ESTIMATED PROBABILITY OF CHEST INJURY DURING AN INTERNATIONAL SPACE STATION MISSION

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INTRODUCTION: The Integrated Medical Model (IMM) is a decision support tool that is useful to spaceflight mission planners and medical system designers when assessing risks and optimizing medical systems. The IMM project maintains a database of medical conditions that could occur during a spaceflight. The IMM project is in the process of assigning an incidence rate, the associated functional impairment, and a best and a worst case end state for each condition. The purpose of this work was to develop the IMM Chest Injury Module (CIM). The CIM calculates the incidence rate of chest injury per person-year of spaceflight on the International Space Station (ISS). The IMM project needs the incidence rate in the form of a probability density function, with the most likely incidence rate and the associated uncertainty determined. While the incidence rate for this medical event is low, the possible outcome (crew evacuation or loss of crew) is quite significant.

METHODS: A historical rate of in-flight chest injury is not available, since such an injury has not occurred to date. Therefore, a combination of deterministic and probabilistic modeling was used to estimate an incidence rate. The initiating event for this injury is an impact to the chest. A rate of chest impact, as the astronauts work and live in space, was used within Poisson's equation to estimate the probability of impact. The severity of an injury resulting from an impact is dependent on the mass and velocity of the impactor. The masses of ISS equipment that could become an impactor and astronaut translational velocities were identified and used as input to a deterministic, lumped, mass-spring-damper, biomechanical model of the chest. The biomechanical model was used to calculate a response to the impact. The impact response of interest was chest compression and was the output of the biomechanical model. Relationships between compression and three different levels of injury severity were developed and used in logistic equations to estimate the probability of injury severity. The probability of impact and the probability of injury severity were multiplied to determine the probability of chest injury per person-year of ISS spaceflight. The CIM parameters were characterized with distributions, so that the variability and uncertainty of each parameter was captured. Monte Carlo simulations were performed in order for the CIM output to be in the form of probability distributions.

RESULTS: Probability distributions were determined for three different levels of chest injury during one year on ISS and were characterized with lognormal distributions. The probability of an Abbreviated Injury Scale (AIS) 1 or greater chest injury during one year on ISS is a lognormal distribution with a mean of 1.2×10^{-2}, standard deviation of 6.0×10^{-3} and 5th and 95th percent values of 5.35×10^{-3} and 2.3×10^{-2}, respectively. The probability of an AIS 2 or greater chest injury during one year on ISS is a lognormal distribution with a mean of 3.9×10^{-3}, standard deviation of 2.2×10^{-3} and 5th and 95th percent values of 1.5×10^{-3} and 7.9×10^{-3}, respectively. The probability of an AIS 3 or greater chest injury during one year on ISS is a lognormal distribution with a mean of 8.9×10^{-4}, standard deviation of 5.8×10^{-4} and 5th and 95th percent values of 2.9×10^{-4} and 2.0×10^{-3}, respectively. The most sensitive parameters of the model for all of the injury cases were: velocity of the impactor; rate of occurrence of an impact; the intercept coefficient in the probability of injury equation; and the mass of the impactor. The order of the most sensitive to least sensitive varied between the different injury cases.

VERIFICATION AND VALIDATION (V&V): The V&V performed for the CIM followed the IMM V&V plan, which is based upon the requirements outlined in NASA STD 7009. V&V for the CIM included an assessment of the pedigree of the data sets used to build the CIM and the data sets used as input data. The documentation maintained for the CIM includes source code comments and a technical report. The software code and documentation is under Subversion configuration management. Verification and validation included comparison of the CIM biomechanical output to the expected output and to referent data. A sensitivity analysis was performed and the CIM report underwent subject matter expert review. The output of the CIM biomechanical thorax model matches the output obtained by the original authors of the biomechanical thorax model, which verifies that it was implemented correctly. Additionally, the output response of the CIM biomechanical thorax model falls within the response corridor derived from the results of another cadaver impact study.

CONCLUSION: The CIM was built so that the probability of chest injury during one year on ISS could be predicted. These results will be incorporated into the IMM Chest Injury Clinical Finding Form and used within the parent IMM model.

