Medical Risks and Capabilities for Human Exploration Spaceflight

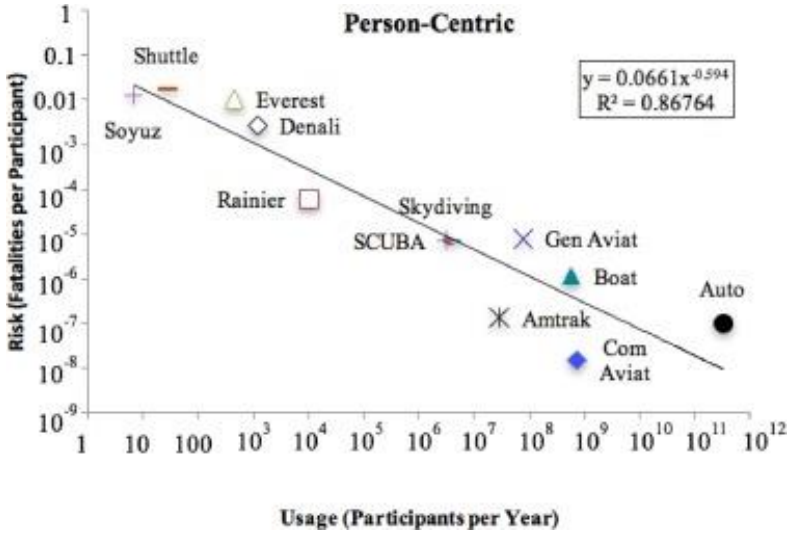
Benjamin Easter, MD, MBA

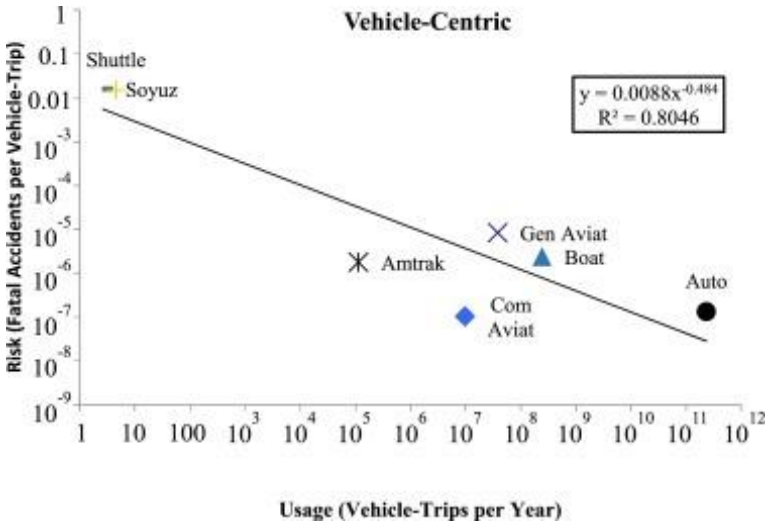
Assistant Professor
Department of Emergency Medicine
University of Colorado School of Medicine

Deputy Element Scientist
Exploration Medical Capability (ExMC)
NASA Human Research Program

Email: benjamin.easter@nasa.gov

Risk of Human Spaceflight





O'Campo RP, Klaus DM. Applying regression analysis to model the risk of space flight and terrestrial activities. Journal of Space Safety Engineering. Sep-Dec 2018;5(3-4): 135-139.

Outline

Outline

- Historical spaceflight medical kits/systems
- Historical occurrence of medical conditions
- Upcoming missions and medical challenges
- Medical risk and spaceflight events
- Medical system and technology integration

Objectives

- Describe the key principles of extreme environmental medicine
- Identify the challenges with telemedicine and remote medical support
- Analyze the steps necessary to increase clinical autonomy
- Outline how using systems engineering principles can improve medical system design

Project Mercury

FIGURE 4.1. Mercury medical kits containing items such as antibiotics, decongestants, stimulants, electrode paste, and medications to treat nausea and diarrhea. (Photo courtesy of NASA)

FIGURE 4.2. Mercury medical kit containing items such as saline solution, bandages, stimulants, and decongestants (Photo courtesy of NASA)

Principles of Clinical Medicine for Spaceflight
Eds. Barratt, Pool, 2008

Gemini and Apollo

TABLE 4.1. Contents of the Gemini VII medical kit [10].

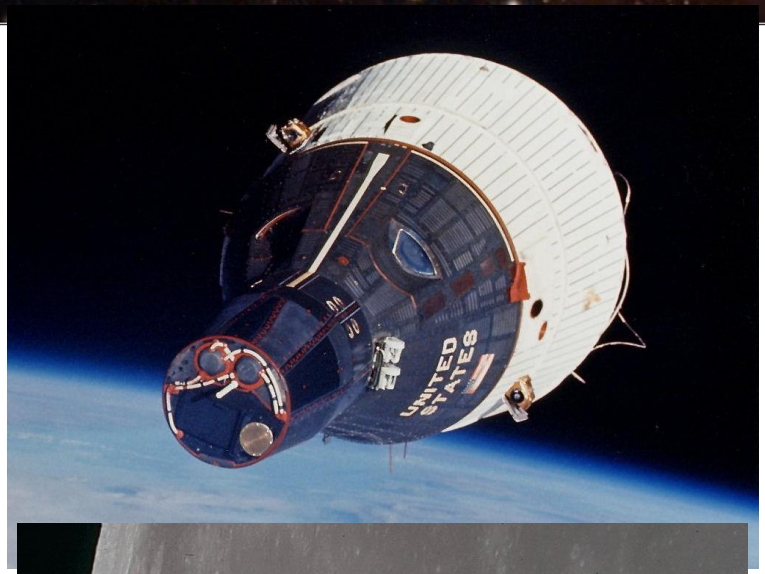
Medication	Indication	Dose	Amount
D-Amphetamine sulfate	Stimulant	5-mg tablets	8
Aspirin-phenacetin-caffeine	Pain	Tablets	16
Cyclizine HCl	Motion sickness	50-mg tablets	8
Diphenoxylate HCl	Diarrhea	2.5-mg tablets	16
Meperidine HCl	Pain	100-mg tablets	4
Methyl cellulose solution	Eye lubricant	15-ml bottle	1
Parenteral cyclizine	Motion sickness	45 mg (0.9-ml injector)	2
Parenteral meperidine HCl	Pain	90 mg (0.9-ml injector)	2
Pseudoephedrine HCl	Decongestant	60-mg tablets	16
Tetracycline HCl	Antibiotic	250-mg coated tablets	16
Triprolidine HCl	Decongestant	2.5-mg tablets	16

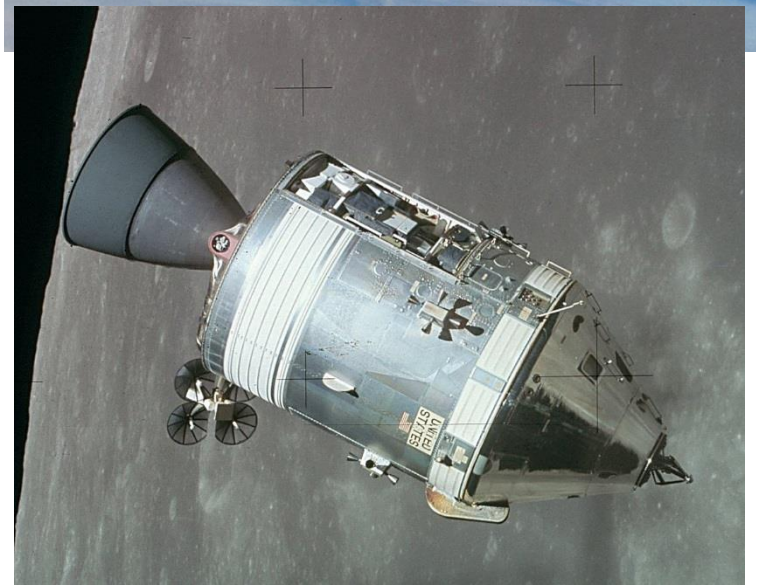
FIGURE 4.3. Apollo medical kit containing items such as skin cream, antibiotic ointment, nasal spray, band-aids, and stimulants (Photo courtesy of NASA)

FIGURE 4.4. Apollo Command Module medical kit (Photo courtesy of NASA)

FIGURE 4.5. Apollo clinical physiological monitoring kit and emergency medical kit (Photo courtesy of NASA)

FIGURE 4.6. Apollo emergency medical kit (Photo courtesy of NASA)





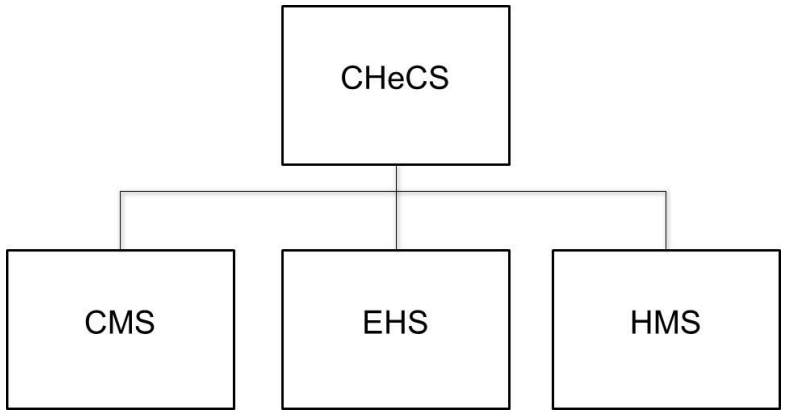
Principles of Clinical Medicine for Spaceflight
Eds. Barratt, Pool, 2008

Space Shuttle

FIGURE 4.7. Shuttle Orbiter Medical System. Following redesign in 2000, components include Saline Supply Bag, EENT Subpack, IV Administration Subpack, Trauma Subpack, Sharps Container, Drug Subpack, and Airway Subpack (Photo courtesy of NASA)

Principles of Clinical Medicine for Spaceflight
Eds. Barratt, Pool, 2008

Health and Medical on ISS



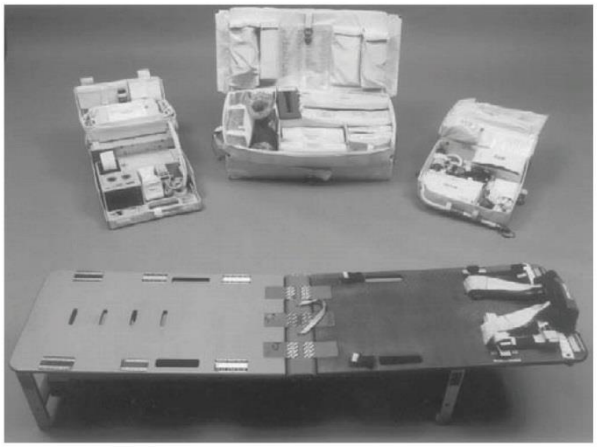


FIGURE 4.8. ISS Health Maintenance System. Components include (from left) defibrillator, Advanced Life Support Pack, Respiratory Support Pack, and Crew Medical Restraint System (Photo courtesy of NASA).

Do we need medicine in spaceflight?

Medical Condition	Events	Medical Condition	Events
Allergic reaction (mild to moderate)	11	Mouth ulcer	9
Ankle sprain/strain	11	Nasal congestion (space adaptation)	389
Back injury	31	Neck injury	9
Back pain (space adaptation)	382	Nose bleed (space adaptation)	6
Barotrauma (ear/sinus block)	31	Otitis externa	3
Choking/obstructed airway	3	Otitis media	3
Constipation (space adaptation)	113	Paresthesias	26
Diarrhea	33	Pharyngitis	11
Elbow sprain/strain	12	Respiratory infection	33
Eye abrasion (foreign body)	70	Shoulder sprain/strain	22
Eye chemical burn	6	Sinusitis	6
Eye infection	5	Skin abrasion	94
Finger dislocation	1	Skin infection	13
Fingernail delamination (EVA)	16	Skin laceration	1
Gastroenteritis	4	Skin rash	94
Headache (CO_2 induced)	20	Smoke inhalation	3
Headache (late)	49	Space motion sickness (space adaptation)	325
Headache (space adaptation)	233	Urinary incontinence (space adaptation)	5
Hemorrhoids	2	Urinary retention (space adaptation) – female	5
Herpes Zoster reactivation (shingles)	1	Urinary retention (space adaptation) – male	4
Indigestion	6	Urinary tract infection – female	5
Influenza	1	Urinary tract infection – male	4
Insomnia (space adaptation	299	Visual impairment/increased intracranial pressure (space adaptation)	15
Insomnia (late)	133	Wrist sprain/strain	5
Knee sprain/strain	7		

Antonsen E, Bayuse T, Blue RS, Daniels V, Hailey M, Hussey S, et al. The Risk of Adverse Health Outcomes and Decrements in Performance due to In-Flight Medical Conditions. National Aeronautics and Space Administration 2017; TR: NASA/TR-2017-0004604

How is medical care provided in mission?

