The Integrated Medical Model:
A probabilistic simulation model for predicting in-flight medical risks

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Integrated Medical Model (IMM) Project

• Conceived in 2005, envisioned development of a simulation model as a means to inform medical resource planning for the International Space Station (ISS) and for future space flight missions

• Additional applications to quantifying aspects of medical conditions could be elucidated with this approach because of the need to quantify risk metrics
  • Loss of Crew Life (LOCL)
  • Consideration of Evacuation (EVAC)
  • Quality Time Lost (QTL)

• Intent was to utilize available space flight community knowledge base as an integral part of the simulation environment
  – Sources: U.S. astronaut data, analog and general population information with appropriate quality and applicability to space flight concepts

• Not envisioned to be
  – A diagnosis tool or definitive assessment of medical treatment
  – A means of assessing countermeasure efficacy or performance decrement
Integrated Medical Model (IMM)

Stochastic simulation model used to predict in-flight medical events, the resources required to treat, and impacts to the spaceflight mission.
IMM Project Flow

IMM Framework

INPUTS

- User-defined Mission Profile
- iMED (knowledge base)

Simulation

- IMM (Coinflipper)

Output

- Probability of EVAC/LOCL
- Quality Time Lost
- Resource Utilization

Optimization

- Optimize Resource choices under mass and volume constraints
IMM Data Flow

Model Inputs:
- Medical Condition Incidence Data
- Medical Condition Impairment, Duration and Outcome Data
- Medical Condition Treatment Data
- ISS Health Maintenance System Resources
- Crew Composition and Attributes
- Mission Duration and Profile

Integrated Medical Model (IMM)

Model Outputs:
- Type and Quantity of all Medical Events
- Risk of EVAC
- Risk of Loss of Crew
- Medical Resources Used
- Crew Health Index
IMM Evidence Database (iMED)

- Lifetime Surveillance of Astronaut Health (LSAH)
  - ISS Expeditions thru 13 (2006)*
  - STS Missions thru STS-114 (2005)
  - Apollo, Skylab, Mir (U.S. crew)
- Bayesian Analysis
- Predictive Models
- Analog, Terrestrial Data
- Flight Surgeon Delphi Study

* More current data used for select conditions

The IMM Conditions

- Have Occurred Inflight (47)
- Are Possible (53)
IMM: User-defined Inputs

Mission Length = 180/365; % mission length in years
% specify Crew profile
Crew_ID = (1:6);
ncrew=max(Crew_ID);
Last = { 'A'; 'B'; 'C'; 'D'; 'E'; 'F'};
First = upper(['Crew'; 'Crew'; 'Crew'; 'Crew'; 'Crew'; 'Crew']);
Female = [0; 0; 0; 0; 1; 1];
Crown = [1; 0; 0; 0; 1; 0];
EVA = [0; 6; 0; 0; 6; 0];
CAC = [1; 0; 0; 0; 0; 0];
Contacts = [0; 0; 1; 1; 0; 1];
HxAbSurg = [0; 0; 0; 1; 0; 0];
Crew = dataset (Crew_ID, Last, First, Female, Crown, EVA, CAC, Contacts, HxAbSurg);
clearvars Crew_ID Last First Female Crown EVA CAC Contacts HxAbSurg;
EVA_schedule=[25, 50, 75, 100, 125, 150];
Imm Conditions