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

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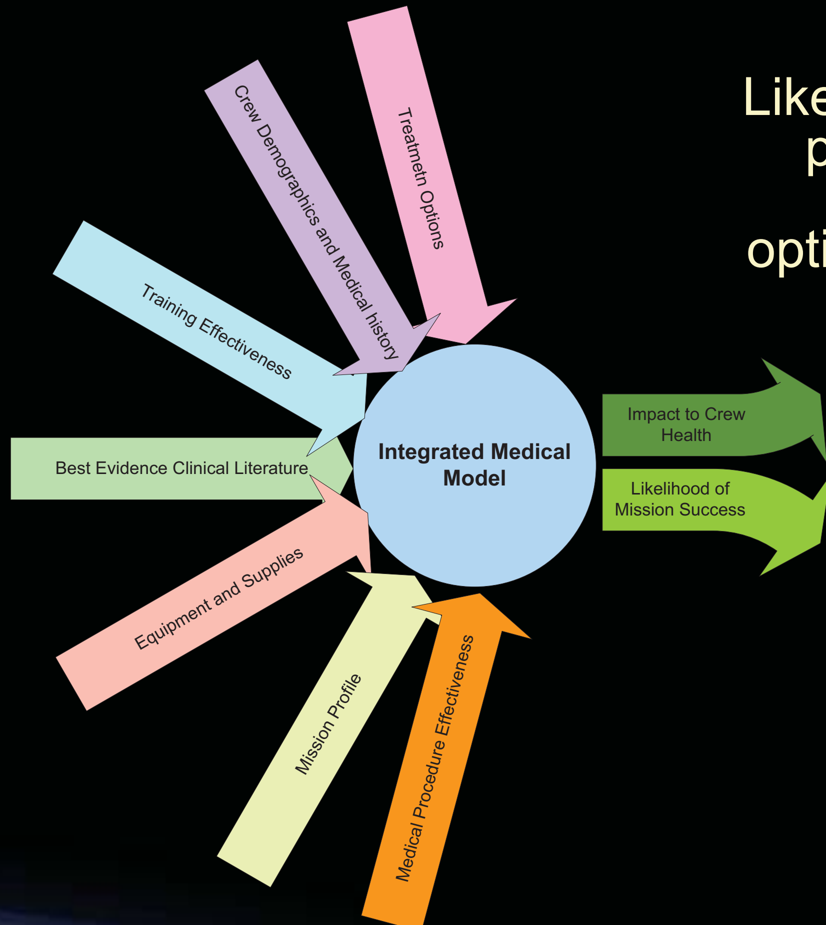
NASA Human Research Program Investigators' Workshop

Galveston, TX, February 12-14, 2013

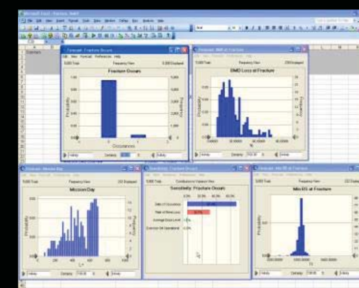
Integrated Medical Model (IMM)

Potential Medical Condition

Evaluate with IMM



Likelihood of occurrence, probable severity of occurrence, and optimization of treatment and resources.



- 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

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

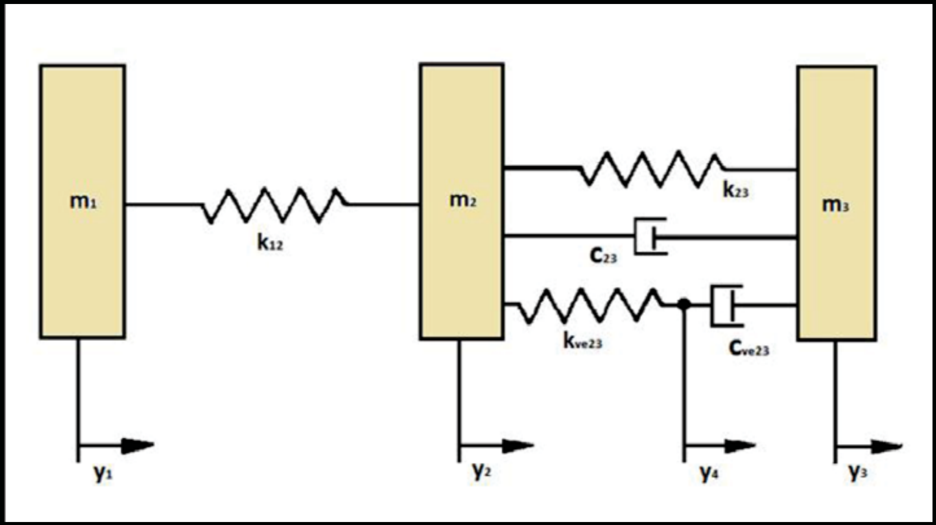
AIS	Injury Severity	Skeletal Injury	Soft Tissue Injury
1	Minor	1 rib fracture	Contusion of bronchus
2	Moderate	2-3 rib fractures Sternum fracture	Partial thickness bronchus tear
3	Serious	4 or more rib fracture on one side 2-3 rib fractures with hemo/pneumothorax	Lung contusion Minor heart contusion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

Berthet et al., "Review of the thorax injury criteria," APROSYS AP-SP51-0038-B, 2006.