- **Live remote guidance**




- **Live monitoring**

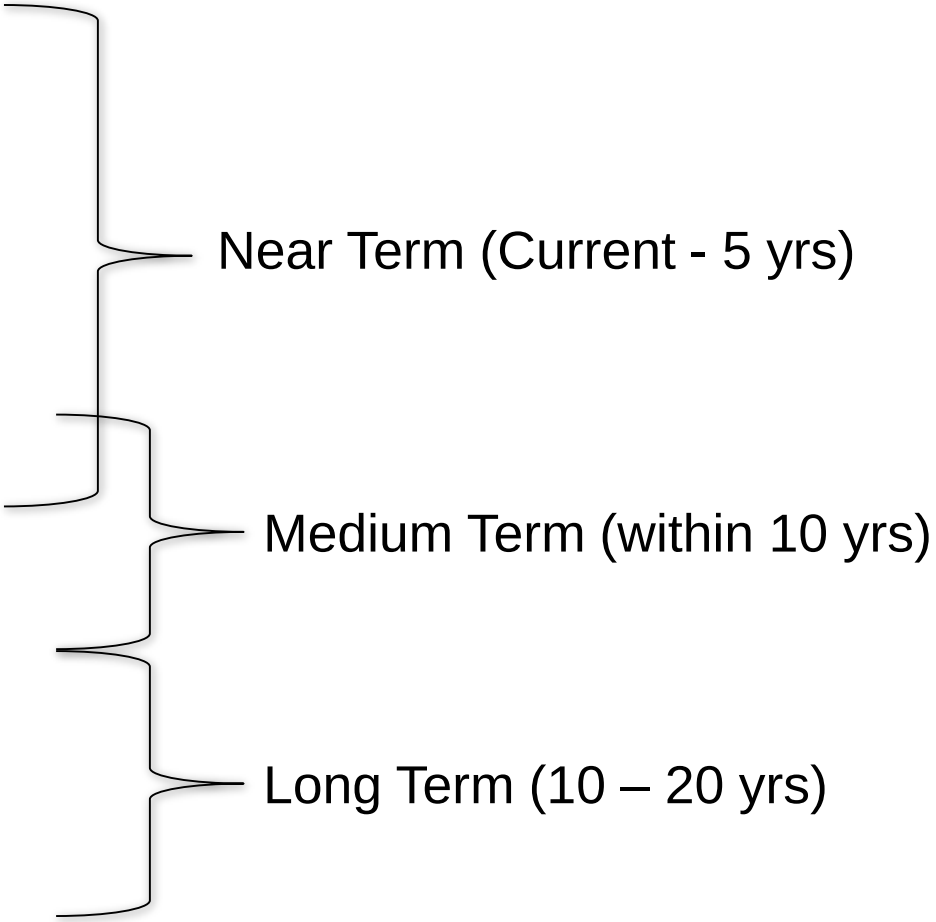
- **Store and forward**

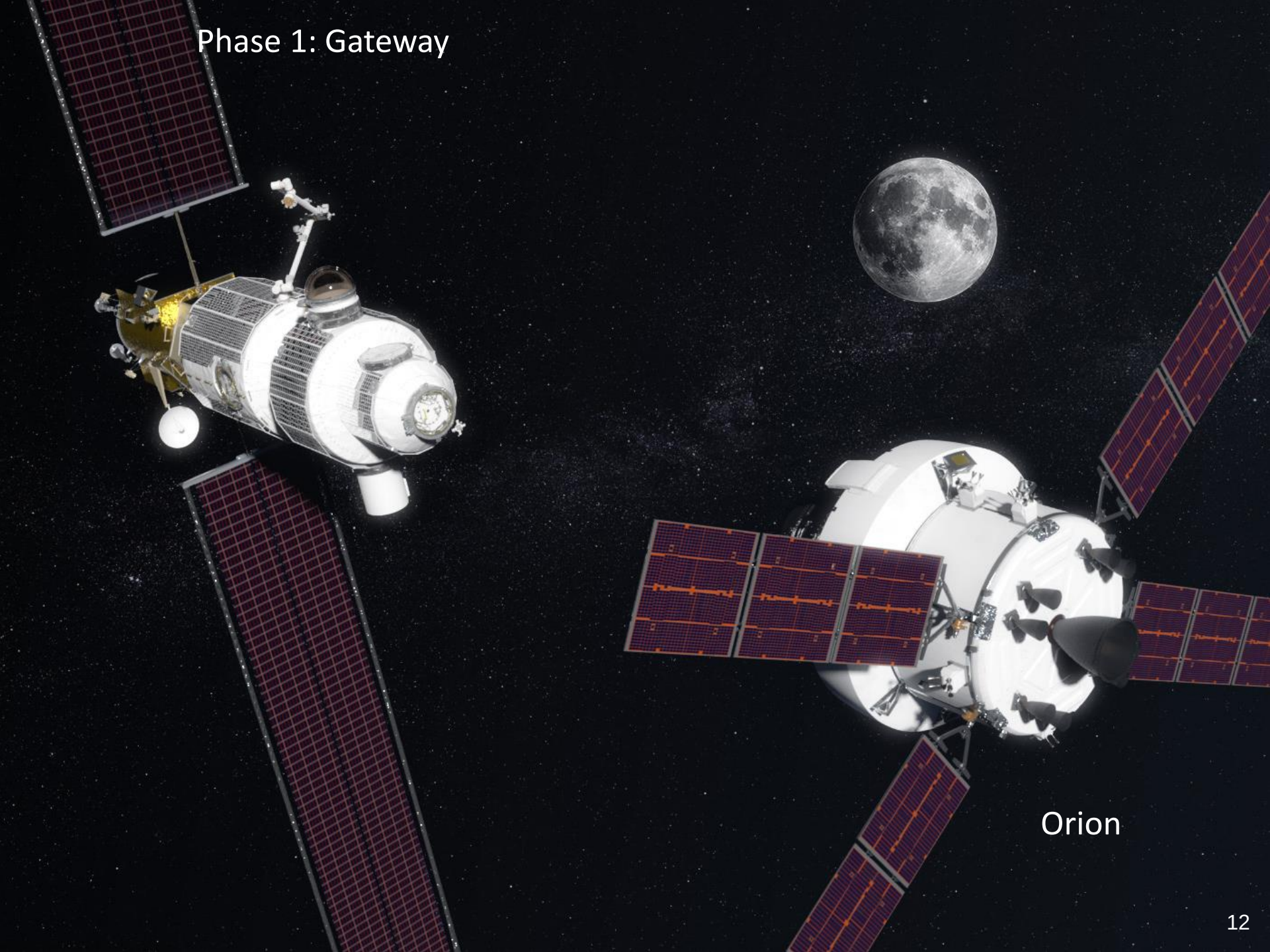



EXPLORATION SPACEFLIGHT

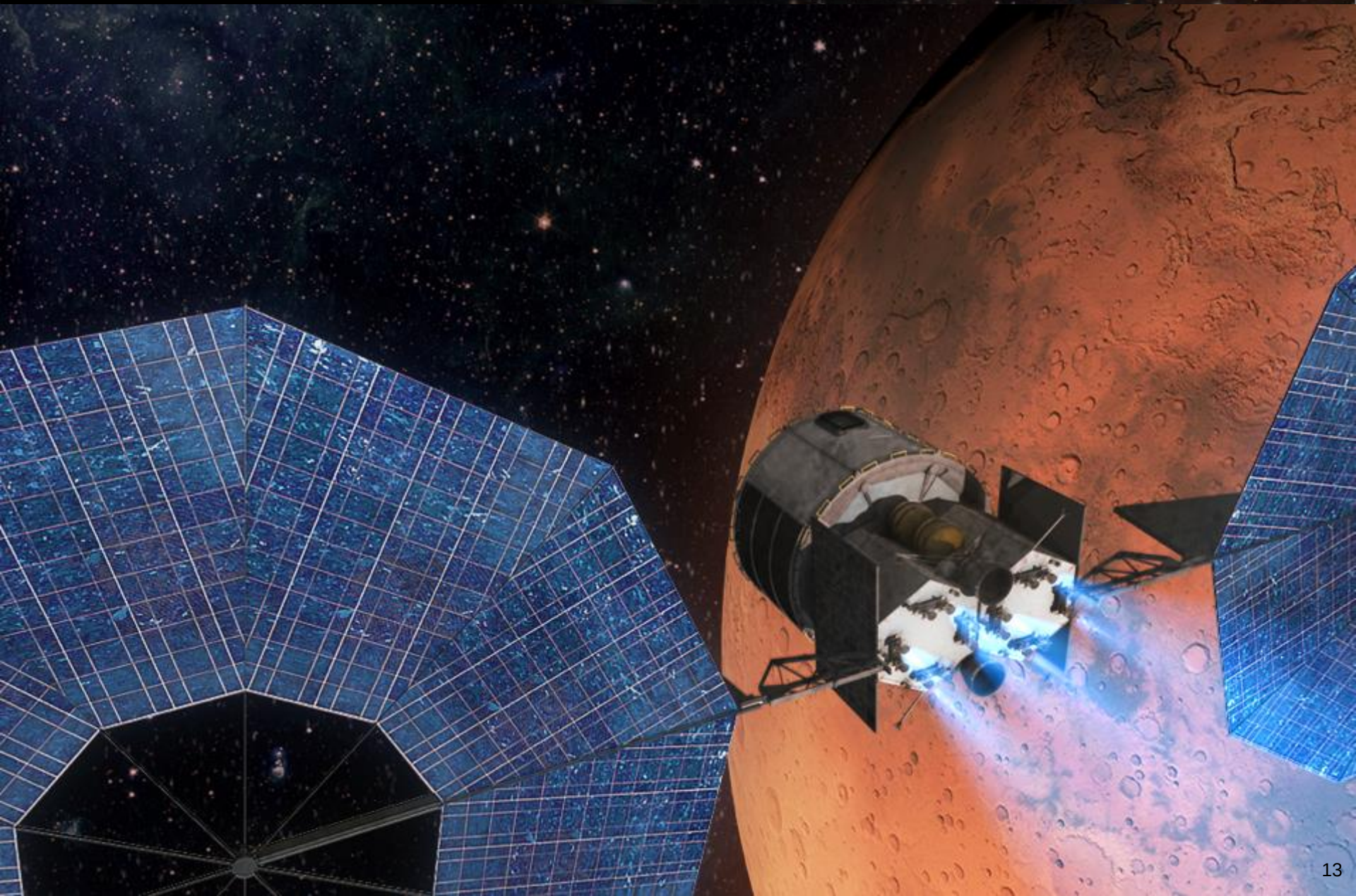
NASA Human Spaceflight Missions

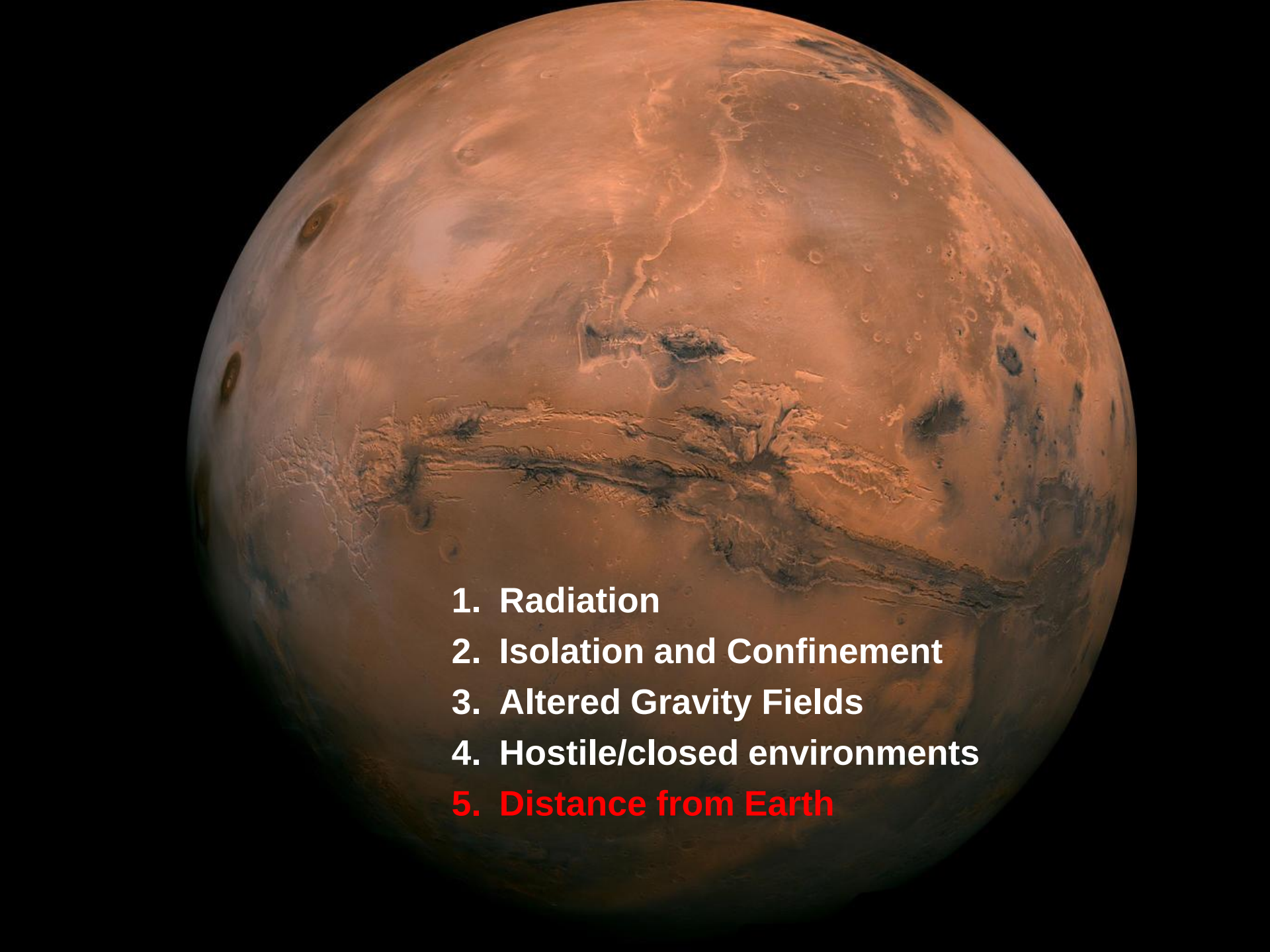
- **Soyuz Launch and Landings**
- **International Space Station**
- **Commercial Crew Program**
- **Multi-Purpose Crew Vehicle**
- **Gateway Habitat**
- **Deep Space Transport**
- **Mars Missions**




Phase 1: Gateway
Orion

What about Mars?

