Exploration Medical Data Architecture

Big Data Big Think Forum
April 6, 2016

Erik Antonsen MD, PhD, FAAEM
Element Scientist

Sandeep Shetye
Chief Data Architect
Exploration Medical Capabilities – Data is a Challenge

- ISS and exploration: Different Medicine requires different capabilities
- What can we learn from ISS?
- A vehicle and a ground challenge
- Risk Modeling – what are we worried about?
- Needs Analysis – what do we think we need?
- Data Architecture – Medicine as a system
HUMAN EXPLORATION
NASA’s Path to Mars

EARTH RELIANT
MISSION: 6 TO 12 MONTHS
RETURN TO EARTH: HOURS
Mastering fundamentals aboard the International Space Station
U.S. companies provide access to low-Earth orbit

PROVING GROUND
MISSION: 1 TO 12 MONTHS
RETURN TO EARTH: DAYS
Expanding capabilities by visiting an asteroid redirected to a lunar distant retrograde orbit
The next step: traveling beyond low-Earth orbit with the Space Launch System rocket and Orion spacecraft

MARS READY
MISSION: 2 TO 3 YEARS
RETURN TO EARTH: MONTHS
Developing planetary independence by exploring Mars, its moons and other deep space destinations

www.nasa.gov
Motivation

Medical Risk: Given that medical conditions will occur during human spaceflight missions, there is a possibility of adverse health outcomes & decrements in performance during these missions and for long term health.

The medical system supports healthy crew to enable completion of mission objectives. We are concerned with health and prevention, not just catastrophic events.

To minimize mission medical risk through medical system design and integration into the overall mission and vehicle design.
Mission Constraints

Exploration missions are different:

- Harsher environmental constraints
- Shrinking resources (mass, volume, power, etc.)
- No evacuation option
- Limited if any resupply
- Delayed or absent communications

- The only resource growing is data handling capability (Moore’s Law)

Exploration may require “Stay and Fight” Medicine, not “Retreat” Medicine.
Medical and Research Data Processing

- Mission Associated Summary of Health
  - Detailed Medical Report
  - 500 page pdf
  - Takes a team 6 months to create

- Biomedical Data Reduction and Analysis
  - Around 100 pages pdf
  - Preparation is pre-mission through 45-60 days post flight

Some version of both of these processes will need to be incorporated and automated in exploration missions.
Challenges

• No single medical database stores all information that is complete
• Leveraging extensive quantity of medical research being published on an ongoing basis
• Integrating new data sources into existing medical systems
• Existing industry systems have limitations
  • Limited utilization and scope
  • Design for specific purpose and difficult to personalize
• Access to knowledge base and other medical data
• Machines can assist but can’t replace humans
How do we get there?

- Risk Mitigation Strategy
  - Planning
    - Concept of Operations Development (Ops Risk Reduction)
  - Characterization of Risk
    - Models and Metrics – Integrated Medical Model (IMM), MONSTR prototype
    - Active Data Gathering – Medical Consumables Tracker (MCT), biosensors, Flexible Ultrasound
  - Active Risk Reduction
    - Medical Data Handling – Exploration Medical System Demonstrator (EMSD), Medical Data Architecture
    - Technology Development – Oxygen Concentrator Module, Medical Suction, IVGen...
    - Training
    - Medical Decision Support
    - Integration of Medical with Vehicle Designers and ECLSS SMTs
The Goal

Provide the crew with the best chance to accomplish mission and get home healthy

Medical Operations
- Nominal Operations
- Contingency Operations
  - Routine
  - Urgent
  - Emergent
Risk Characterization

• Identify the medical conditions that are likely to occur.
• Identify how likely and how often they might occur.
• Identify what resources are desired to address them.

Medical Optimization Network for Space Telemedicine Resources (MONSTR)

Event Probability (IMM)

Medical Capability (MONSTR)
The IMM Medical Conditions

SKIN
- Burns secondary to Fire
- Skin Abrasion
- Skin Laceration

EYES
- Acute Glaucoma
- Eye Corneal Ulcer
- Eye Infection
- Retinal Detachment
- Eye Abrasion
- Eye Chemical Burn
- Eye Penetration

EARS, NOSE, THROAT
- Barotrauma (sinus block)
- Nasal Congestion (SA)
- Nosebleed (SA)
- Acute Sinusitis
- Hearing Loss
- Otitis Externa
- Otitis Media
- Pharyngitis