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:

$$m_1\ddot{y}_1 + k_{12}y_1 - k_{12}y_2 = 0$$
$$m_2\ddot{y}_2 + C_{23}\dot{y}_2 - C_{23}\dot{y}_3 + (k_{12} + k_{23} + k_{ve23})y_2 - k_{12}y_1 - k_{23}y_3 - k_{ve23}y_4 = 0$$
$$m_3\ddot{y}_3 + (C_{23} + C_{ve23})\dot{y}_3 - C_{23}\dot{y}_2 - C_{ve23}\dot{y}_4 + k_{23}y_3 - k_{23}y_2 = 0$$
$$C_{ve23}\dot{y}_4 - C_{ve23}\dot{y}_3 + k_{ve23}y_4 - k_{ve23}y_2 = 0$$

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:

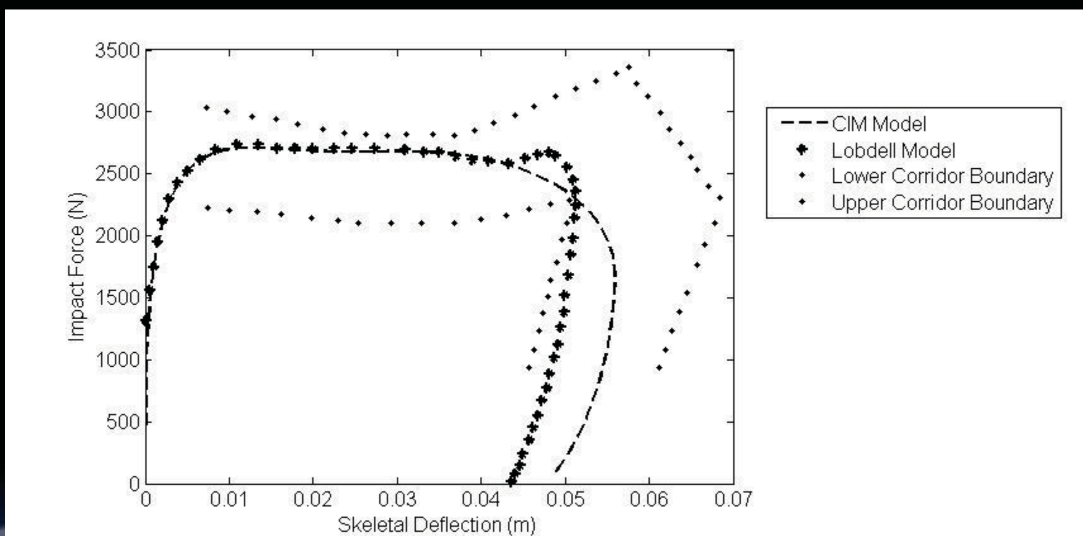
$$d_{skel} = y_2 - y_3$$
$$NC = \frac{d_{skel}}{CD}$$

Viano, "Biomechanics of chest and abdomen impact," *Aviat Space Environ Med*, 49(1) , 125-35, 1978.

