Challenges of Anesthesia & Intensive Care During Future Interplanetary Space Missions

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2018 Society for Technology in Anesthesia

The extension of life beyond Earth is the most important thing we can do as a species.

Human spaceflight

- 555 people
- Over 24 beyond low Earth orbit
- Over 12 on the Moon
- Cumulated presence: ± 140 person-years

[Source: Wikipedia]
Missions to Mars

von Braun, 1952
- 1000 rocket launches
- Fleet of 10 spacecrafts to Mars
- Crew of 70

2009 Constellation program: crew of 6 for 900 days.

100 people per trip
Fully reusable ship
Time of flight 80-150 days
Target price $200,000 per ticket
1 million people on Mars in 40-100 years

Medical


SELF OPERATION

L.L. ROSSOV
Physician, Soviet Antarctic Expedition

In the meeting of March 28, 1962, let us first tell. The antioxidant must not exceed 300 g. Long-term pathogen-free transportation of the patients was achieved by cryopreservation. This method allows to preserve cells and tissues for up to 10 years. The cryopreservation processes in the brain, heart, liver, and kidneys are performed in liquid nitrogen at a temperature of -196 °C. The main goal of the presented pathogen-free transportation is to preserve the health of the patients during the journey. The patients are kept in a coma throughout the journey. Once they reach their destination, the patients are awake and free from any pathologies. The cryopreservation technology is widely used in medical practice. It allows to store cells and tissues for long periods of time and to use them for transplantation.
Challenges for healthcare delivery in space

<table>
<thead>
<tr>
<th>On Earth</th>
<th>In space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient's physiological status</td>
<td>Pathological state</td>
</tr>
<tr>
<td>No</td>
<td>Perfect fitness before launch</td>
</tr>
<tr>
<td>Technical constraints</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>Major</td>
</tr>
<tr>
<td>Medical skills limitations</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>Important</td>
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</table>


The Space Environment

Weightlessness

O₂ 21%
Pressure 101.3 kPa
Temperature 23.6 °C
60% relative humidity
Spaceflight dynamics

Barometric pressure: 0 kPa
Temperature: -120 to +150 °C
Solar and galactic radiation
Space debris

Medical concerns for space exploration missions
Space analogue environments

<table>
<thead>
<tr>
<th>Low Earth Orbit</th>
<th>LMIC / humanitarian</th>
<th>Combat</th>
<th>Isolated &amp; Confined Env.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of LEO as analogue for interplanetary travel research.</td>
<td>Resource-poor setting with lack of equipment and medical expertise.</td>
<td>Out of hospital austere setting, high prevalence of severe ac. mountain, high altitude, polar, jungle, desert.</td>
<td>Expeditions in environments such as: mountain, high altitude, polar, jungle, desert.</td>
</tr>
</tbody>
</table>

Mission to Mars: concerns for medical operations

- Radiation
- Bone loss
- Cardiovascular deconditioning
- Fitness for surface activities?
- Psychological screening and team composition?
- Onboard medical skills?
- Hypobaric DCS
- Increased remoteness, no evacuation, no telemedicine
- Increased mission duration = increased risk of medical events

Risk of events requiring anesthesia

- **Barratt & Pool, 2008:**
  - 1 surgical event every 3-6 years for a 6-person space station.
- **Comet, 2002:**
  - 2.6 year mission, 6-person crew.
  - Conditions requiring anesthesia: 2.8% risk of occurrence.
- **Billica, 1996:**
  - 1 significant illness during a 2.5 year mission to Mars for 6-person crew.
Designing a medical kit for Mars

• Must balance:
  • Crew skills
  • Expected load of medical conditions
  • Weight and volume restrictions (Mars>>ISS)
• Statistical approach: the NASA Integrated Medical Model
  • Principle: Monte Carlo simulations of outcomes under various constraints
  • Prediction of station evacuation and loss of crew life in different scenarios and with different medical kits
  [Kerstmann 2014]

Medical skills on board

• On the ISS:
  • 1 crew medical officer, not necessarily MD
  • If not MD: 50 hours of medical training
  • Can reach medical facility on Earth in 12-24h
• For Mars: best profile could be an emergency medicine physician with additional skills in surgery and wilderness medicine
• Maintenance of skills during the mission?
• What if physician ill, injured or dead?
• Skills redundancy?
  [Saluja 2008, Kuypers 2013]

ISS Crew Health Care System (CheCS)