DENTAL
- Abscess
- Caries
-Exposed Pulp
-Tooth Loss
-Crown Loss
-Filling Loss

CARDIOVASCULAR
- Angina/Myocardial Infarction
- Atrial Fibrillation / Atrial Flutter
- Cardiogenic Shock secondary to Myocardial Infarction
- Hypertension
- Sudden Cardiac Arrest
- Traumatic Hypovolemic Shock

GASTROINTESTINAL
- Constipation (SA)
- Abdominal Injury
- Acute Cholecystitis
- Acute Diverticulitis
- Acute Pancreatitis
- Appendicitis
- Diarrhea
- Gastroenteritis
- Hemorrhoids
- Indigestion
- Small Bowel Obstruction

Pulmonary
- Choking/Obstructed Airway
- Respiratory Infection
- Toxic Exposure: Ammonia
- Smoke Inhalation
- Chest Injury

NEUROLOGIC
- Space Motion Sickness (SA)
- Head Injury
- Seizures
- Headache
- Stroke
- Paresthesia
- Headache (SA)
- Neurogenic Shock
- VIIP (SA)

MUSKULOSKELETAL
- Back Pain (SA)
- Abdominal Wall Hernia
- Acute Arthritis
- Back Injury
- Ankle Sprain/Strain
- Elbow Dislocation
- Elbow Sprain/Strain
- Finger Dislocation
- Fingernail Delamination (EVA)
- Hip Sprain/Strain
- Hip/Proximal Femur Fracture
- Knee Sprain/Strain
- Lower Extremity Stress fracture
- Lumbar Spine Fracture
- Shoulder Dislocation
- Shoulder Sprain/Strain
- Acute Compartment Syndrome
- Neck Injury
- Wrist Sprain/Strain
- Wrist Fracture

PSYCHIATRIC
- Insomnia (Space Adaptation)
- Late Insomnia
- Anxiety
- Behavioral Emergency
- Depression

GENITOURINARY
- Abnormal Uterine Bleeding
- Acute Prostatitis
- Nephrolithiasis
- Urinary Incontinence (SA)
- Urinary Retention (SA)
- Vaginal Yeast Infection

INFECTION
- Herpes Zoster (shingles)
- Influenza
- Mouth Ulcer
- Sepsis
- Skin Infection
- Urinary Tract Infection

IMMUNE
- Allergic Reaction
- Anaphylaxis
- Skin Rash
- Medication Reaction

ENVIRONMENT
- Acute Radiation Syndrome
- Altitude Sickness
- Decompression Sickness (EVA)
- Headache (CO2)

47 have occurred in spaceflight
Provides a tool to help informed decision making

Mission Specific Inputs
- Crew Member Attributes
- Crew Composition
- Mission Duration and Profile

Monte Carlo Simulations
- CliFFs
- Integrated Medical Model

Quantified Outputs
- Type and Quantity of all Medical Events
- Risk of EVAC
- Risk of Loss of Crew
- Quality Time Lost
- Medical Resources Used
- Optimized Medical System within Vehicle Constraints

Informed Analysis
- Flight Surgeon
MONSTR

- MONSTR provides a way of quantifying a ‘Needs Analysis’
- Uses the same 100 conditions as IMM
- Identifies resources ‘desired’ for diagnosis and treatment (In an ideal world)
- Ranks those resources on:
  - Medical criticality and generalizability to multiple conditions
  - Incorporates Probability of Occurrence
  - Provides a ‘value’ estimate to help prioritize research investments
All Conditions & Resources

Advanced Airway – Worst Case

Advanced Airway – Best Case

Filtered on Advanced Airway
What’s Next?

• Once you've characterized the medical risk and assessed what you need to address it, what is next?

Put those needs together in a system designed to maximize good outcomes and minimize medical errors.

MEDICAL DATA ARCHITECTURE
Active Risk Reduction

• A comprehensive medical system to support the crew in Exploration Missions targeting autonomy.

• In order to do this, ExMC will need integration with vehicle systems – single point solutions are not desirable for Exploration Missions.