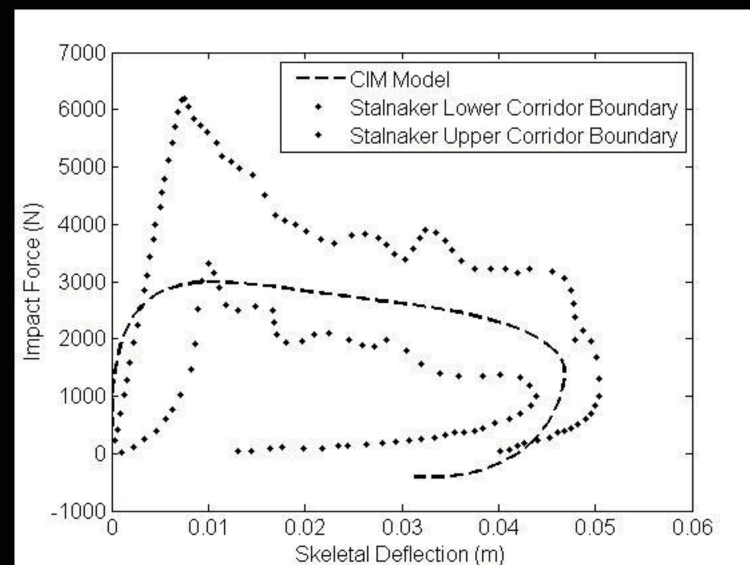
Parameter Name	Parameter Symbol
Mass of impactor	m_1
Mass of sternum	m_2
Mass of thorax	m_3
Interface between impactor and sternum	k_{12}
Rib cage elasticity	k_{23}
Damping effects of air and blood	c_{23}
Muscle tissue elasticity	k_{ve23}
Muscle tissue viscosity	c_{ve23}
Displacement of m_1	y_1
Velocity 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_{skel}
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)



C. Kroell, "Thoracic Response to Blunt Frontal Loading," in *The Human Thorax - Anatomy, Injury and Biomechanics* , Warrendale, PA: Society of Automotive Engineers, Inc., 1976.