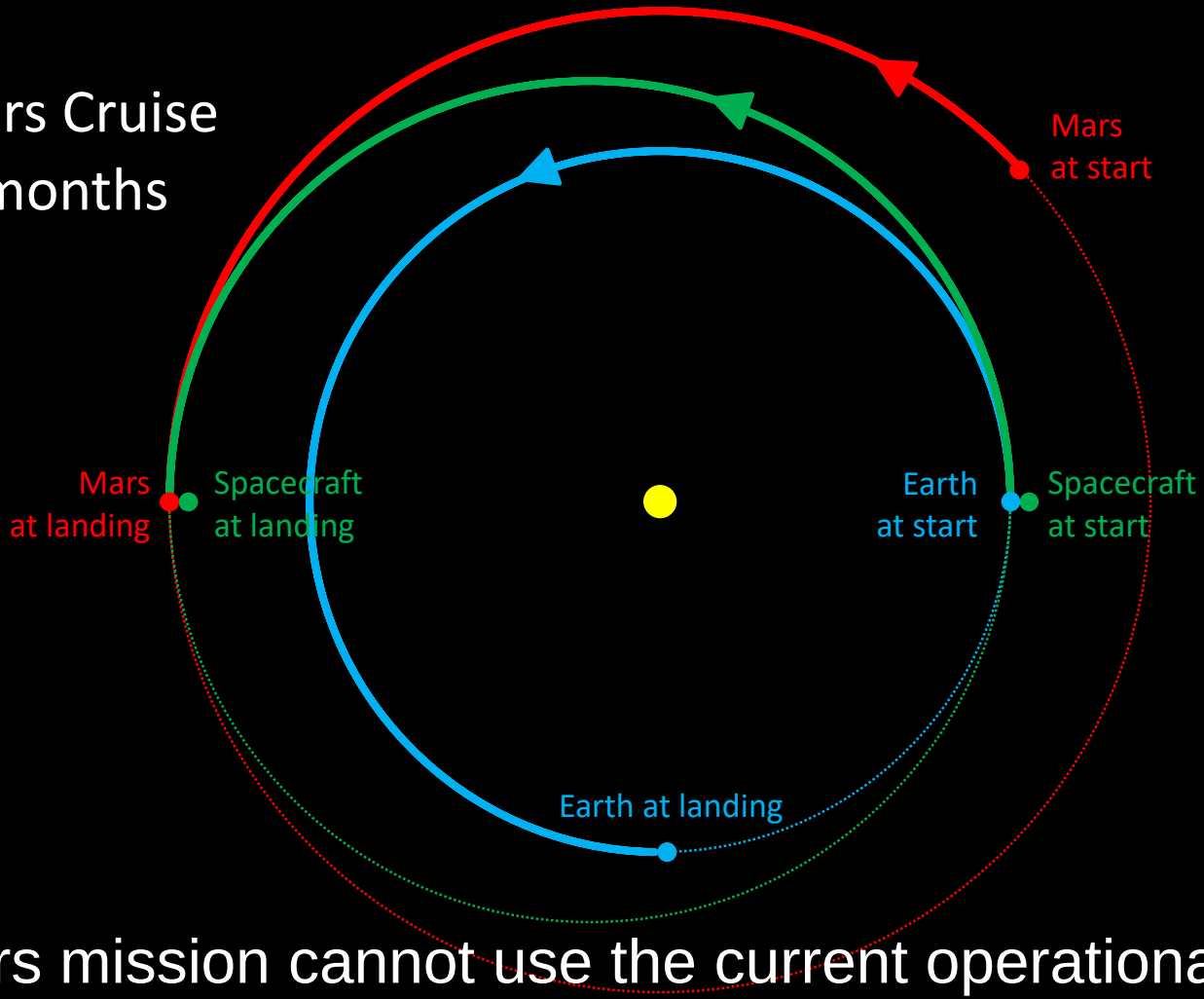



1. Radiation
2. Isolation and Confinement
3. Altered Gravity Fields
4. Hostile/closed environments
5. Distance from Earth

A Mars mission cannot use the current operational medical approach because that approach is dependent on evacuation for delivery of definitive care.

Access to the Deep Space Network for the vehicle may be as limited as 1 hour in a 24 hour period.

Trans-Mars Cruise
About 9 months



A Mars mission cannot use the current operational medical approach because that approach is totally dependent on real-time communication with the ground.

S. Love, E. Nelson, Mars Mission Concept of Operations, Aug 2016

A Mars mission cannot use the current operational medical approach because that approach requires frequent resupply.

A Mars mission cannot use the current operational medical approach because that approach requires significant, continuous ground support.

Paradigm Shift

How do we scope a medical system to meet the needs of a planetary mission that is:

2-3 times as long as any prior mission

>500 times as far as any prior mission

Vehicle is committed after trans-Martian injection?

MEDICAL PROBABILISTIC RISK ANALYSIS

Exploration 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

*SA – Space Adaptation

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

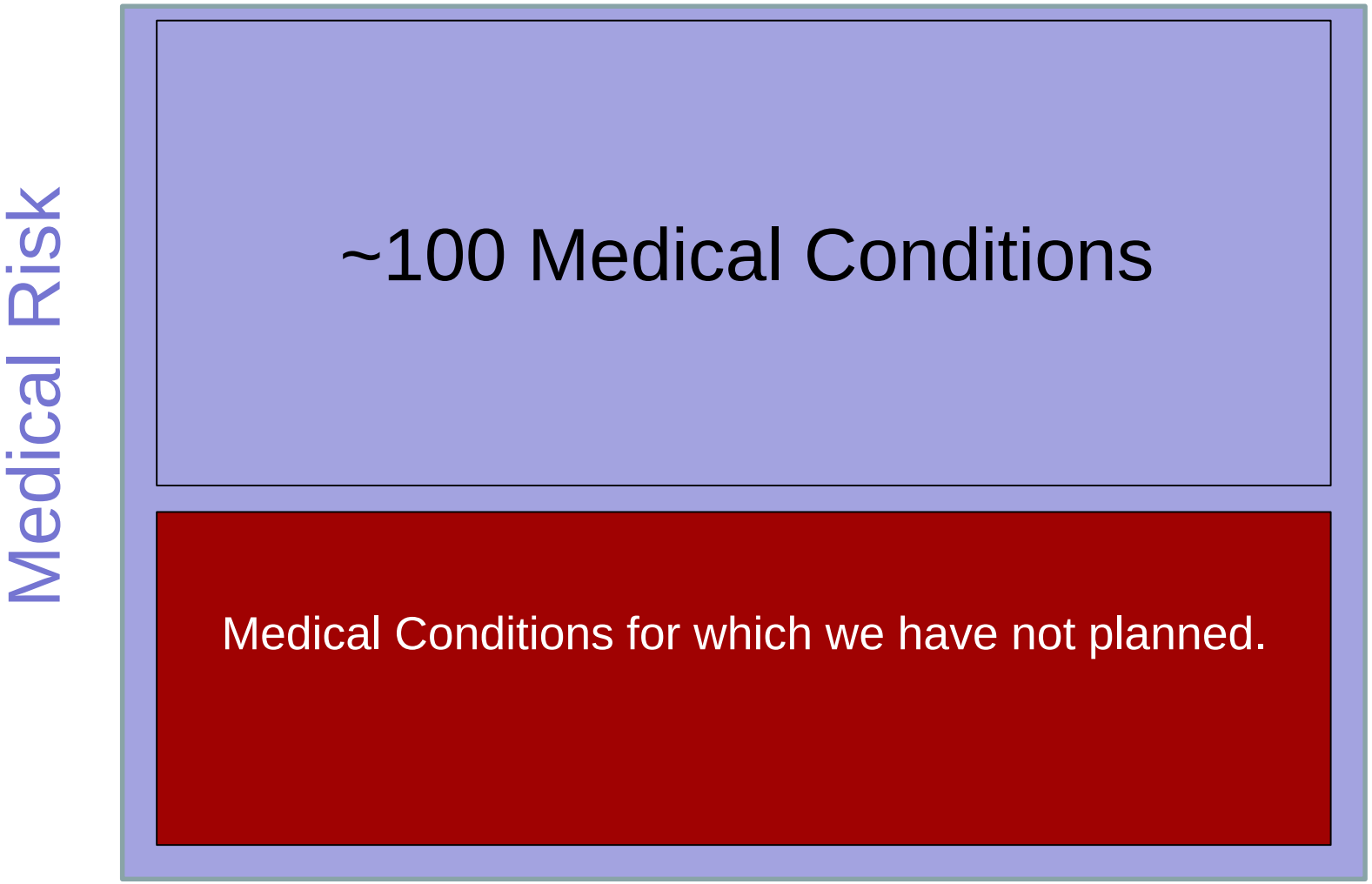
GENITOURINARY
- Abnormal Uterine Bleeding
- Acute Prostatitis
- Nephrolithiasis
- Urinary Incontinence (SA)
- Urinary Retention (SA)
- Vaginal Yeast Infection

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

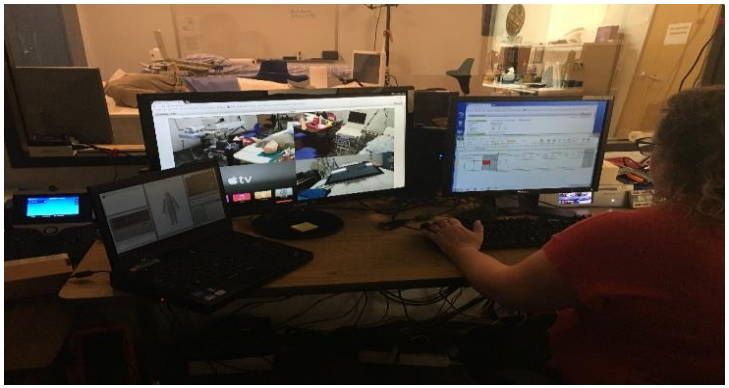
IMMUNE
- Allergic Reaction
- Anaphylaxis
- Skin Rash
- Medication Reaction

ENVIRONMENT
- Acute Radiation Syndrome
- Altitude Sickness
- Decompression Sickness (EVA)
- Headache (CO_2)