• Medical System
  – Provide for centralized medical care
  – Enhance available knowledge base
  – Provide for electronic training needs
  – Monitor supplies for crew
  – Monitor crew as needed
  – Streamline communication with ground flight surgeons
  – Decrease likelihood of medical errors
Medical System Integrates with other needs

- **Behavioral Health and Performance**
  - Dashboard program
  - Actiwatch
  - Technology for monitoring and intervention needs to communicate with this system

- **Human Health and Countermeasures**
  - Exercise countermeasures and monitoring
  - Laboratory and analysis capability
  - These tools provide early warning for medical issues and crossover for rehabilitation needs

- **Space Human Factors and Habitability**
  - Training methods and procedures
  - Crew interface for the medical system
  - Medical Hab design

- **Space Radiation**
  - Radiation monitoring
  - Long-Term Health Effects

- **Other Vehicle Systems**
  - Environmental sensors (CO$_2$ levels, cabin temperature, etc.)
  - Vital signs monitoring via use of vehicle cameras
  - Medical system integrated with vehicle data, hardware and information systems
Medical System Capture Diagram

- **Sensors**
  - Biomonitors
  - Environmental
  - EVA
  - Exercise
  - Behavioral

- **Tracking**
  - Consumables
  - Food
  - Medications
  - Fluids
  - Medical Eq.

- **Data Streaming**
  - Displays / Conferencing

- **Medical Equipment**
  - Imaging
  - 3-D Printing
  - Devices
    - Medications
    - Rehab

- **Performance**
  - Behavioral Monitor
  - Exercise Monitor

- **Training**
  - Medical Procedures
  - Imaging Techniques
  - Behavioral Intervention

- **EMS**
  - Caregiver Interface
  - Vehicle Data Interface

- **Intelligence Augmentation**
  - Caregiver Interface

- **Models**
  - IMM
  - MONSTeR
  - Digital Astronaut
  - Radiation

- **References**
  - Pharmacologic
  - Toxicologic
  - Medical Imaging
  - Training Modules
  - Up-To-Date ™

- **Medical Decision Support**
  - Telemedicine
  - Autonomy

- **EMR**
  - Semi-autonomy
Data Architecture and Medical Data Analytics

• Data Architecture
  – Capture and collect from disparate data sources
  – Transform and integrate all data
  – Provide uniform access to data
  – Build analytics datamarts

• Analytics of patient health data
  – Monitor data
  – Process data and infer adverse health events
  – Aid crew medical officer in a broad range of diagnostic tasks
  – Enhance crew safety
Data Transformation Model

Data Sources

- Data Policy Manager
- Data Aggregation & Fusion: pre-processing, filtering, QA, “ETL” rules
- Data Enrichment, Classification
- Scalable Database
- Data Analytics: Reasoning engine, modeling, predictions

Interactive Query

Data Discovery, Search & Access

Data Delivery & Visualization

- HTTP
- REST APIs
- Web Dashboard

User Applications
ExMC Data Architecture

Data Sources Layer
- Structured
  - Health Records
  - Medical Records
  - Clinical Trials
  - Other
- Unstructured
  - Medical devices
  - Monitoring System
  - Images
  - Logs & Notes
  - Exercise Machine
  - Other
- Streams
  - Bio Sensors
  - Env. Sensors
  - Other

Data Storage Layer
- Data Assets
  - Knowledge Models
    - EHR
    - Documents
    - Sensor
    - Vitals
  - Other
- Integration
  - HL7 - Adapters - Messaging Bus - Data ETL
- HL7 - Adapters - Messaging Bus - Data ETL
- HL7 - Adapters - Messaging Bus - Data ETL

Analytical Layer
- Clinical Decision Support System
- Analytics Data Mart
- Knowledge Base
- Data Service
- Data Models
  - Annotate
  - Correlate
  - Classify

Discovery & Analytics
- Reports
  - Dashboard
- Data Mining
  - Text Classification
  - Computational Statistics
- Modeling & Analytics
  - Diagnostic
  - Predictive
- Discovery
  - Ontological Search
- Real Time Apps
  - Alerts
- Cognitive Computing
  - Adaptive, Interactive, Contextual

User Interface
- Applications & Prototypes
- User Interface & Visualization
- Metadata & Data Standards
- Federated Access & Delivery Infrastructure (FADI)

Data Virtualization
- Knowledge Models
- Data Assets
Medical Decision Support System (MDSS)

A knowledge system designed to use patient medical data and medical knowledge to generate case-specific assessment and recommendations to help medical staff make medical decisions.

