Estimated Probability of Traumatic Chest Injury During an International Space Station Mission

Beth Lewandowski, PhD, John Brooker, Aaron Weaver, PhD and Jerry Myers, PhD
NASA Glenn Research Center, Cleveland, OH

Eric Milo
Florida State University, Tallahassee, FL

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Integrated Medical Model (IMM)

- Probability and consequences of medical risks
- Integrate best evidence in a quantifiable assessment of risk
- Identify medical resources necessary to optimize health and mission success

Likelihood of occurrence, probable severity of occurrence, and optimization of treatment and resources.
Probabilistic modeling of rare medical events

• Event has not happened during a space mission
  – No incidence rate
  – Many unknowns

• Construct a computational model
  – Define the initiating event scenario and resulting injury
  – Determine available data and develop parameter distributions
  – Mathematically model the physiological response
  – Perform Verification and Validation
  – Relate the physiological response to probability of injury
  – Determine probability of occurrence

• Use probabilistic risk assessment methodology
  – Monte Carlo simulations
  – Estimate the most likely probability and confidence intervals
Initiating Event Scenario and Injury Definition

- An astronaut translating with equipment too large to see around accidently impacting another astronaut in the chest with attention focused elsewhere.

- Traumatic chest injury defined as an injury with an Abbreviated Injury Scale (AIS) score of 3 or higher.

AIS definitions for skeletal and soft tissue injuries of the thorax:

<table>
<thead>
<tr>
<th>AIS</th>
<th>Injury Severity</th>
<th>Skeletal Injury</th>
<th>Soft Tissue Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minor</td>
<td>1 rib fracture</td>
<td>Contusion of bronchus</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>2-3 rib fractures</td>
<td>Partial thickness bronchus tear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sternum fracture</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Serious</td>
<td>4 or more rib fracture on one side</td>
<td>Lung contusion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-3 rib fractures with</td>
<td>Minor heart contusion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hemo/pneumothorax</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Flail chest</td>
<td>Bilateral lung laceration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 or more rib fractures on each side</td>
<td>Minor aortic laceration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 or more rib fractures with</td>
<td>Major heart contusion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hemo/pneumothorax</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Critical</td>
<td>Bilateral flail chest</td>
<td>Major aortic laceration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lung laceration with tension pneumothorax</td>
</tr>
<tr>
<td>6</td>
<td>Maximum</td>
<td>Bilateral aortic laceration with</td>
<td>Aortic laceration with haemorrhage not</td>
</tr>
<tr>
<td></td>
<td></td>
<td>haemorrhage not confined to mediastinum</td>
<td>confined to mediastinum</td>
</tr>
</tbody>
</table>

Parameter distributions

- **Astronaut parameters**
  - Astronaut mass
  - Chest depth
  - Translational velocity

- **Mission parameters**
  - ISS equipment masses

- **Research data**
  - Thorax stiffness and damping characteristics
  - Experimental impact response – normalized compression
  - Injury severity resulting from experimental impacts

- **Spaceflight data**
  - Impact rate
Biomechanical Model of the Chest

Equations of motion:
\[ m_1 \ddot{y}_1 + k_{12} y_1 - k_{12} y_2 = 0 \]
\[ m_2 \ddot{y}_2 + c_{23} \dot{y}_2 - c_{23} \dot{y}_3 + (k_{12} + k_{23} + k_{ve23}) y_2 - k_{12} y_1 - k_{23} y_3 - k_{ve23} y_4 = 0 \]
\[ m_3 \ddot{y}_3 + (c_{23} + c_{ve23}) \dot{y}_3 - c_{23} \dot{y}_2 - c_{ve23} \dot{y}_4 + k_{23} y_3 - k_{ve23} y_2 = 0 \]
\[ c_{ve23} \dot{y}_4 - c_{ve23} \dot{y}_3 + k_{ve23} y_4 - k_{ve23} y_2 = 0 \]

Initial conditions:
\[ y_1(0) = y_2(0) = y_3(0) = y_4(0) = 0 \]
\[ \dot{y}_1(0) = v_o \]
\[ \dot{y}_2(0) = \dot{y}_3(0) = 0 \]

Output:
\[ d_{ske1} = y_2 - y_3 \]
\[ NC = \frac{d_{ske1}}{CD} \]