Spaceflight Medical Risk

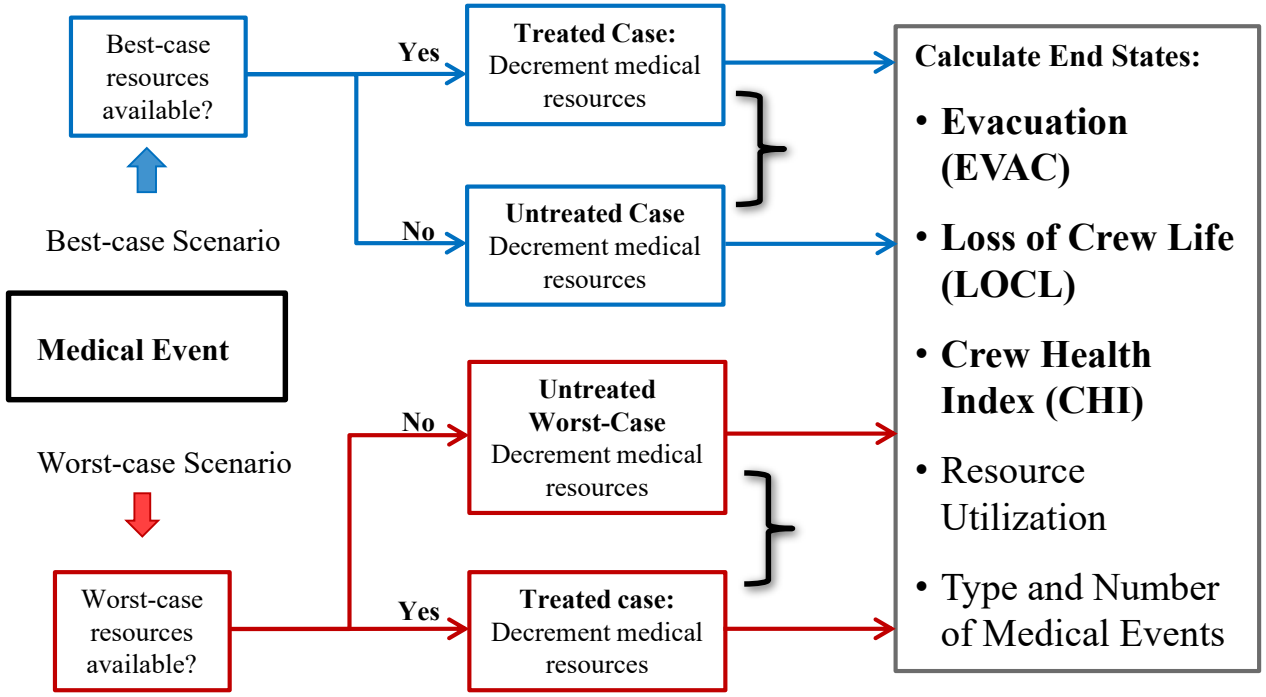


Extrapolating Medical Risk



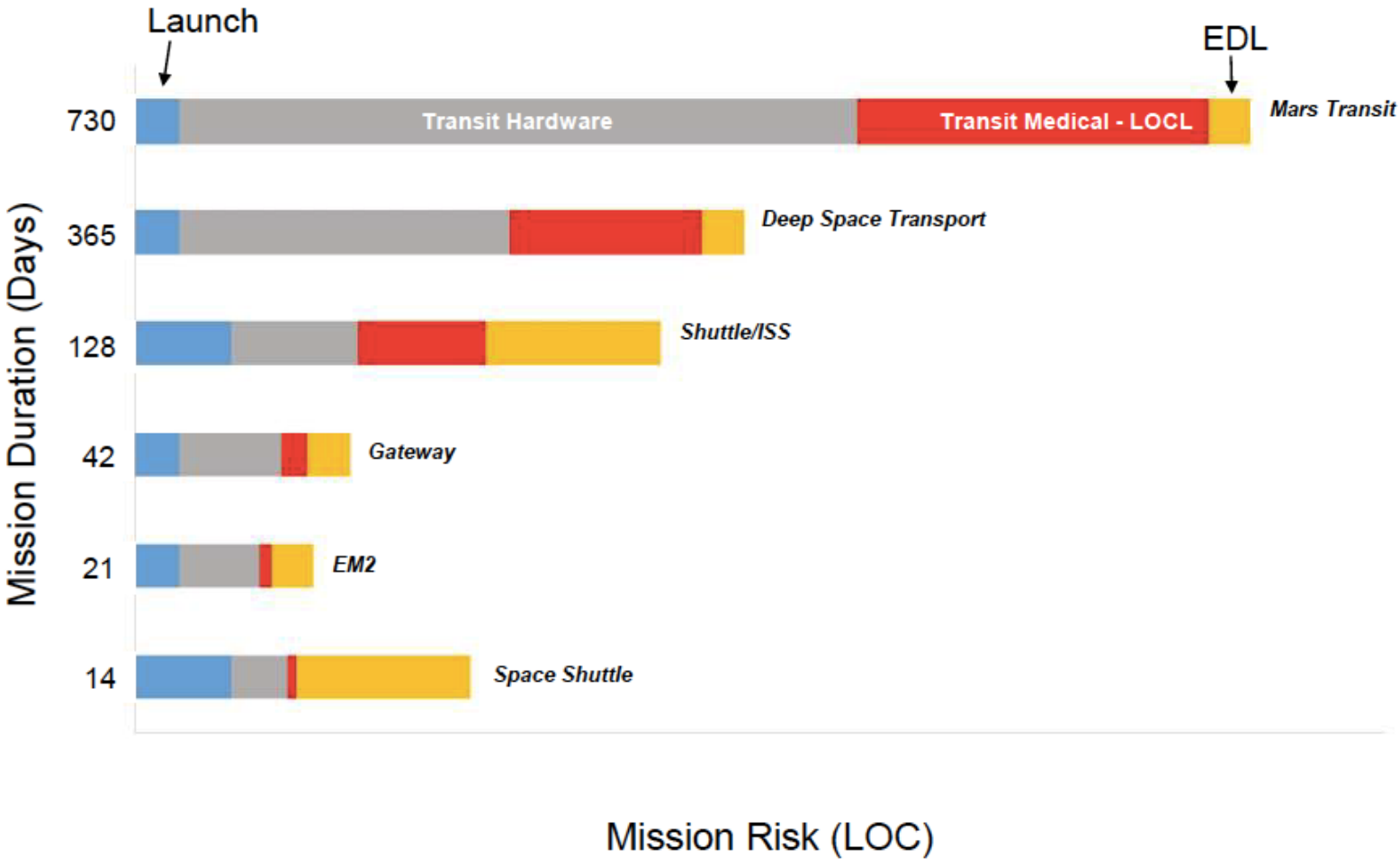
- **Lack of single source for data**
- **Flight data- high internal validity, small volume**
- **Analog data- Lower validity, higher volume**
- **Expert opinion**

Probabilistic Risk Assessment



Slide courtesy of E Kerstman

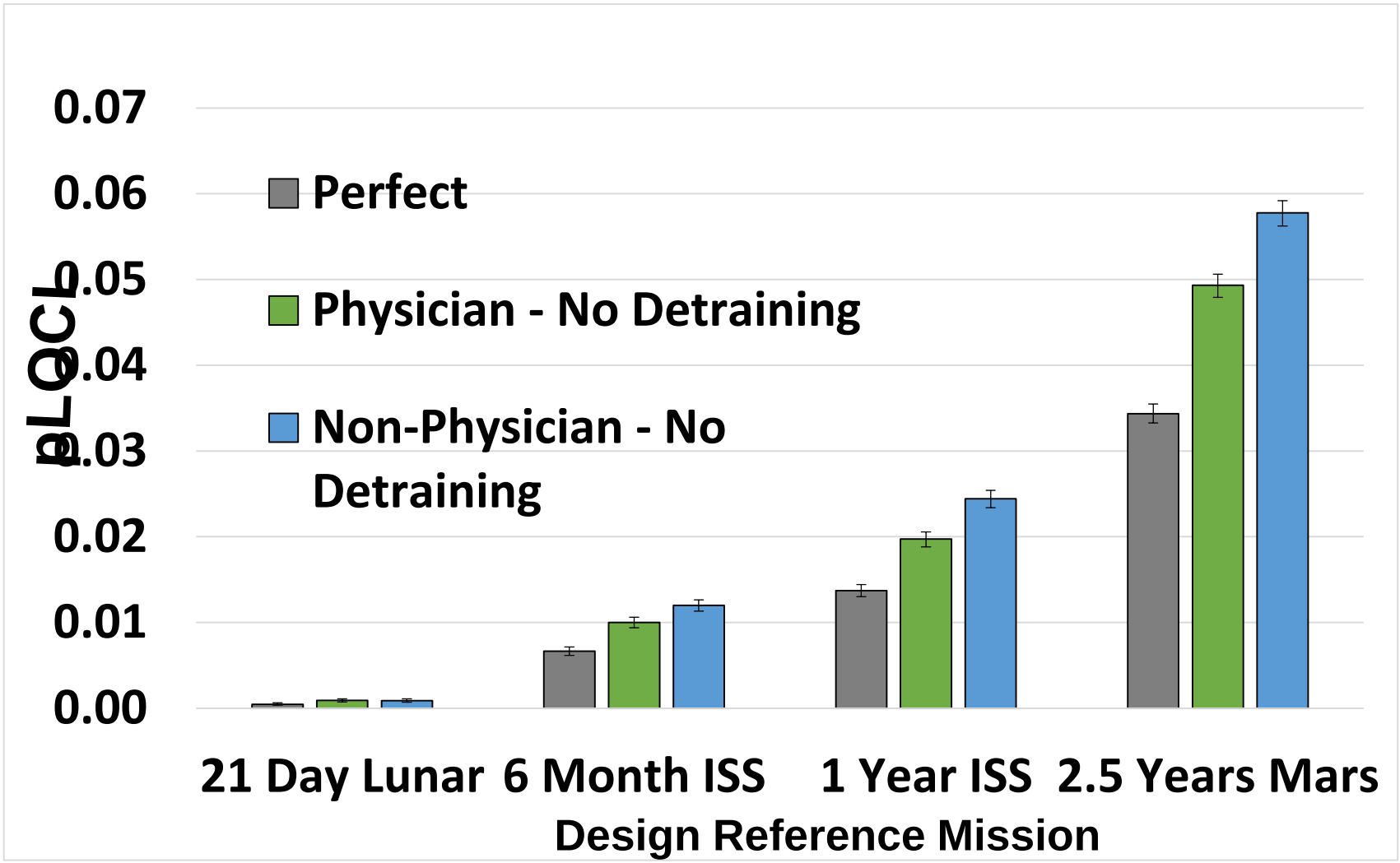
Proportion of Mission Risk attributable to Medical



Some IMM Assumptions…

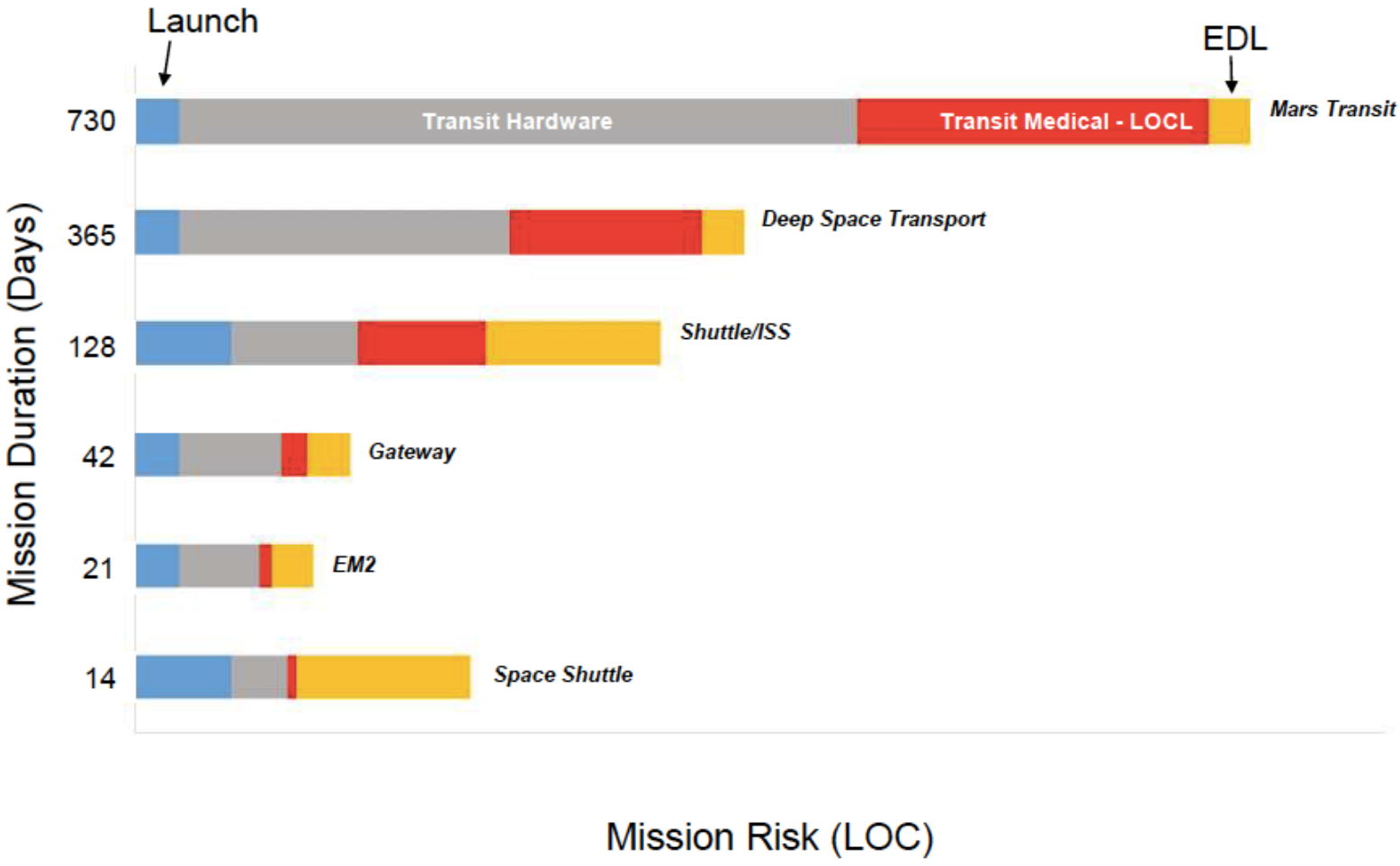
1. All diagnoses are 100% accurate.
2. All events receive appropriate treatment.
3. All meds and equipment are 100% reliable and effective.
4. All events respond as they would terrestrially.
5. No mistakes in medical procedures (regardless of training)
6. Power, water, oxygen unlimited