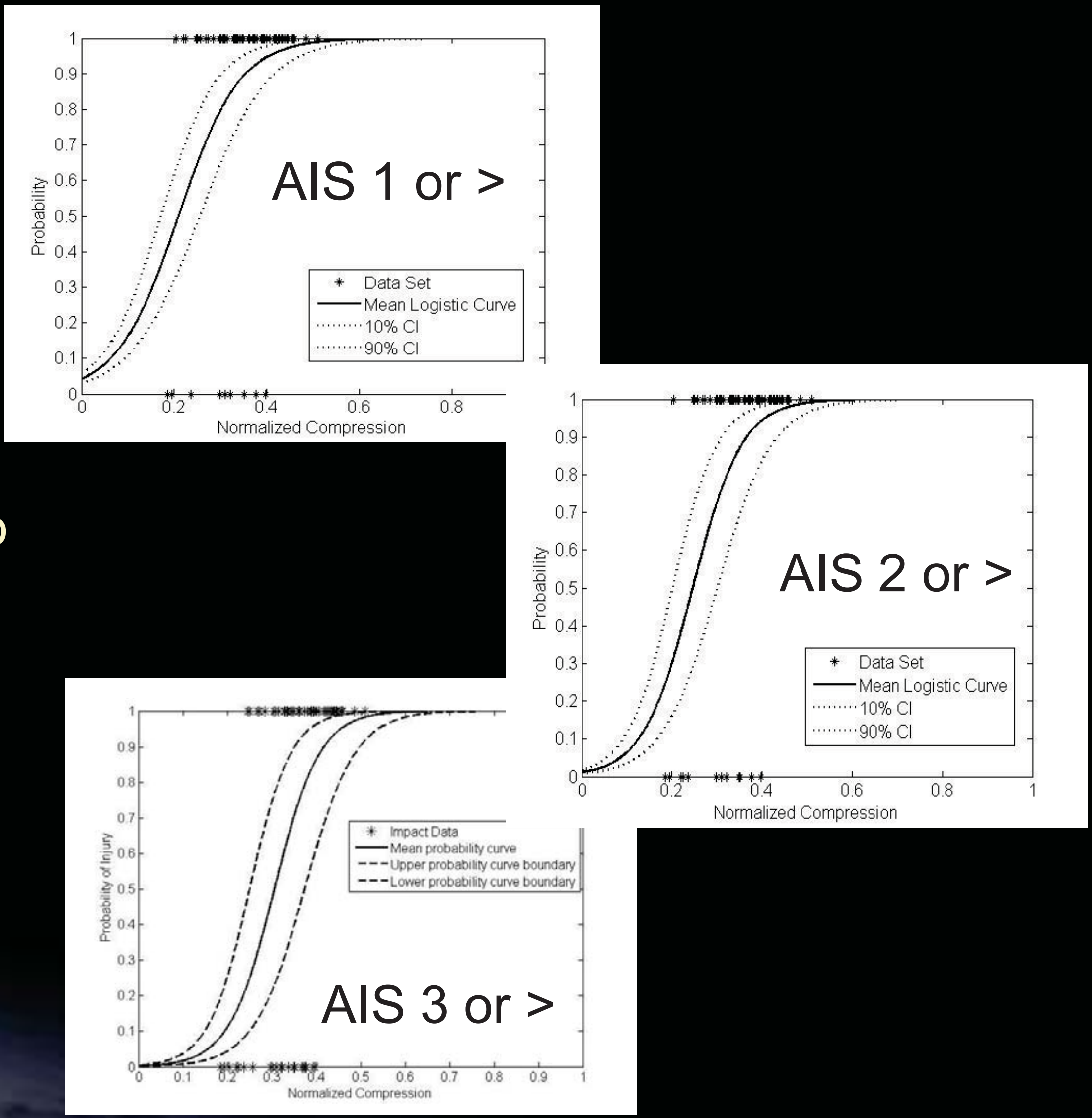


Stalnaker et al., "Human Torso Response to Blunt Trauma," in *Human Impact Response Measurement and Simulation*. New York, NY: Plenum Press, 1973.

Probability of Injury

- Translation between normalized compression and injury probability
  - Normalized compression and AIS scores were from impact studies
  - AIS score data was converted to binary data (Data points in graph)
  - Matlab's glmfit was used to find the logistic regression coefficients (A & B) for the probability equation:

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



Viano, "Biomechanics of chest and abdomen impact," *Aviat Space Environ Med*, 49(1) , 125-35, 1978.
Kroell et al.. "Impact tolerance and response of the human thorax II,", SAE Paper No. 741187, 1974.
Kroell, "Thoracic Response to Blunt Frontal Loading," in *The Human Thorax - Anatomy, Injury and Biomechanics* , Warrendale, PA: Society of Automotive Engineers, Inc., 1976.
Yoganandan et al., "Thoracic deformation and velocity analysis in frontal impact," *J. Biomech. Eng*, 117(1), 48-52, 1995.

Probability of Impact

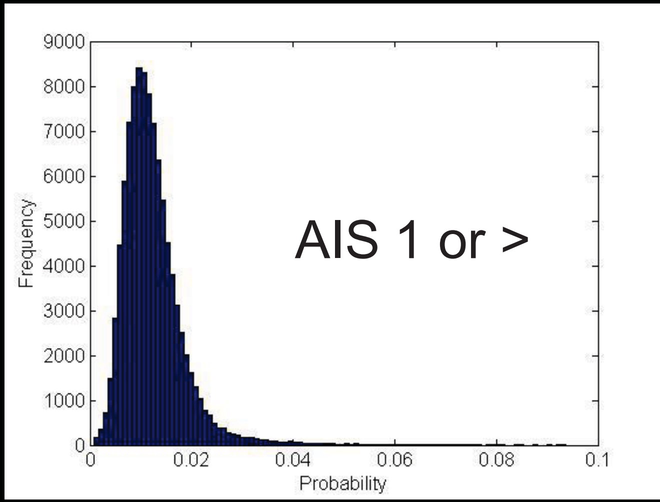
- Ideally, we would use a rate of the number of times an astronaut accidently impacts a piece of equipment with his or her chest during a mission
- However, this data does not exist
- Instead, we know there have been 6 minor trunk injuries in 26.4 years of flight and 0 traumatic chest injuries
- Since an impact must have occurred to cause the minor injuries, we use it as our impact rate
- 6 impacts in 26.43 person-years was the rate used to update an arbitrary non-informed prior uniform distribution (0 to 12) using Bayesian analysis to develop a distribution for the impact rate (λ)
- The impact probability equation is:

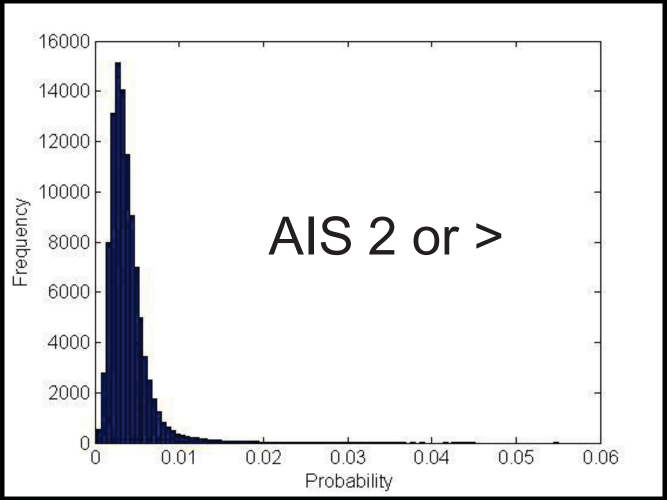
$$P_{Impact}(\lambda) = 1 - e^{-\lambda}$$

