpolating the nodal response of each mesh onto a uniformly-spaced post-processing grid with a resolution of 0.1 mm. Distribution plots for peak pressure, von Mises stress, and shear strain were generated for each case. Distribution plot deviation was based on averaging the absolute difference between cases at each point in the post-processing grid. The highest-resolution head mesh coupled with the highest-resolution air mesh was used as the baseline case. The non-cavitating CSF model was used in the mesh sensitivity analysis. Paired t-tests were used to determine significance between mesh distributions.
3.0 Mesh Sensitivity Results

The results of the mesh sensitivity analysis indicate that the pressure and deformation responses in the brain were sensitive to size of both the air mesh and the head mesh size. Peak pressure values attenuated quicker for all coarser meshes, but were most noticeable with coarser air meshes (Figure 1). Generally, simulations with a finer air mesh resulted in higher peak pressures throughout the brain when compared to results using a coarser air mesh (Figure 2A). Deviation of peak pressure from the baseline case was found to increase significantly (p < 0.001, α = 0.05) with air mesh size (Figure 2B), and increase slightly with head mesh size, although not statistically significant (p = 0.085).

Figure 1: Distributions of peak pressure (top) and von Mises stress (bottom) in the brain for the finest meshes (left) and the coarsest meshes for the 500 kPa / 4 ms blast condition

The pattern of the peak von Mises stress distribution in the brain tissue was not consistent for all mesh cases. In the finest head meshes, the highest peak stress values were concentrated
near the interface of the brain tissue and the CSF, and in the anterior portion of the white matter (Figure 1). As the head mesh increased in size, the highest stresses were found deeper in the brain tissue, mainly in the white matter and around the grey-white matter interface (Figure 1). Air mesh size did not appear to have any influence on the peak von Mises stress distribution. Generally, simulations with finer head mesh resulted in lower peak stresses throughout the brain when compared to coarser head mesh (Figure 3A). Deviation from the baseline case was found to increase significantly ($p < 0.001$, $\alpha = 0.05$) with head mesh size (Figure 3B), and was independent of air mesh size ($p = 0.90$).

![Figure 2](image1.png)

**Figure 2:** A) Cumulative distribution of peak pressure by mesh size, and B) the average peak pressure deviation from the finest mesh case for the 500 kPa / 4 ms blast condition

![Figure 3](image2.png)

**Figure 3:** A) Cumulative distribution of peak von Mises stress by mesh size, and B) the average von Mises stress deviation from the finest mesh case

Frequency spectrum analysis of the brain pressure time-history traces highlighted differences in pressure wave frequency only for very high frequencies (greater than 10 kHz) (Figure 4A). Because of the short duration of the simulations used in the mesh sensitivity study (5 ms), it was difficult to resolve the deviatoric frequency spectrum for lower frequencies (less...
than 2 kHz) (Figure 4B). From the shear strain time-history traces, we estimate the dominate frequency to be approximately 300 Hz corresponding to the deformation of the skull model, and this was consistent for all head mesh sizes.

Based on this analysis, it was determined that the 1 mm head mesh and the 2 mm air mesh would be used for the remaining simulations in this study. Average deviations of this mesh combination to the baseline case was 6% in peak pressure and 3% in peak stress (relative to the maximum recorded pressure and stress respectively), while requiring approximately 25% of the simulation time.
Appendix B – Artificial Bulk Viscosity Sensitivity Analysis

1.0 Background

Shocks are treated using an artificial bulk viscosity approach to eliminate oscillations from discontinuities by smearing the shock into rapidly varying, but continuous transition region over three to five elements [4]. In LS-Dyna, the artificial bulk viscosity added to the pressure term in both the momentum and energy equations of each element is:

\[ q = \rho l \left( Q_1 l \dot{e}_{kk}^2 - Q_2 a \dot{e}_{kk} \right) \text{ if } \dot{e}_{kk} < 0 \]

\[ q = 0 \text{ if } \dot{e}_{kk} > 0 \]

Equation 1

where \( Q_1 \) and \( Q_2 \) are dimensionless coefficients, \( \rho \) is the material density, \( l \) is the characteristic length, and \( a \) is the speed of sound of the element.