1. Abdominal Injury
2. Abdominal Wall Hernia
3. Abnormal Uterine Bleeding
4. Acute Arthritis
5. Acute Cholecystitis / Biliary Colic
6. Acute Compartment Syndrome
7. Acute Diverticulitis
8. Acute Glaucoma
9. Acute Pancreatitis
10. Acute Prostatitis
11. Acute Radiation Syndrome
12. Acute Sinusitis
13. Allergic Reaction (mild to moderate)
14. Altitude Sickness
15. Angina/ Myocardial Infarction
16. Anaphylaxis
17. Ankle Sprain/Strain
18. Anxiety
19. Appendicitis
20. Atrial Fibrillation/ Flutter
22. Back Pain (SA)
23. Barotrauma (sinus block)
24. Behavioral Emergency
25. Burns secondary to Fire
26. Cardiogenic Shock secondary to Infarction
27. Chest Injury
28. Choking/Obstructed Airway
29. Constipation (SA)
30. Decompression Sickness Secondary to EVA
31. Dental : Exposed Pulp
32. Dental Caries
33. Dental: Abscess
34. Dental: Avulsion (Tooth Loss)
35. Dental: Crown Loss
36. Dental: Filling Loss
37. Dental: Toothache
38. Depression
39. Diarrhea
40. Elbow Dislocation
41. Elbow Sprain/Strain
42. Eye Abrasion (foreign body)
43. Eye Chemical Burn
44. Eye Corneal Ulcer
45. Eye Infection
46. Eye Penetration (foreign body)
47. Finger Dislocation
48. Fingernail Delamination (EVA)
49. Gastroenteritis
50. Head Injury
51. Headache (CO2 induced)
52. Headache (Late)
53. Headache (SA)
54. Hearing Loss
55. Hemorrhoids
56. Herpes Zoster
57. Hip Sprain/Strain
58. Hip/Proximal Femur Fracture
59. Hypertension
60. Indigestion
61. Influenza
62. Insomnia (SA)
63. Knee Sprain/Strain
64. Late Insomnia
65. Lower Extremity Stress Fracture
66. Lumbar Spine Fracture
67. Medication Overdose / Reaction
68. Mouth Ulcer
69. Nasal Congestion (SA)
70. Nephrolithiasis
71. Neurogenic Shock
72. Nose bleed (SA)
73. Otitis Externa
74. Otitis Media
75. Paresthesias
76. Pharyngitis
77. Respiratory Infection
78. Retinal Detachment
79. Seizures
80. Sepsis
81. Shoulder Dislocation
82. Shoulder Sprain/Strain
83. Skin Abrasion
84. Skin Infection
85. Skin Laceration
86. Skin Rash
87. Small Bowel Obstruction
88. Smoke Inhalation
89. Space Motion Sickness (SA)
90. Stroke (CVA)
91. Sudden Cardiac Arrest
92. Toxic Exposure: Ammonia
93. Traumatic Hypovolemic Shock
94. Urinary Incontinence (SA)
95. Urinary Retention (SA)
96. Urinary Tract Infection
97. Vaginal Yeast Infection
98. VIIP – Visual Impairment/ Increased Intracranial Pressure (SA)
99. Wrist Fracture
100. Wrist Sprain/Strain
iMED Clinical Findings Form (CliFF)
Mission Simulation

For each condition and crewmember, randomly select incidence rate based on input data.

Generate occurrence times of medical condition based on incidence rate.

For each medical condition occurrence, randomly select the scenario (best or worst-case).

Based on the scenario and order of medical condition occurrence, determine resource requirements and utilization.

Based on the scenario and treatment status, generate functional impairment, duration and outcome (evacuation and/or loss of crew life) data for the medical condition occurrence.
IMM Medical Event Simulation

- All possible conditions are matched with crewmembers defined in the profiles
- For each simulated mission, the time of onset of each condition is generated
- Conditions fall under 4 distinct categories when it comes to the simulation:
  - **Space Adaptation Syndromes** are simulated as yes/no events based on an incidence proportion. If yes, then the onset time is generated from a specified distribution
  - **EVA-related conditions** are simulated as yes/no events based on an incidence proportion. If yes, the onset time is set at the pre-specified EVA time
  - **General condition** onset times are simulated with exponential waiting times based on an incidence rate
  - **Acute Radiation Syndrome (ARS)** is simulated separately under 2 steps
    1. The timing of Solar Particle Events (SPE) is generated using exponential waiting times based on an incidence rate
    2. For each generated SPE, ARS is generated as a yes/no event for each crewmember based on an incidence proportion. If yes, the time of onset is set as the time of the SPE
IMM Condition Severity

• Each medical condition is defined based on a dichotomized level of severity (best/worst-case scenarios)
• For each generated event, whether the condition goes best-case or worst-case is assigned according to pre-specified probability ranges in the simulation
• Each best-case or worst-case medical condition defines the treatment required
IMM Medical Condition Outcome Distributions

• Outcome distributions are defined based on the two extremes
  – Full treatment available
  – No treatment available