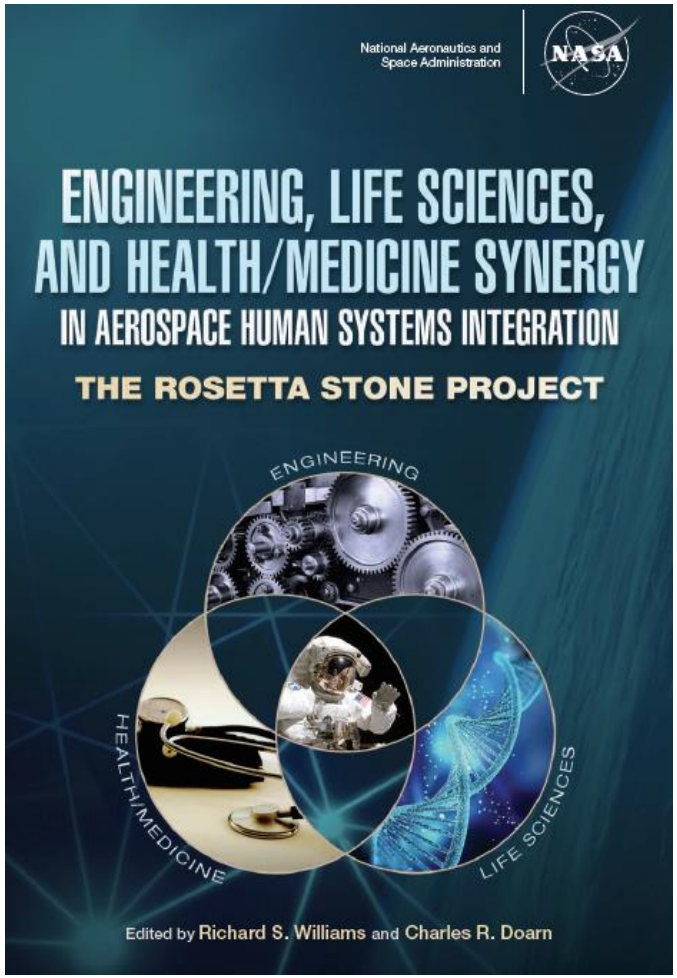
PRA Estimates of Loss of Crew Life



Slide courtesy of E Kerstman

Proportion of Mission Risk attributable to Medical



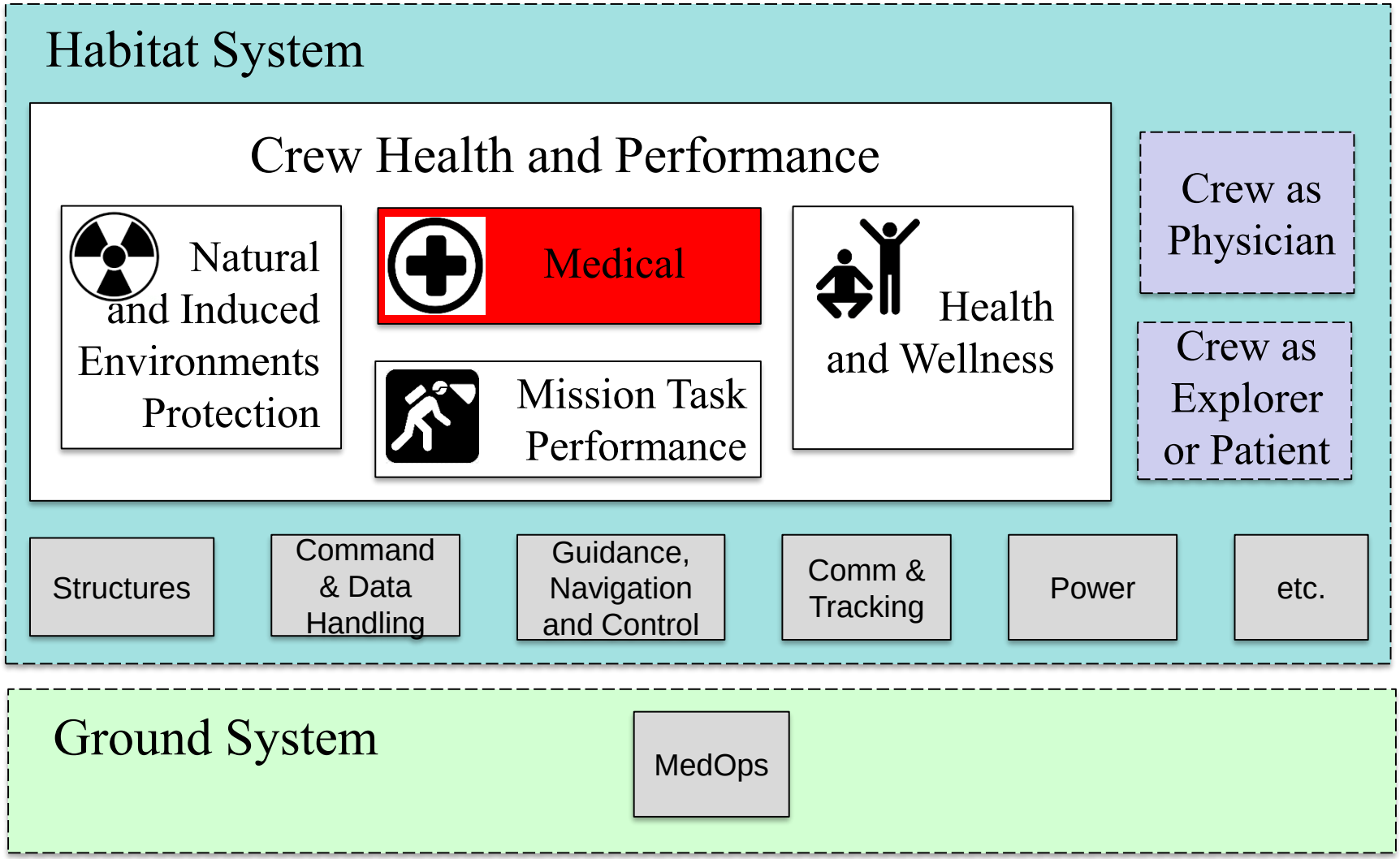


"…[The] assumption has been that **risk of vehicle system malfunction far outweighs the risk of human system failure**…NASA buys down the risk of failure of the human system through rigorous selection of individuals designed to minimize medical issues and optimize available capability in flight."

NASA SP-2017-0633

CREW HEALTH AND PERFORMANCE SYSTEM

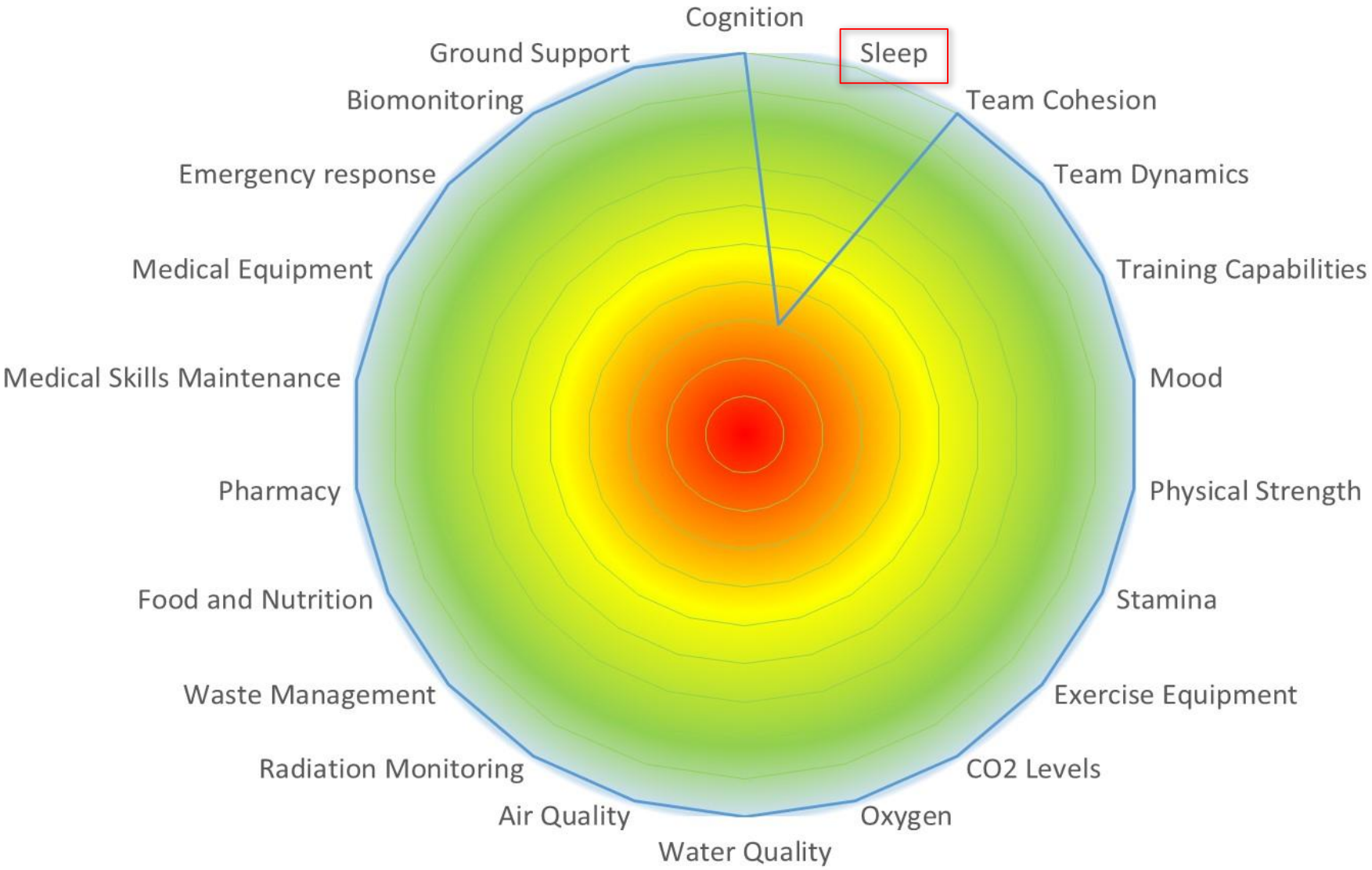
Vehicle/Mission Architecture Integration



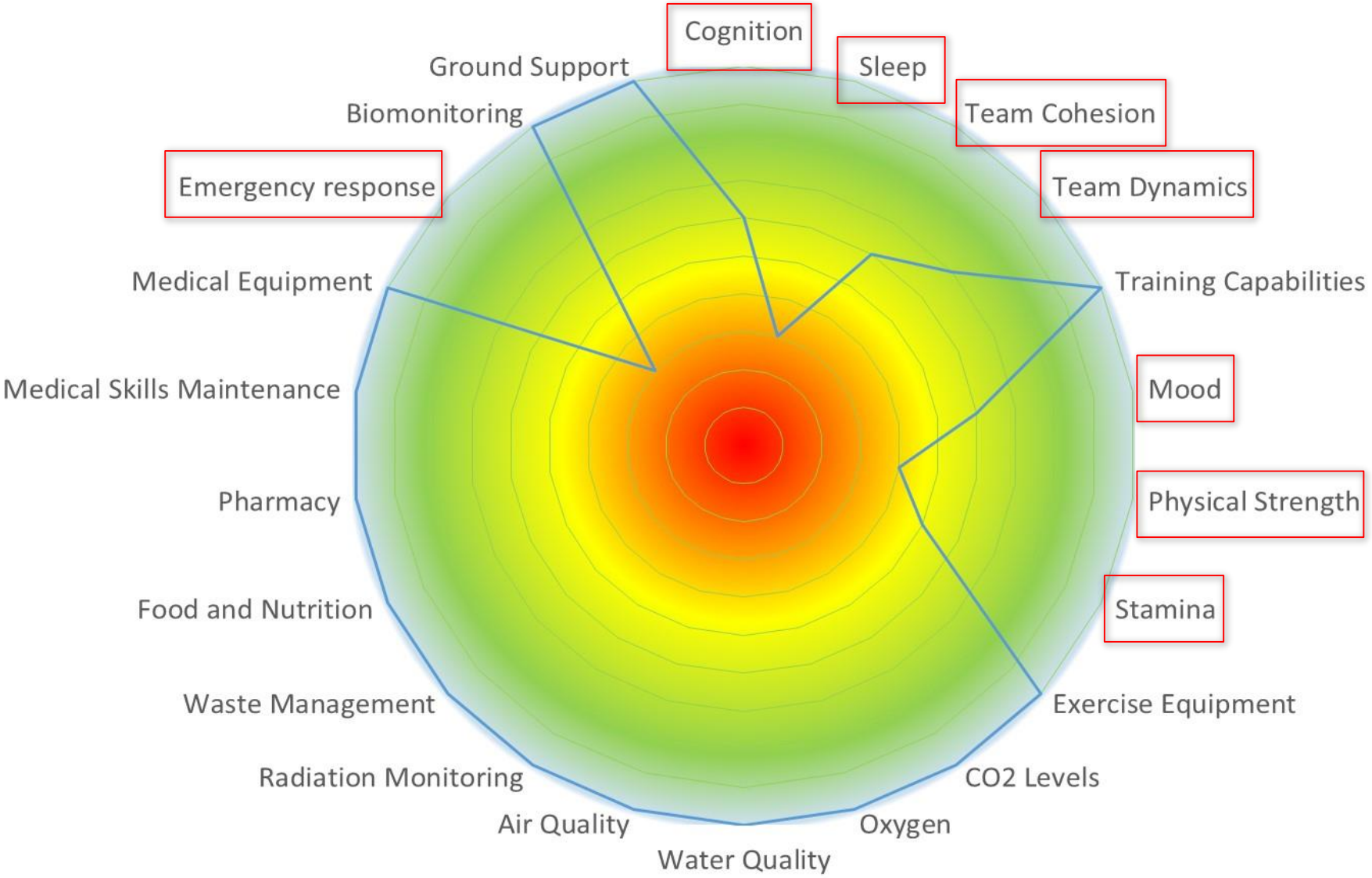
Crew Health and Performance System Must…

- **Protect from environmental hazards**
  - Radiation protection
  - Noise, vibration, CO_2, etc.
- **Keep healthy crew well**
  - Exercise
  - Other physiological countermeasures
  - Food
  - Behavioral health
- **Prevent, diagnose, treat, manage long-term health care**
  - Data system
    - Medical Data Capture
    - Medical Training
  - Medical devices
  - Medical supplies
- **Support crew to accomplish mission tasks**
  - Procedures
  - Training
  - User interfaces

System Performance Threatened by Sleep Deficit



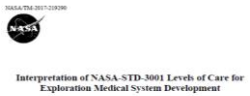
Sleep Deficit Affects Other System Aspects



Translate Medicine to Engineering

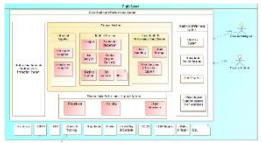
Stakeholder needs, goals

NASA Standards


Interpretation of NASA-STD-3001 Levels of Care for Exploration Medical System Development

Program requirements & architecture

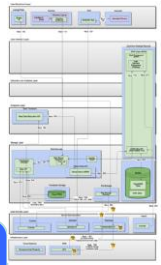
System functions & behaviors



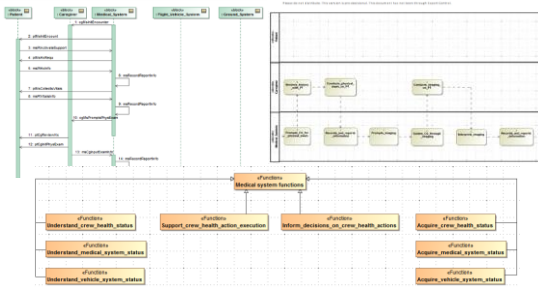
System requirements & architecture


Medical System Concept of Operations for Mars Exploration Missions
Exploration Medical Capability (ExMC) Element
Human Research Program
Verify that this is the correct version before use.
Pre-Baseline
February 2017