With this method, the solution is unperturbed away from the shock, the shock thickness is independent of shock strength and of the same order as the mesh spacing, and the Rankine-Hugoniot jump conditions are satisfied [1]. The bulk viscosity coefficients can be calibrated to assure an optimal balance between the attenuation of spurious oscillations and the smearing of the shock, but this calibration is problem specific and depends on mesh size, materials, and loading conditions. By default LS-Dyna sets the coefficients \( Q_1 \) and \( Q_2 \) to be 1.5 and 0.06 respectively, and these coefficients provide a good balance of attenuation and shock propagation for most simulation solutions.

2.0 Artificial Bulk Viscosity Sensitivity Methods

In lieu of calibrating the bulk viscosity coefficients for every material in the model for the wide range of loading conditions encountered in our simulations, we chose to assess the sensitivity of the entire model solution to variations in the artificial bulk viscosity.

Five bulk viscosity conditions (Table 1) were simulated using the non-cavitating head model with a peak incident overpressure of 500 kPa and duration of 4 ms (approximately a 155-mm artillery-round at 3 m standoff). Distribution plots for peak pressure, and maximum shear strain were generated for each case. Distribution plot deviation was based on averaging the relative error between cases at each point in the post-processing grid. The default bulk viscosity scheme was used as the baseline case.

Table 1: Conditions for bulk viscosity sensitivity analysis

<table>
<thead>
<tr>
<th>Bulk Viscosity Condition</th>
<th>Q1</th>
<th>Q2</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0.25</td>
<td>0.375</td>
<td>0.015</td>
</tr>
<tr>
<td>x0.5</td>
<td>0.75</td>
<td>0.03</td>
</tr>
<tr>
<td>Default</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>x2</td>
<td>3</td>
<td>0.12</td>
</tr>
<tr>
<td>x4</td>
<td>6</td>
<td>0.24</td>
</tr>
</tbody>
</table>
3.0  Artificial Bulk Viscosity Sensitivity Results

The results of the mesh sensitivity analysis indicate that there is little sensitivity in the pressure response and almost no sensitivity in the strain response of the brain (Figure 1A). The pressure response of the brain model showed less than 2% variation for 100% variation in bulk viscosity, and less than 1% variation in strain response over the same interval. Increasing the bulk viscosity tended to decrease the magnitude of the peak pressure distribution throughout the entire brain, but had no effect on the peak strain distribution (Figure 2). The bulk viscosity scheme only affected the magnitude of the initial pressure spike in the brain response, and post-shock response of the brain did not change with bulk viscosity scheme (Figure 3).

Figure 1: (A) Average error of the distribution between peak pressure and peak strain of the range of bulk viscosity schemes relative to the default scheme. (B) Comparing the overpressure traces in the air immediately adjacent to the forehead.

Comparing the pressure traces of the air material immediately adjacent to the forehead at the location where the blast wave initially interacts with the head (Figure 1B) shows that increasing the bulk viscosity scheme will decrease the arrival time of the blast (i.e. increases shock wave speed), but decreases peak pressure. Interestingly, decreasing the coefficients below the default values introduces spurious oscillations in the pressure time-history, indicating that the default coefficients are a good balance for modeling air blasts at this level of pressure. Based on this analysis, it was determined that the default bulk viscosity scheme would be used for the simulations in this study.
Figure 2: Comparing the peak pressure (top) and peak strain (bottom) distribution throughout the brain for the range of artificial bulk modulus schemes.

Figure 3: Comparing pressure (A) and maximum shear strain (B) time-history response in the frontal portion of the brain for the range of artificial bulk modulus schemes.
References