• The outcome distributions are shifted between the extremes, when some but not all the essential required resources are available at the time the condition occurs (Partial Treatment)
IMM Medical Condition Outcomes

Functional Impairment (FI) and Durations

- Each condition is divided into 3 stages (Clinical Phases)
  - Initial diagnosis and treatment
  - Ongoing treatment
  - Recovery/mission end state (remainder of the mission)

- Each stage is assigned an FI
  - Functional impairment is adapted from a standardized guidelines used in the Insurance industry. To adjust for the temporary nature of the impairment, the IMM FI algorithm calculates based on general principals and rules of the American Medical Association (AMA) “Guides to the Evaluation of Permanent* Impairment”.

Quality Time Lost (QTL)

- Sum of the FI*duration over the 3 Clinical Phases of the condition

EVAC and LOCL are generated from specified probability distributions

* IMM uses same classes as AMA but adjusts for mission time
Additional Condition Assumptions

- Crewmembers cannot get the same condition for which they are already being treated (no identical conditions during CP1-CP2) with the exception of DCS secondary to EVA.
- Crewmembers can get no further conditions after EVAC or LOCL, and FI = 1 for the remainder of the mission.
- Crewmembers that require the same resource for multiple conditions during a time interval will use the maximum required quantity for each condition to treat both simultaneously.
IMM Predictions (Mission-level Outputs)

- **Probability (Consideration) of EVAC**
  - Proportion of simulated missions with at least one EVAC
  - Confidence limits estimated by bootstrap resampling

- **Probability of LOCL**
  - Proportion of simulated missions with at least one LOCL
  - Confidence limits estimated by bootstrap resampling

- **Quality Time Lost (QTL)**
  - Sum of FI x Duration over the mission
  - FIs are adjusted for overlapping (in time) impairments within crewmembers
  - Defined on [0, mission length]
Crew Health Index (CHI)

Definition: Proportion of mission time not lost to medical events

\[ 1 - \frac{\sum QTL}{L \times n} = CHI \]

n = # crew,

L = mission length,

QTL = quality time lost for each condition

• CHI is a normalized calculation of Quality Time Lost. Can be a useful metric when comparing two or more mission profiles.
Example Results ISS6  
(6 crew, 6 months, 6 two-crew EVAs)

<table>
<thead>
<tr>
<th></th>
<th>No Medical Resources</th>
<th>ISS Health Maintenance System</th>
<th>Unlimited Medical Resources</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% Confidence Interval</td>
<td>Mean</td>
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<tr>
<td></td>
<td>Lower Bound</td>
<td>Upper Bound</td>
<td>Lower Bound</td>
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<tr>
<td>TME</td>
<td>98.3</td>
<td>73</td>
<td>122</td>
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<td>CHI</td>
<td>59.2</td>
<td>43.36</td>
<td>71.25</td>
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<td>pEVAC</td>
<td>66.9</td>
<td>66.57</td>
<td>67.14</td>
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<tr>
<td>pLOCL</td>
<td>2.89</td>
<td>2.78</td>
<td>2.99</td>
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</table>
Example Results ISS6
(6 crew, 6 months, 6 two-crew EVAs)
Total Medical Events

- No Medical Resources
- ISS Health Maintenance System
- Unlimited Medical Resources
Example Results ISS6
(6 crew, 6 months, 6 two-crew EVAs)
Crew Health Index

- No Medical Resources
- ISS Health Maintenance System
- Unlimited Medical Resources

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Example Results Exploration (6 crew, 2.5 years, 231 two-crew EVAs)
Crew Health Index
## IMM Contacts

### ExMC - IMM Project / Technical Management

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<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Email</th>
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<tbody>
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### IMM Development Team

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<thead>
<tr>
<th>Role</th>
<th>Name</th>
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<tbody>
<tr>
<td>Lead Team (SSC, Wyle)</td>
<td>John Arellano</td>
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<td></td>
<td>Lynn Boley</td>
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<td>Eric Kerstman</td>
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<td>David Reyes</td>
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<td>Lynn Saile</td>
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<td>Marlei Walton</td>
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<td>Millennia Young</td>
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<td>Support Team (GRC)</td>
<td>Debra Goodenow</td>
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<td>Donald Jaworske</td>
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