• Packs and subpacks
  • 31 kg
  • 133 litres
• Available gas (tanks)
  • 100% O2
  • Nitrogen
  [CheCS Hardware Catalog Version 10.0, 2011]
ISS Advanced Life Support Pack
- Assessment Pack
- IV Administration Pack
- Drug Pack
- Intravenous Fluid: 5L Sodium Chloride Solution
- Airway Pack
- Ambu® Bag and Mask
- Emergency Surgery Pack

Crew Medical Restraint System (CMRS)

Automated External Defibrillator
Cardiopulmonary resuscitation

Proposed cardiac massage techniques:

- Handstand
- Reverse bear hug
- Evetts-Russomano

Dalmarco et al., 2006
Rehnberg et al., 2011

Intubation kit / Airway pack

- Ambu® bag
- Face mask
- Oral and NP airway
- Laryngoscope
- Macintosh 3 blade
- Size 7 and 8 tubes
- Magill forceps
- Fastrach®
- Surgical tracheostomy kit

Respiratory Support Pack (RSP)
Ultrasound

Automated diagnostic systems

CONVOLUTIONAL NEURAL NETWORK

[MathWorks.com]
[On the ISS,] “we can stabilize someone who has a dramatic injury but we can’t sustain a patient for long” — Dr Michael Barratt

Ethical dilemma of severe medical conditions during future interplanetary flights

- Non survivable conditions → no ethical issue
- Condition that could be survivable but would require using all available resources → decision?
- Ethically very difficult:
  - Maximum treatment?
  - Substandard treatment?
  - Palliation?

Clinical scenarios
Scenario: sepsis during the transit

Cardiovascular system in microgravity

Intravenous fluids?

- Currently < 4L on the ISS
- For Mars: IV fluid generator is needed
- NASA experiment IVGEN

Prototype: Clearwater IV-Grade Water Filtration System.
Fluid administration in microgravity

ISS Drugs Pack

- 190 medications
- Will need profound update for space exploration missions.

Scenario: orthostatic hypotension

- Off-nominal Mars landing
- Capsule capsized
- Require emergency egress
Orthostatic hypotension on return to gravity

“The most significant operational risk associated with the cardiovascular system of astronauts.”

Hypovolemia
Hyporeactivity of vascular receptors
Artificial gravity

Concept Nautilus-X

E.g., with diameter 12m and rotation speed 7.5 RPM: gravity = 0.38 G

Credit: NASA TAAT

Closed-loop hemodynamic optimization

Feasibility of automated titration of vasopressor infusions using a novel closed-loop controller.

Scenario: fracture on Mars

• Significant risk of trauma & fractures during surface activities: 500 EVAs planned (NASA)
• On Mars surface, crew geologist falls from height.
• Open ankle fracture inside suit, suit intact.
• Need external reduction and fixation.
• What would you do? (all equipment available)
  • Orthopedic treatment alone
  • Femoral + sciatic block
  • Spinal
  • GA
Surgery in space
- Research is active [Drudi 2015, Ball 2012, Campbell 2009, Kirkpatrick 2009…]
- Anesthesia represents a gap in space medicine knowledge and technology.

Choice of anesthetic technique
- Limit to a small number of safe, widely applicable techniques
- General anesthesia use should be minimized whenever possible

<table>
<thead>
<tr>
<th>Limited surgery?</th>
<th>Painful quick procedure?</th>
<th>Peripheral (limb) surgery?</th>
<th>Invasive head or torso surgery?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local infiltration</td>
<td>Conscious sedation = no apnea, no intubation</td>
<td>Regional blocks</td>
<td>General anesthesia with intubation</td>
</tr>
</tbody>
</table>

[Local infiltration = Conscious sedation = no apnea, no intubation = Regional blocks = General anesthesia with intubation]

Perimedullar anesthesia?
- Spinal anesthesia
  - depends on gravity to establish the affected dermatome
  - sympatholytic effects \(\rightarrow\) risk of cardiovascular collapse
- Epidural blocks
  - also somewhat dependent on gravity
  - risk of cervical diffusion, phrenic nerve block
  - sympatholytic effects \(\rightarrow\) risk of cardiovascular collapse
- Effectiveness and safety in partial gravity?

[Spinal cord block = Epidural block with sympatholytic effect]

[Komorowski 2016, Silvermann 2008]
Which induction cocktail?