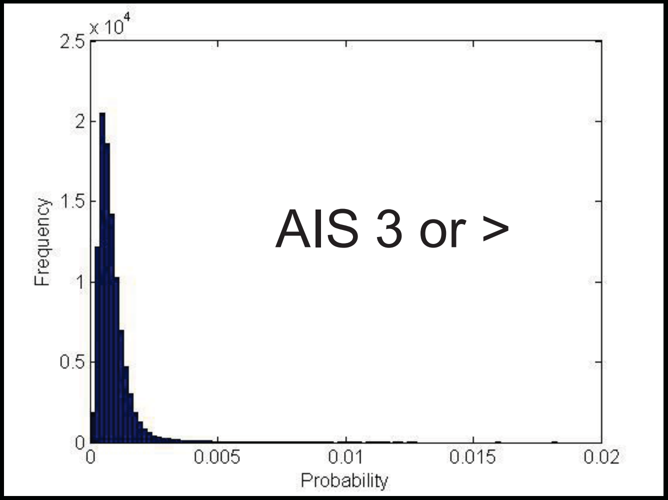
Scheuring et al, "Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts," *Aviat Space Environ Med*, 80(2), 117-24, 2009.

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







Total Injury Probability	Mean	Standard Deviation	5%	95%
AIS 1 or >	1.2×10^{-2}	6.0×10^{-3}	5.35×10^{-3}	2.3×10^{-2}
AIS 2 or >	3.9×10^{-3}	2.2×10^{-3}	1.5×10^{-3}	7.9×10^{-3}
AIS 3 or >	8.95×10^{-4}	5.8×10^{-4}	3.0×10^{-4}	1.9×10^{-3}

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

AIS 1 or >

Parameter	% Contribution to Variance
Rate of Impact, λ	42.37
Velocity of the impactor, $v0$	33.38
Probability coefficient, A	17.43
Mass of the impactor, m_1	6.4
Probability coefficient, B	0.232
Spring constant, k_{23}	0.033
Astronaut Mass, AM	0.0295
Sternum mass, m_2	0.0295
Thorax mass, m_3	0.0295
Chest depth, CD	0.0295
Damping constant, c_{23}	0.0238
Damping constant, c_{ve23}	0.004
Spring constant, k_{12}	2.34×10^{-4}
Spring constant, k_{ve23}	6.92×10^{-5}

AIS 2 or >

Parameter	% Contribution to Variance
Velocity of the impactor, $v0$	43.32
Rate of Impact, λ	27.55
Probability coefficient, A	20.40
Mass of the impactor, m_1	8.264
Probability coefficient, B	0.274
Damping constant, c_{23}	0.042
Astronaut Mass, AM	0.033
Sternum mass, m_2	0.033
Thorax mass, m_3	0.033
Chest depth, CD	0.033
Spring constant, k_{23}	0.016
Spring constant, k_{ve23}	0.0015
Damping constant, c_{ve23}	0.0004
Spring constant, k_{12}	5.24×10^{-7}

AIS 3 or >

Parameter	% Contribution to Variance
Velocity of the impactor, $v0$	44.56
Probability coefficient, A	27.76
Rate of Impact, λ	21.3
Mass of the impactor, m_1	7.91
Probability coefficient, B	0.3308
Damping constant, c_{23}	0.0295
Spring constant, k_{23}	0.0263
Astronaut Mass, AM	0.0175
Sternum mass, m_2	0.0175
Thorax mass, m_3	0.0175
Chest depth, CD	0.0175
Damping constant, c_{ve23}	0.0049
Spring constant, k_{12}	0.002
Spring constant, k_{ve23}	0.0013

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 will be incorporated into the parent Integrated Medical Model and assessed relative to other potential medical events

Acknowledgements

- This work is funded by the NASA Human Research Program, managed by the NASA Johnson Space Center. Specifically, the work is part of the Integrated Medical Model, which is part of the Exploration Medical Capability Element

- Special thanks to:
  - Eric Kerstman, Marlei Walton, John DeWitt and Mitzi Laughlin for model review
  - Molly Townsend for technical work
  - Sharmi Watkins, DeVon Griffin and Marsha Nall for project management