Subsystem requirements & architecture

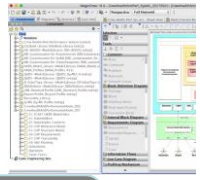


Characterize system



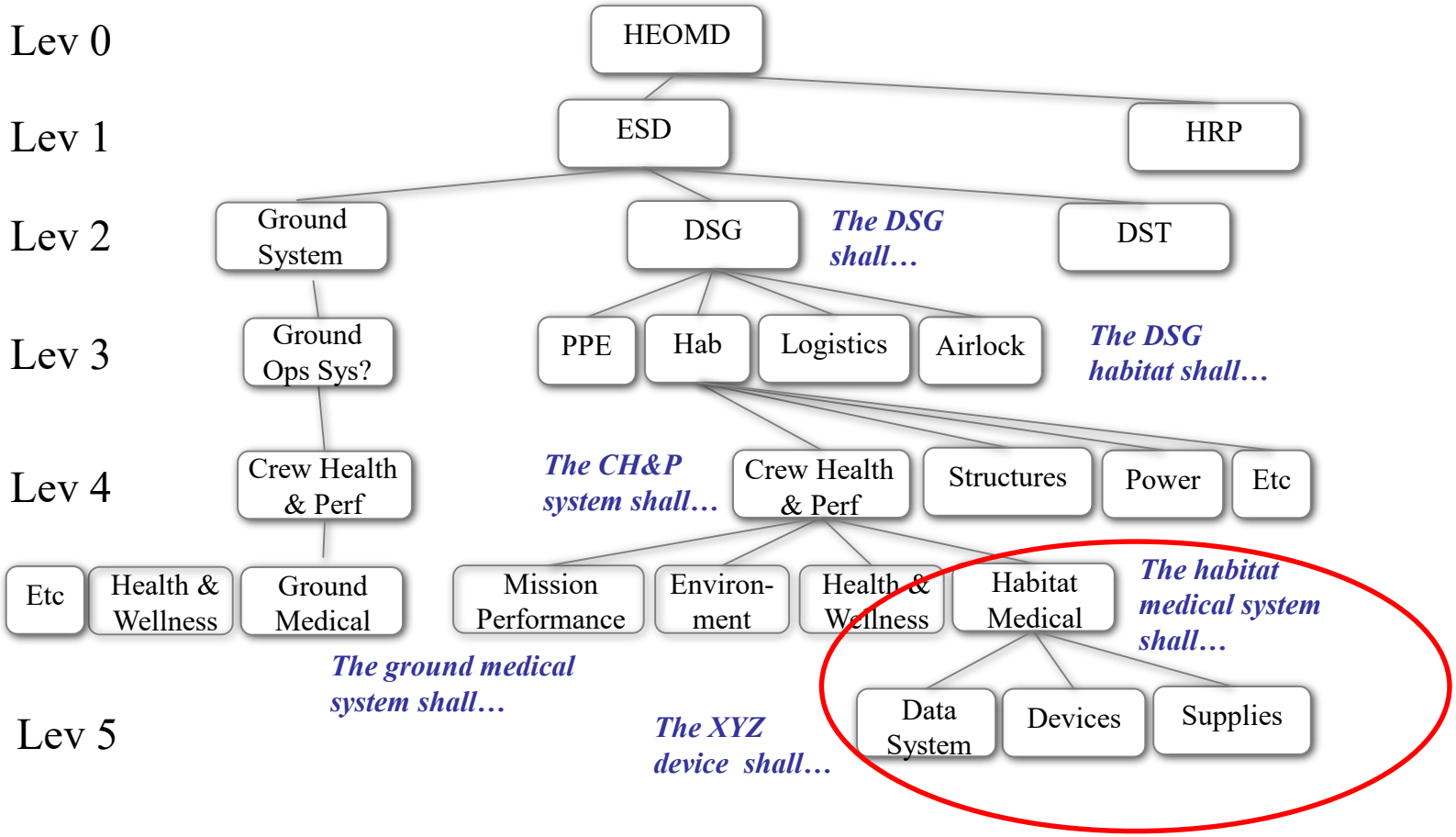
Do we have the capabilities to meet the needs?
What allocations are necessary?

Analyze & trade



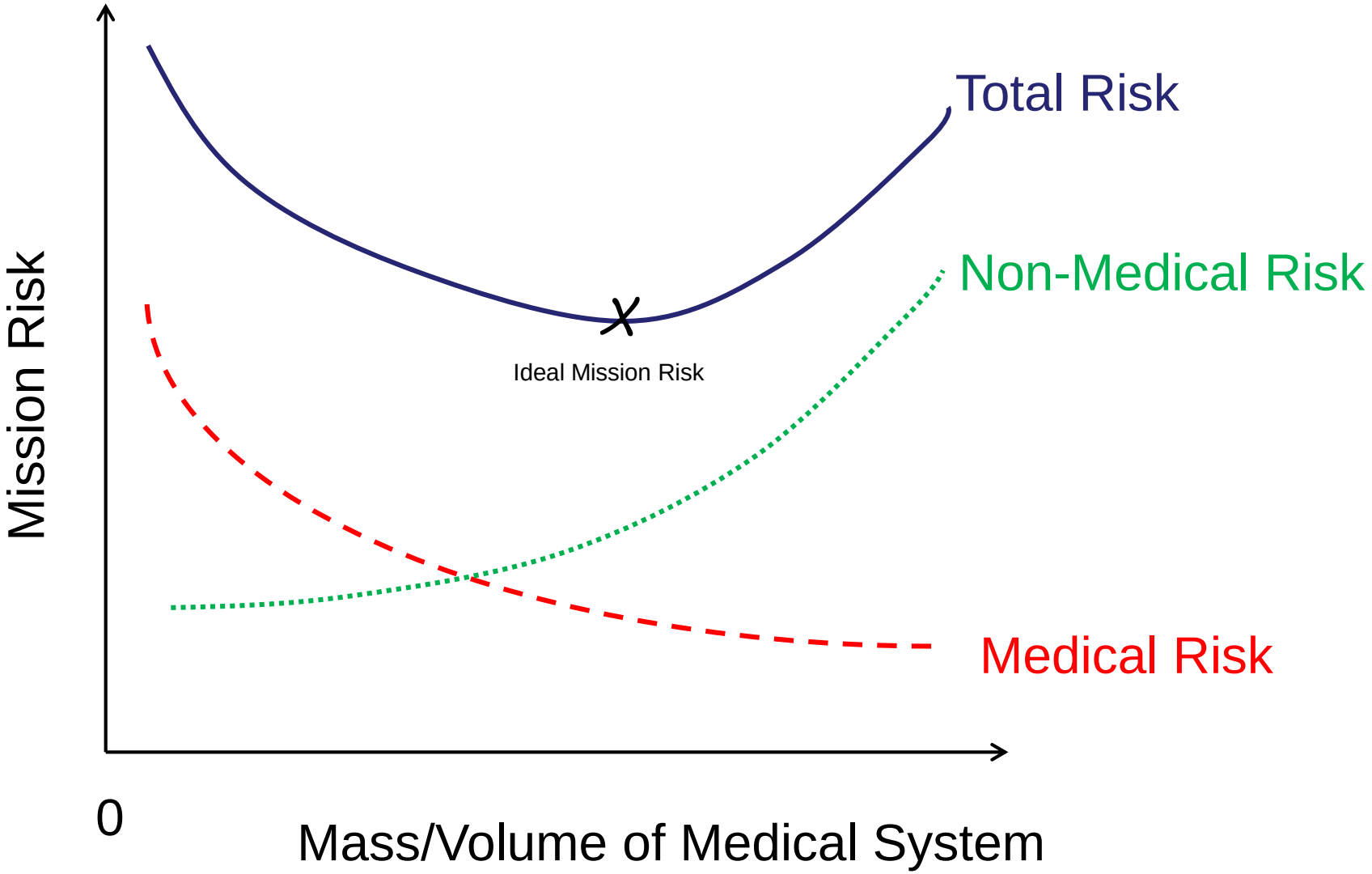
Design & Build

NOT Official – best guess on requirements context



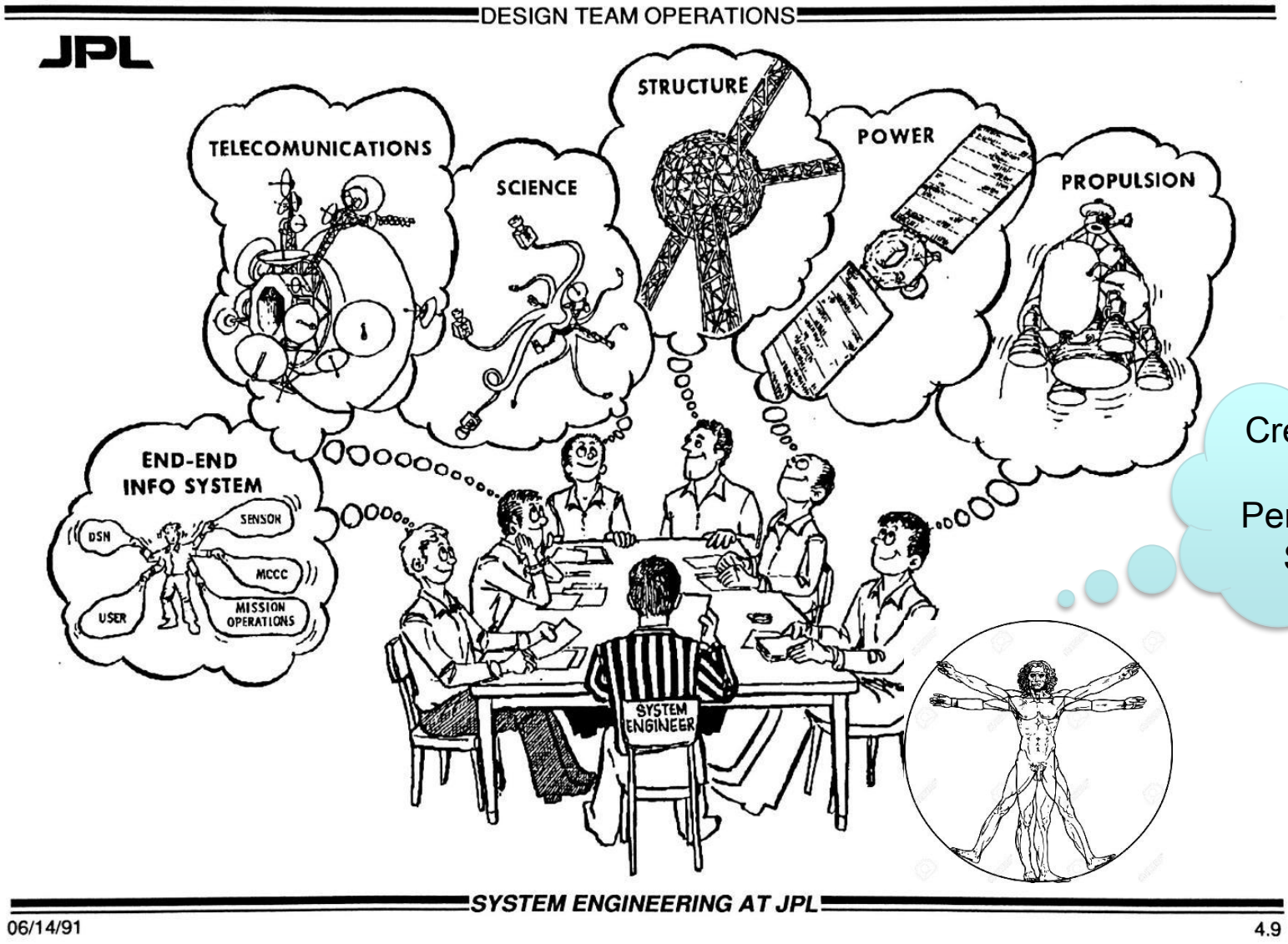
TRADE SPACE ANALYSIS

Medical and Non-medical Risk



Notional

Medical Systems Engineering



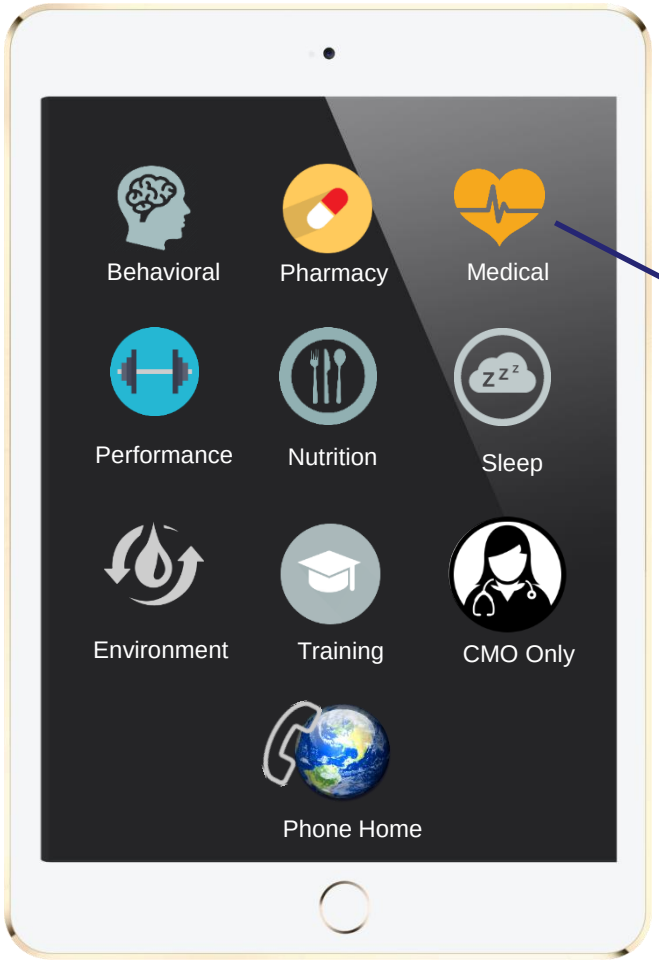
Crew Health and Performance System

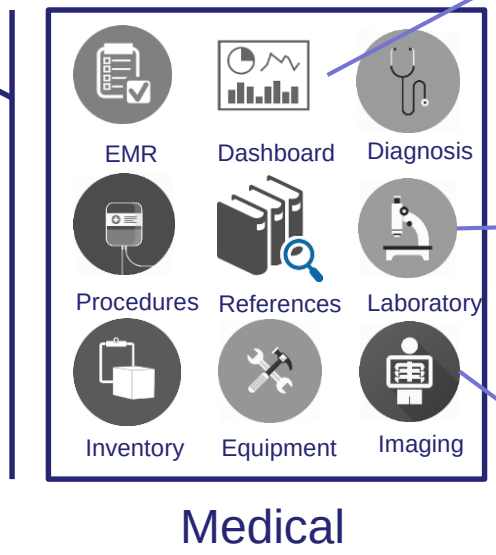
From "System Engineering at JPL" training course material, June 1991