Parameter Name | Parameter Symbol |
--- | --- |
Mass of impactor | \( m_1 \) |
Mass of sternum | \( m_2 \) |
Mass of thorax | \( m_3 \) |
Interface between impactor and sternum | \( k_{12} \) |
Rib cage elasticity | \( k_{23} \) |
Damping effects of air and blood | \( c_{23} \) |
Muscle tissue elasticity | \( k_{ve23} \) |
Muscle tissue viscosity | \( c_{ve23} \) |
Displacement of \( m_1 \) | \( y_1 \) |
Velocity of \( m_1 \) | \( \dot{y}_1 \) |
Acceleration of \( m_1 \) | \( \ddot{y}_1 \) |
Displacement of \( m_2 \) | \( y_2 \) |
Velocity of \( m_2 \) | \( \dot{y}_2 \) |
Acceleration of \( m_2 \) | \( \ddot{y}_2 \) |
Displacement of \( m_3 \) | \( y_3 \) |
Velocity of \( m_3 \) | \( \dot{y}_3 \) |
Acceleration of \( m_3 \) | \( \ddot{y}_3 \) |
Displacement between \( k_{ve23} \) and \( c_{ve23} \) | \( y_4 \) |
Velocity between \( k_{ve23} \) and \( c_{ve23} \) | \( \dot{y}_4 \) |
Initial velocity | \( v_o \) |
Chest deflection | \( d_{ske1} \) |
Normalized compression | \( NC \) |
Chest depth | \( CD \) |

Biomechanical Model Verification and Validation

- Model output fits within data corridors:
  - Data corridor upon which the model was built (Verification)
  - Data corridor from data set not used to build model (Validation)


Probability of Injury

- Translation between normalized compression and injury probability
  - Normalized compression and AIS score from several impact studies were used
  - A 0 was given to an AIS of 2 or lower, a 1 was given to an AIS of 3 or higher (Data points in graph)
  - Matlab’s glmfit was used to find the logistic regression coefficients (A & B) for the probability equation, $A = -6.06 \pm 10\%$, $B = 19.75 \pm 10\%$
  - The probability equation is:

\[
P_{\text{Injury}}(NC) = \frac{1}{1 + e^{-(A+B*NC)}}
\]

Probability of Impact

- Ideally, we would use a rate of the number of times an astronaut accidently impacts a piece of equipment with his or her chest during a mission.
- However, this data does not exist.
- Instead, we know there have been 6 minor trunk injuries in 26.4 years of flight and 0 traumatic chest injuries.
- Since an impact must have occurred to cause the minor injuries, we use it as our impact rate.
- The impact rate ($\lambda$) is developed as an uniform distribution with $6/26.4$ impacts/person*year as the maximum value and $0/26.4$ impacts/person*year as the minimum value.
- The impact probability equation is:

$$P_{Impact}(\lambda) = 1 - e^{-\lambda}$$

Results

- Probability of impact and probability of injury are multiplied to obtain probability of traumatic chest injury
- 100,000 Monte Carlo simulation trials performed to obtain most likely probability of traumatic chest injury

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>5%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Injury Probability</td>
<td>$5.32 \times 10^{-4}$</td>
<td>$5.95 \times 10^{-4}$</td>
<td>$4.16 \times 10^{-5}$</td>
<td>$1.39 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Sensitivity Analysis

- Impactor velocity and rate of impact are the two most sensitive parameters in the model
- Better estimates of these values could reduce the uncertainty in the probability estimate

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>% Contribution to Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of the impactor, $v_0$</td>
<td>48.18</td>
</tr>
<tr>
<td>Rate of impact, $\lambda$</td>
<td>36.22</td>
</tr>
<tr>
<td>Probability coefficient, $A$</td>
<td>13.36</td>
</tr>
<tr>
<td>Mass of the impactor, $m_1$</td>
<td>1.89</td>
</tr>
<tr>
<td>Probability coefficient, $B$</td>
<td>0.279</td>
</tr>
<tr>
<td>Damping constant, $c_{23}$</td>
<td>0.031</td>
</tr>
<tr>
<td>Spring constant, $k_{23}$</td>
<td>0.024</td>
</tr>
<tr>
<td>Astronaut Mass, $AM$</td>
<td>0.0042</td>
</tr>
<tr>
<td>Sternum mass, $m_2$</td>
<td>0.0042</td>
</tr>
<tr>
<td>Thorax mass, $m_3$</td>
<td>0.0042</td>
</tr>
<tr>
<td>Chest depth, $CD$</td>
<td>0.0042</td>
</tr>
<tr>
<td>Damping constant, $c_{ve23}$</td>
<td>0.0001</td>
</tr>
<tr>
<td>Spring constant, $k_{12}$</td>
<td>0.000008</td>
</tr>
<tr>
<td>Spring constant, $k_{ve23}$</td>
<td>0.000007</td>
</tr>
</tbody>
</table>
Conclusions

- A computational model has been developed to predict the probability of traumatic chest injury on ISS

- The risk is uncertain because the medical event hasn’t happened, but the model bounds this uncertainty

- The estimated probability of traumatic chest injury is small, but the impact to the mission could be significant if it were to happen

- These results have been incorporated into the parent Integrated Medical Model and assessed relative to other potential medical events
Acknowledgements

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