Collaborative effort with Canadian Space Agency
Hybrid Approach for Implementation

• Knowledge based
  • Use of knowledge bases
  • Inference engine
  • Decisions based on rules

• Non-knowledge based
  • Machine learning
  • Neural Networks (ANN/CNN) and algorithms
  • Derive knowledge from patient data
  • Learn from decision trees
Medical Decision Support Module

Medical & health records
Bio & Env. sensors
Images
Test results
Training
References

Medical Decision Support Module

Knowledge base & Inference engine

Data Integration and Transformation

Information Interpretation

Machine learning & Patterns

Health Assessment & Predictions
Medical System Development

- Initial Focus is on Use Cases defined with the Clinical Team
- Later development is driven by the Concept of Operations
- An early testbed with a subset of systems is created from use cases
- An incremental and iterative testing pathway is created to build up the system
Medical Data Architecture

Ground Based and Vehicle Data Architectures:

- Clinical Operational Needs
- Research Data Capture
- Long Term Health Information

- Flight Surgeon/BME
- External Consults

Mirrored Delayed Data Presentation for situational awareness/support

Vehicle Exploration Medical System

- Crew Medical Officer
- Crew Medical Support

Real-Time Data Processing for Crew
Sample Visualizations

Summary Analysis (manual)

MedB Sharepoint Site
LSAH (lab results & Nutrition Data)
Archive data (on FTP site)

MASH report

MedB test timeline by Crew Member

Colors represent the type of test – Immunology, Env. Monitoring, EVA, Bone & Calcium Physiology

Example – JFK assassination timeline
Summary

• The ExMC research plan builds on what is known about medicine and physiology in spaceflight to
  – Characterize the likely medical risks
  – Identify medical needs to address those risks
  – Map out a medical system to optimize crew response to those risks
    • Medical Data Architecture
    • Medical Decision Support to Crews
    • Interface with Ground Data Architecture for clinical and research needs
  – Engage in a testing pathway to validate and improve that system

• This necessitates integration with vehicle design concepts early in the design cycle

• It’s all about the DATA and knowledge gleaned from data that enable good decisions

• Data Architecture and Data Management approaches are keys to Mission Success
BACKUP
SLIDES
The document presents a system approach aimed at reducing medical risk through various technologies and strategies.

### System Approach Reduces Medical Risk

#### Key Technologies
- Safe and Effective Pharmacy
- Oxygen Delivery
- Medical Suction
- Ultrasound Imaging
- Laboratory Analysis
- Biosensors/EKG

#### Medical System Components
- Concept of operations
- Pharmacy recommendation
- Select technologies
- Integrated medical system
- Optimized medical system

#### Medical System Chart

<table>
<thead>
<tr>
<th>Risk</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY14</td>
<td>FY15</td>
</tr>
<tr>
<td>ISS 1YR</td>
<td>Asteroid Phase A</td>
</tr>
<tr>
<td>Initial Concept of Operations</td>
<td>Integrated Medical System</td>
</tr>
</tbody>
</table>

#### Medical Risk Timeline

- **Rev-PPBE17 + FY16Q1 Updates**

The diagram illustrates the progression from risk to capability through various fiscal years (FY14 to FY28). Each year marks a step towards the optimized medical system.
Spaceflight Medical Events Risk

Top 100 In Mission Medical Events and 30 Specific Human Risks

~30 Specific Human Risks

Aerobic Capacity
Dynamic Loads (overlap)
Electric Shock
HSDI
Immune (some overlap)
Micro (some overlap)
Muscle
Nutrition/Food
Neuro-vestibular
Long Term Osteoporosis
Medication Storage
Orthostatic Intolerance
Radiation (long term)
Sunlight Exposure
Team Cooperation

Acute Radiation
Altitude Sickness
Cardio
  Angina/ Myocardial Infarction
  Atrial Fibrillation/ Flutter
  Stroke
  Sudden Cardiac Arrest
Back Pain
Behavioral/Depression
Bone Fracture
Carbon Dioxide (headache)
Celestial Dust Exposure

Decompression Sickness
EVA Injuries
Hearing Loss
Renal Stones
Sleep
Specific Toxic Exposure
Urinary Retention
VIIP

~100 Medical Events in IMM

Abdominal Injury
Abdominal Wall Hernia
Abnormal Uterine Bleeding
Appendicitis
Acute Diverticulitis
Anaphylaxis
Eye Abrasions
Dental
Diverticulitis
Gall Bladder
Hernia
Indigestion
Med Overdose/Reaction
Pancreatitis
Sepsis
……
……

…..
Spaceflight Medical Events Risk

This risk will integrate the likelihood and consequence of all human spaceflight risks for each DRM.

Medical Conditions for which we have not planned.
Risk Characterization

But what if it happens?
- Secondary Prevention
- Diagnosis
- Treatment
- Chronic Management
- Rehabilitation

For known risks:
- How do we decrease this?