MEDICAL DATA ARCHITECTURE

We're not bringing an Intensive Care Unit but…

Crew Health and Performance System



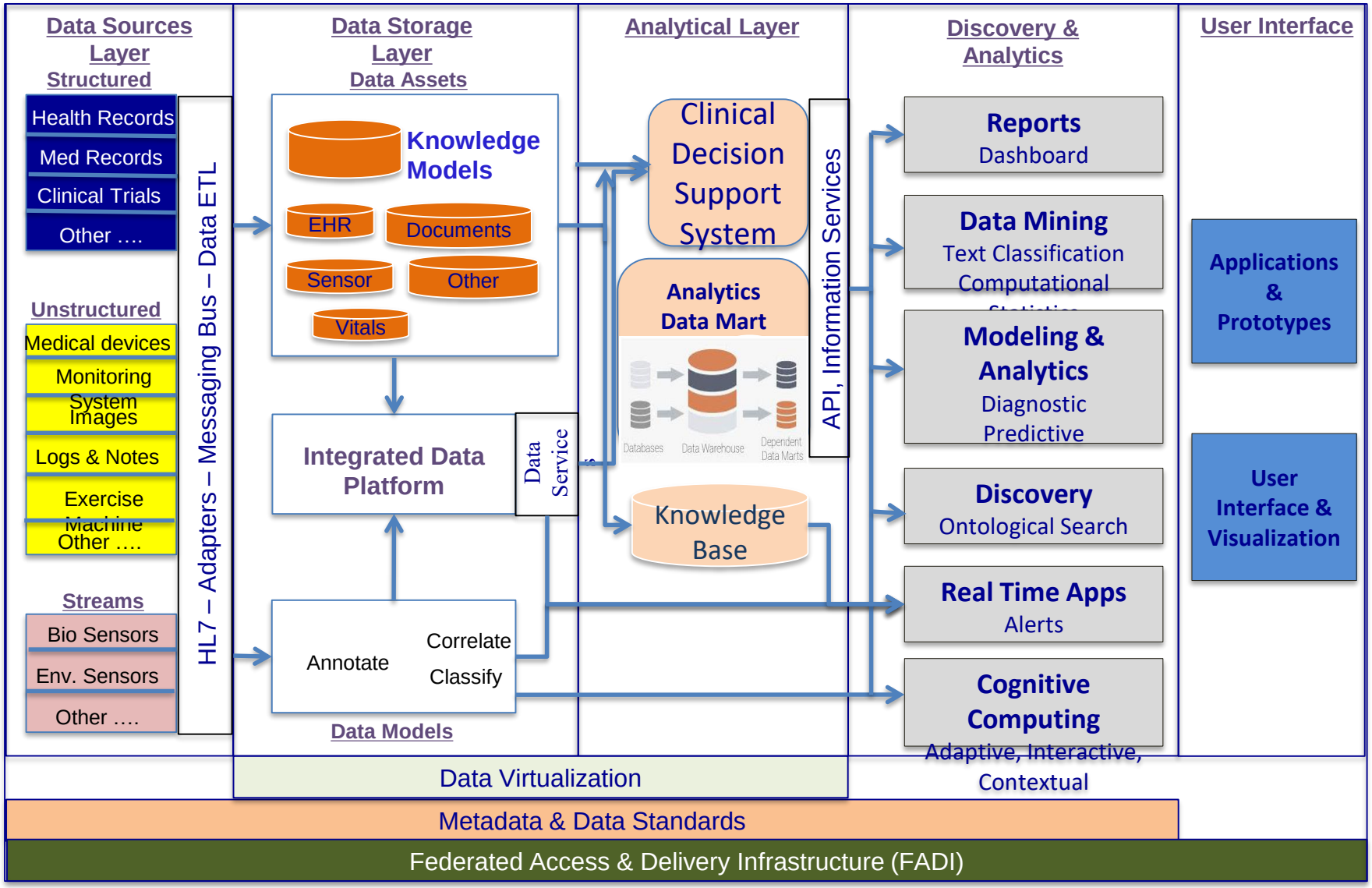


Medical

These technologies exist today

Notional

Where are we today? MDA



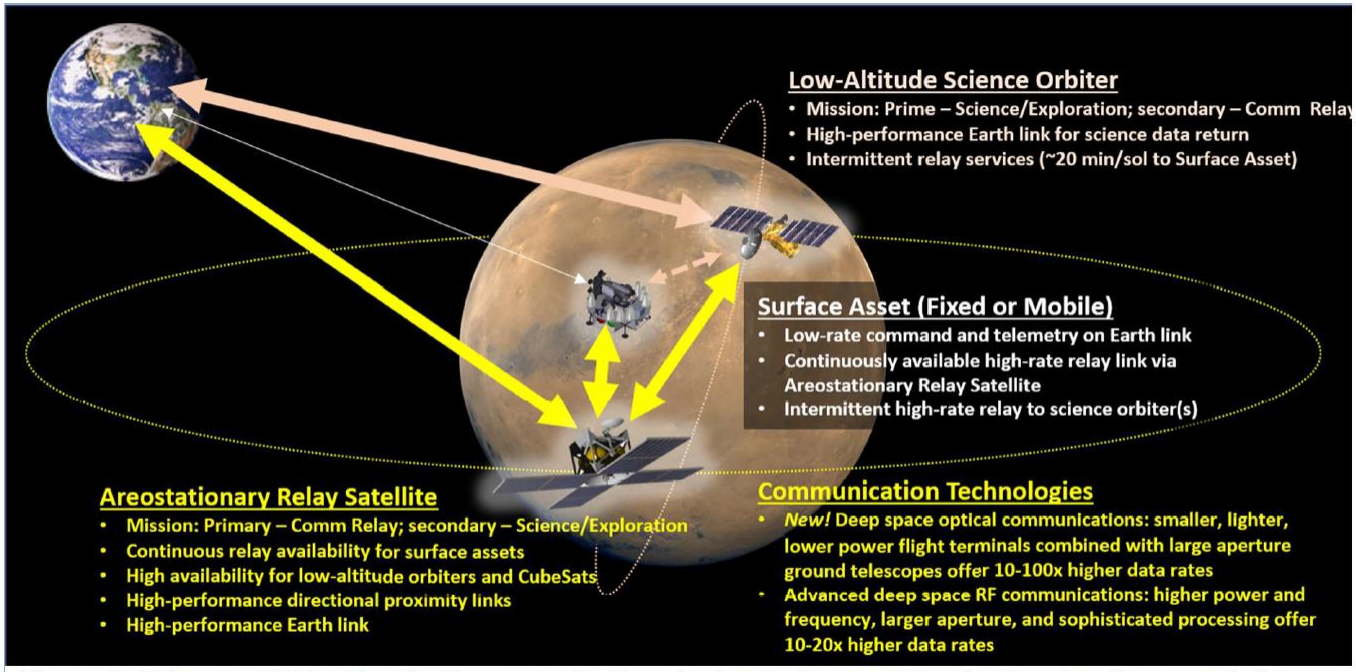


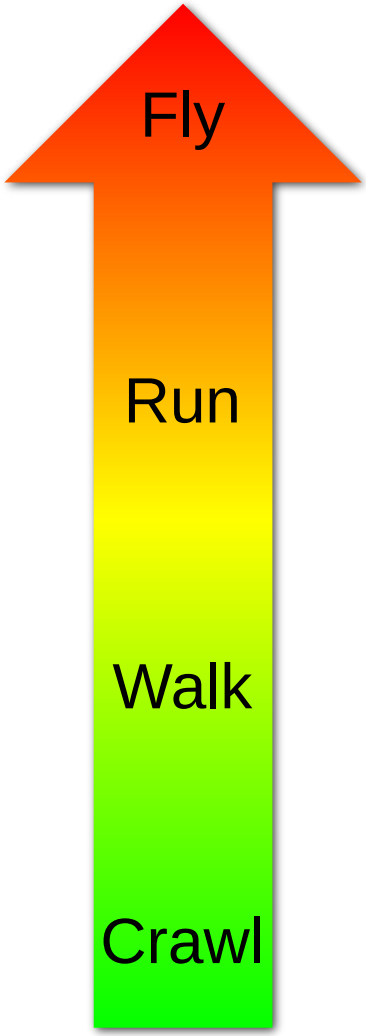
Figure 1. Advanced RF and optical communications technologies combined with using the areostationary orbit offer 100-1000x greater data return from Mars and nearly continuous availability.

Table 1. High-Performance Mars-Earth Trunk Line Capability

	Frequency Band	Maturity	S/C Aperture	S/C Txmt Power	Ground Receiver	Data Rate (@ 2 AU)
Current State-of-the-Art (MRO)	X-band	Operational	3 m	100 W	34 m DSN BWG antenna	**1 Mb/s**
Next-Generation Trunk Line Options	Ka-band	TRL 6	3 m	200 W	34 m DSN BWG antenna	**5 Mb/s**
		TRL 3-4	5 m	1 kW	34 m DSN BWG antenna	**70 Mb/s**
	Optical (1550 nm)	TRL 6 (DSOC; to fly on 2023 Psyche Discovery Mission	22 cm	4 W	5 m ground telescope	**1 Mb/s**
		TRL 3	50 cm	50 W	12 m ground telescope	**100 Mb/s**

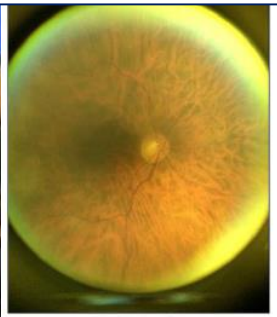
Can we replace the doctor?

- **Full Artificial Intelligence**
- **Integrative Health and Performance Prediction**
- **Condition Specific Guidance**
- **Differential Diagnosis Generation**
- **Automated Image/Data Analysis**
- **Knowledge Support/Known Algorithm Provision**
- **Preventive Care Strategies**



Autonomy - COMfORT

Fundoscopy – Retinal Imaging

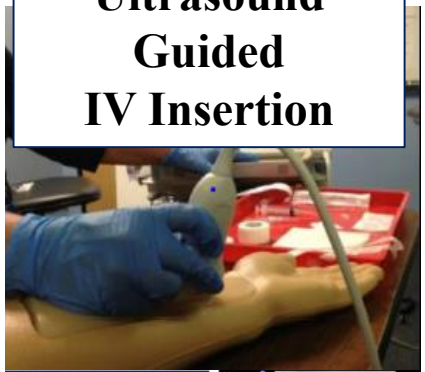


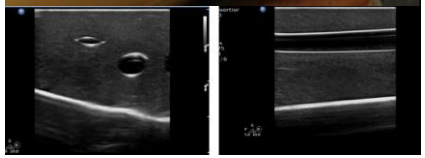
Good composition

Urinary Tract – Kidney and Bladder Ultrasound Imaging

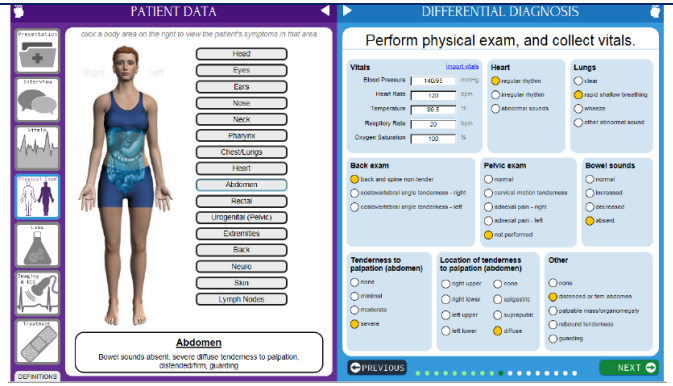
Intubation Emergency

Ultrasound Guided IV Insertion





Diagnosis and Treatment Exercise



Fundoscopy Module

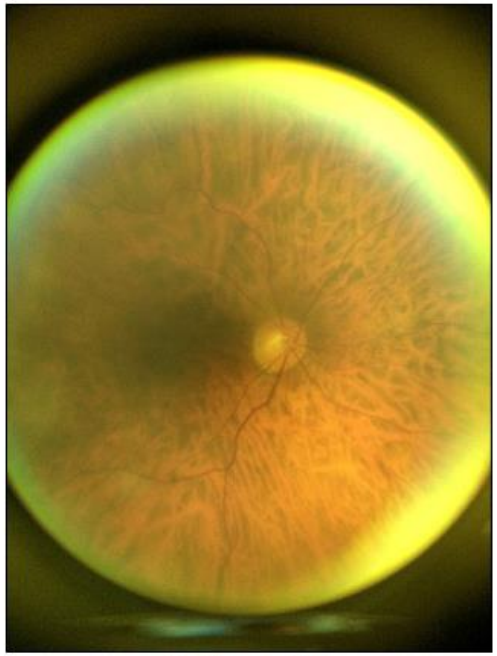
Taking a Good Image: Composition

Tips for good composition:

To move the optic disc down the subject needs to look up.

To move the optic disc right the subject needs to look right.

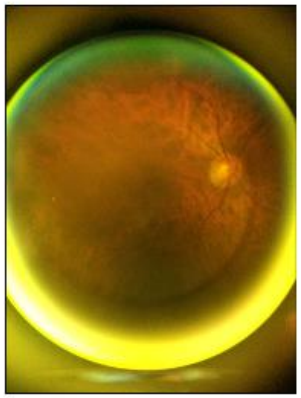
In a good composition the optic disc is centered.



Good composition

Bad composition

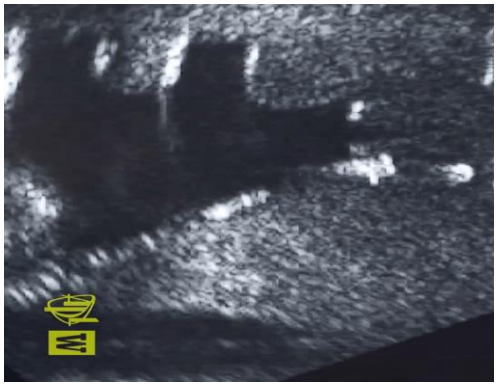
In poor composition, the optic disc is not centered or not visible.



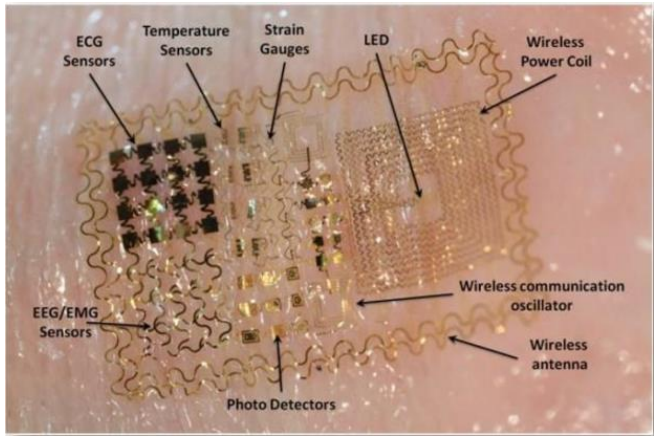
Bad composition
Optic disc is too far right

Bad composition
Optic disc is too low

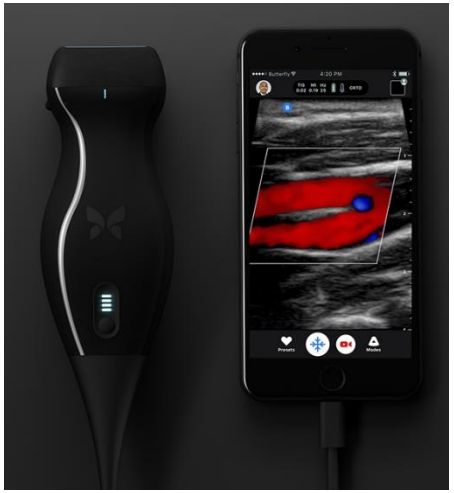
Medical Technology Development



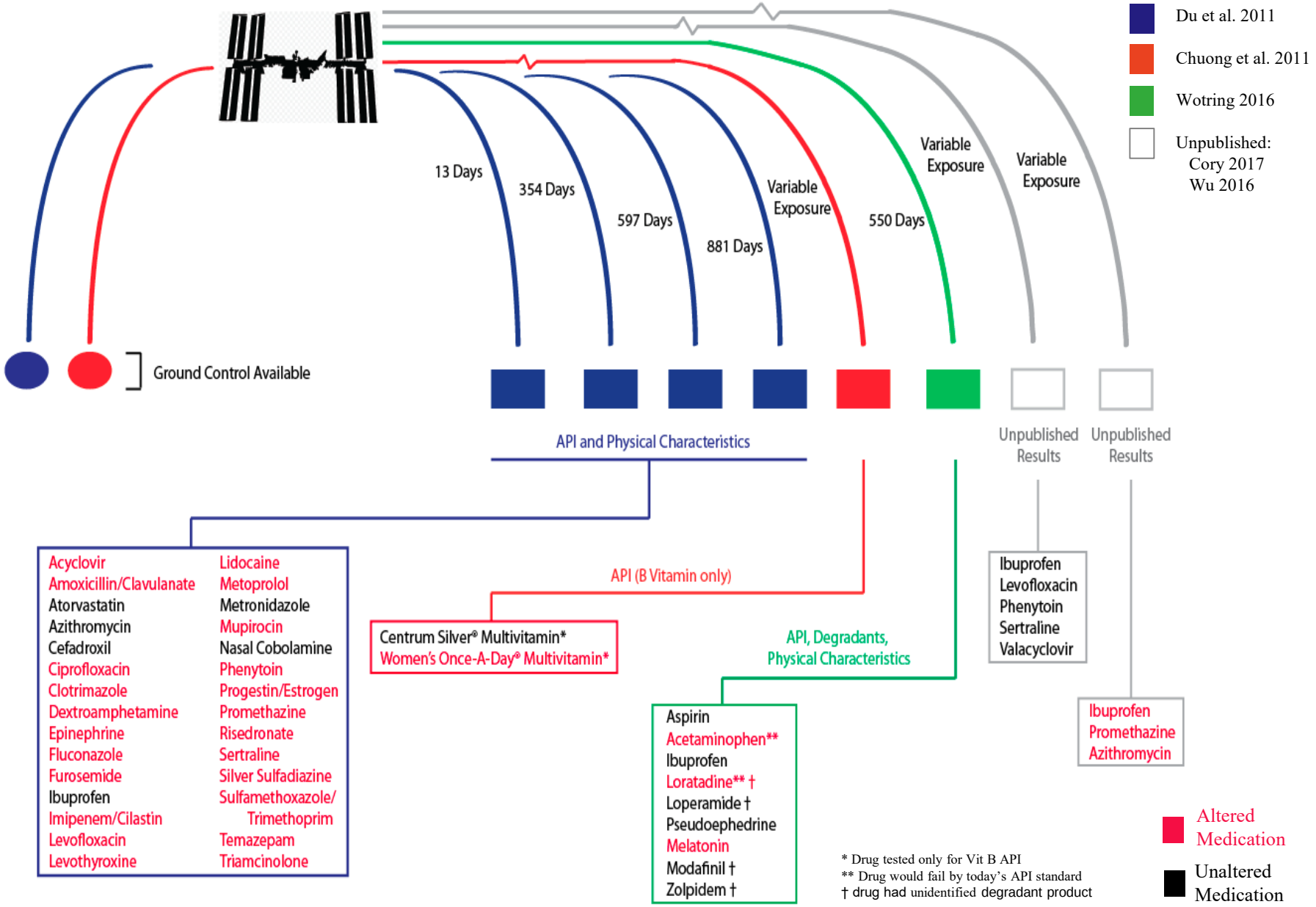
FUS moving stone in ER patient



SEEQ Mobile Cardiac Telemetry System: Medtronic



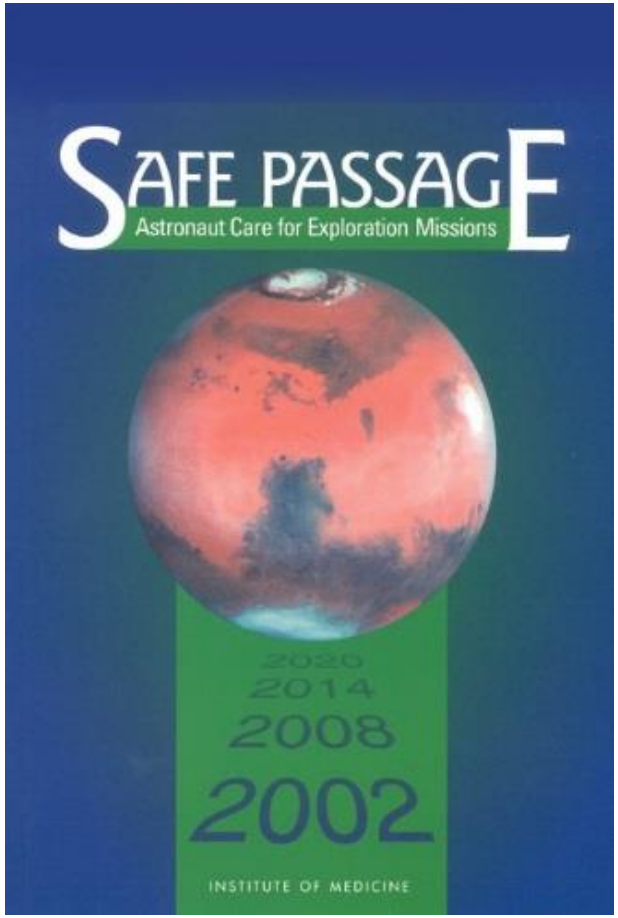
PHARMACY


Du et al. 2011
Chuong et al. 2011
Wotring 2016
Unpublished:
Cory 2017
Wu 2016
13 Days
354 Days
597 Days
881 Days
Variable Exposure
550 Days
Variable Exposure
Variable Exposure
Ground Control Available
Unpublished Results
Unpublished Results
API and Physical Characteristics
Acyclovir
Amoxicillin/Clavulanate
Atorvastatin
Azithromycin
Cefadroxil
Ciprofloxacin
Clotrimazole
Dextroamphetamine
Epinephrine
Fluconazole
Furosemide
Ibuprofen
Imipenem/Cilastin
Levofloxacin
Levothyroxine
Lidocaine
Metoprolol
Metronidazole
Mupirocin
Nasal Cobolamine
Phenytoin
Progestin/Estrogen
Promethazine
Risedronate
Sertraline
Silver Sulfadiazine
Sulfamethoxazole/ Trimethoprim
Temazepam
Triamcinolone
API (B Vitamin only)
Centrum Silver® Multivitamin*
Women's Once-A-Day® Multivitamin*
API, Degradants, Physical Characteristics
Aspirin
Acetaminophen**
Ibuprofen
Loratadine** †
Loperamide †
Pseudoephedrine
Melatonin
Modafinil †
Zolpidem †
Ibuprofen
Levofloxacin
Phenytoin
Sertraline
Valacyclovir
Ibuprofen
Promethazine
Azithromycin
* Drug tested only for Vit B API
** Drug would fail by today's API standard
† drug had unidentified degradant product
Altered Medication
Unaltered Medication

Other Topics within In-Flight Medical Conditions

- Imaging
- Rehabilitation
- Lab Analysis
- Biomonitoring and Wearables
- Personalized Medicine
- Renal Stones

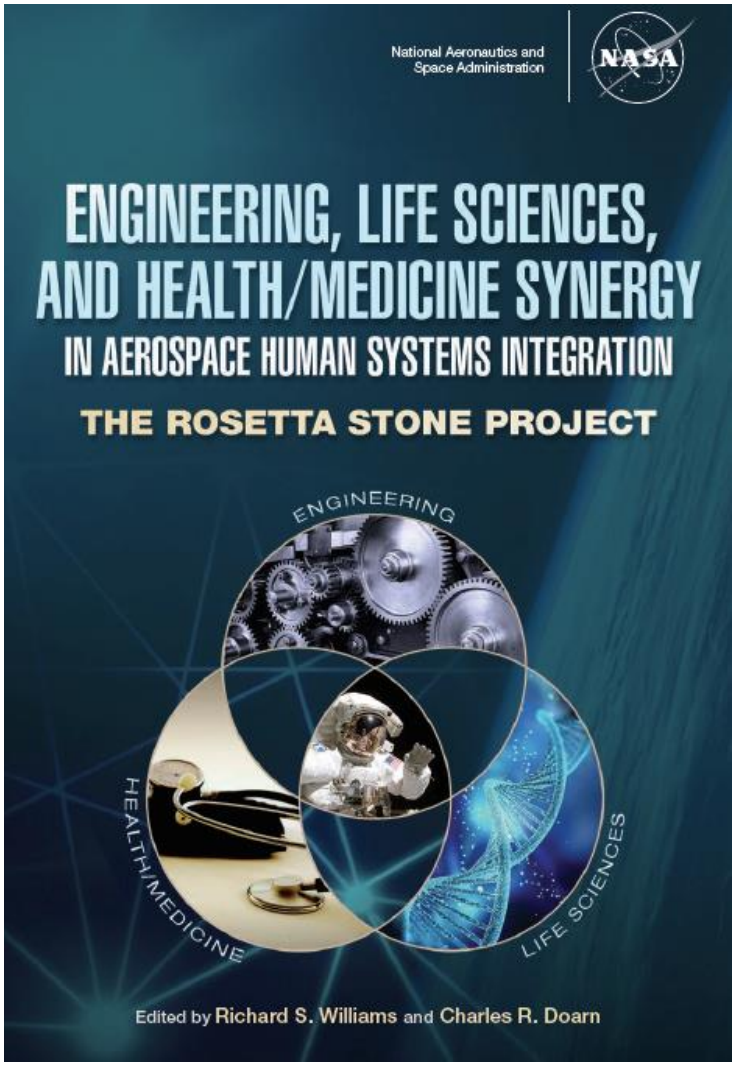
Safe Passage



- *From Conclusion 6:*
- *"The human being must be integrated into the space mission in the same way in which all other aspects of the mission are integrated."*

Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit, Board on Health Sciences Policy and I. O. Medicine, *Safe Passage: Astronaut Care for Exploration Missions,* Institute of Medicine of the National Academies Press, 2001.

Rosetta Stone



Questions?

benjamin.easter@nasa.gov