Keep it from happening?
- Selection
- Screening
- Primary Prevention
- Vehicle Design Standards
- Mission Architecture
Challenges

• Networked Complexity
• Communication
  – Centers
  – Elements
  – Outside HRP – SD, EA, HSRB, OCHMO and many others
• Increment and Iterate
  – Modified agile system development approach needed
  – Flexibility in approach
• Optimization pathway
  – The solution today is likely not the solution in 10 years
  – Flexibility in architecture
  – Standards definition and upgrades
How are resources ranked?

- Summed across all conditions

\[
M_C = (1) \sum_{i=1}^{100} CR1_i + (2) \sum_{j=1}^{100} CR2_j + (3) \sum_{k=1}^{100} CR3_k
\]

\[
WM_C = (1) \sum_{i=1}^{100} (CR1_i)(p_i) + (2) \sum_{j=1}^{100} (CR2_j)(p_j) + (3) \sum_{k=1}^{100} (CR3_k)(p_k)
\]

\[Mc = \text{Aggregate Criticality Score}\]
\[WMc = \text{Weighted Aggregate Criticality Score}\]
\[CR1 = \text{Resource Criticality Score of 1}\]
\[CR2 = \text{Resource Criticality Score of 2}\]
\[CR3 = \text{Resource Criticality Score of 3}\]
\[P = \text{Probability of Occurrence}\]
Gap Conceptual Flow

The Concept of Operations Drives System Design
# Medical Risk

## New Gaps

<table>
<thead>
<tr>
<th>Med01</th>
<th>We do not have a concept of operations for medical care during exploration missions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Med02</td>
<td>We do not have the capability to provide a safe and effective pharmacy for exploration missions.</td>
</tr>
<tr>
<td>Med03</td>
<td>We do not know how we are going to apply personalized medicine to reduce health risk for a selected crew.</td>
</tr>
<tr>
<td>Med04</td>
<td>We do not have a defined rehabilitation capability for injured or de-conditioned crew members during exploration missions.</td>
</tr>
<tr>
<td>Med05</td>
<td>We do not know how to train crew for medical decision making or to perform diagnostic and therapeutic medical procedures to enable extended mission or autonomous operations.</td>
</tr>
<tr>
<td>Med06</td>
<td>We do not know how to define medical planning or operational needs for ethical issues that may arise during exploration missions.</td>
</tr>
<tr>
<td>Med07</td>
<td>We do not have the capability to comprehensively process medically-relevant information to support medical operations during exploration missions.</td>
</tr>
<tr>
<td>Med08</td>
<td>We do not have quantified knowledge bases and modeling to estimate medical risk incurred on exploration missions.</td>
</tr>
<tr>
<td>Med09</td>
<td>We do not have the capability to predict estimated medical risk posture during exploration missions based on current crew health and resources.</td>
</tr>
<tr>
<td>Med10</td>
<td>We do not have the capability to provide computed medical decision support during exploration missions.</td>
</tr>
<tr>
<td>Med11</td>
<td>We do not have the capability to minimize medical system resource utilization during exploration missions.</td>
</tr>
<tr>
<td>Med12</td>
<td>We do not have the capability to mitigate select medical conditions</td>
</tr>
<tr>
<td>Med13</td>
<td>We do not have the capability to implement medical resources that enhance operational innovation for medical needs</td>
</tr>
</tbody>
</table>
How to decompose the work

Incremental and Iterative Approach

Pedigree: DoDAF
Background

• Exploration Medicine is unique:
  – NO regular resupply of materials
  – NO real-time communications
  – NO potential for evacuation if serious medical concerns arise.

• Medical care includes:
  – Screening
  – Prevention
  – Diagnostic capability
  – Treatment capability
  – Follow up care and Rehabilitation
  – Prognosis

• Characterize the likely medical risks
• Identify medical needs to address those risks
• Create a medical system to optimize crew response to those risks
• Engage in a testing pathway to validate and improve that system
• Work with vehicle engineers and flight surgeons to ensure useful implementation of that system

Exploration may require “Stay and Fight” Medicine, not “Retreat” Medicine.
ExMC Responsibilities

Risk Title: Risk of Adverse Health Outcomes & Decrements in Performance due to Inflight Medical Conditions

Description: Given that medical conditions will occur during human spaceflight missions, there is a possibility of adverse health outcomes and decrements in performance during these missions and for long term health.

Other ExMC Risks:
1. Risk of bone fracture due to spaceflight induced changes in bone.
2. Risk of ineffective or toxic medications due to long term storage.