- Hypnotic
  - Inhaled agents?
  - Propofol?
  - Etomidate?
  - Pentobarbital?
  - Ketamine?
- Opioid?
- Muscle blocker
  - Depolarizing muscle blocker contra-indicated!
  - Rocuronium + sugammadex?
- Rapid Sequence Induction or not?

Closed-loop anesthesia?

Intubating in weightlessness

[Groemer 2005]

[Bosch 2005]
Videolaryngoscopy?

March 2018 ESA/CNES parabolic flight campaign

What if the crew doctor is the patient?

Intubation after rapid sequence induction performed by non-medical personnel during space exploration missions: a simulation pilot study in a Mars analogue environment

The Mars Society Desert Research Station
Results

- No major complication:
  - No cardiac arrest
  - No cardiovascular collapse.
  - No failed intubation

- Median apnea time 3 min 5 s (max 4 min 10 s).
- "Unassisted personnel with minimal medical training (...) may be able to perform advanced medical care in a safe and efficient manner."

"It will not be the engineering problems but rather the limits of the human frame that will make the final decision as to whether manned space flight will eventually become a reality."

— Wernher von Braun, 1951
Drug stability is impaired in space

→ Need of space-hardy pharmaceuticals packaging technologies

Scenario: acute radiation sickness

3 naturally occurring sources:
• Trapped radiation
• Galactic cosmic radiation
• Solar particle events
• 3-year return trip to Mars
• Total individual doses: 1 to 1.2 Sv
  \( \pm 330 \text{ times} \) terrestrial dose for 3 years
  \( \pm 10,000 \text{ chest X-Rays} \)
• Risk of acute radiation sickness
• Delayed effects: risk of cardiovascular event, cancer, CNS toxicity, cataract & reduced fertility

Management of acute radiation sickness
• Hypovolaemia
  • From emesis & diarrhea
  • IV fluids, electrolytes, loperamide, ondansetron
• Bone marrow syndrome
  • Death from infection & haemorrhage
  • +/- Autologous stem cell transplant
• CNS & cardiovascular syndromes: fatal

[Epelman & Hamilton 2006]

Magnetic shielding

The interaction of a flowing plasma with a dipole magnetic field: measurements and modelling of a diamagnetically-coupled cavity relevant to spacecraft protection
Management of massive blood loss?

- No blood bank on Mars!
- Blood substitutes? (don’t exist)
- Fresh whole blood homologous transfusion? “Walking blood bank”

Scenario: AKI

- The most common organ failure in ICU
- Cause:
  - Increased risk of kidney stone and obstructive AKI in space
  - AKI occurs in 20-60% of sepsis, 2-10% of which require dialysis
  - > 90% recover after 2-3 weeks of dialysis
- On Mars: no dialysis machine!

Peritoneal Dialysis?

- Substandard solution: poor solute clearance
- But minimal equipment, no need for anticoagulation, purified water supply or specialised replacement fluid

**Recipe:**

1. Infuse up to 3L of LR or Hartmann’s with 1.5-4.5% glucose
2. Dwell 1-4h
3. Drain

**Equipment Needed for PD**
- Drp, catheter (closed system)
- Any other tube device with dialate port valves may also be used
- Drainage bag (implantable, HP bag, blood collection
- Foley catheter with roller clamp
- Manometer
- Stomach pump
- Sterile
Scenario: ARDS on Mars
- Following pneumonia, smoke or chemical inhalation
- Challenges: quantity of hardware, consumables, oxygen and IV drugs required for sedation, paralysis and organ support.
- On-board oxygen concentrator?
- Suggestion: management without invasive ventilation?
  - NIV used on the ground in ± 15% ARDS
  - ICU mortality higher in NIV with PaO₂/FiO₂ < 150 [Bellani AJRCCM 2016]
- Most severe cases likely not survivable

Scenario: respiratory failure
- Following pneumonia, smoke or chemical inhalation
- Challenges: quantity of hardware, consumables, oxygen and IV drugs required for sedation, paralysis and organ support.
- On-board oxygen concentrator?
- Suggestion: management without invasive ventilation?
  - NIV used on the ground in ± 15% ARDS
  - ICU mortality higher in NIV with PaO₂/FiO₂ < 150 [Bellani AJRCCM 2016]
- Most severe cases likely not survivable

Scenario 1
- En route to Mars.
- Crewmember suffers head injury secondary to explosion of gas canister.
- GCS 6 with blown right pupil. Likely epidural hematoma, needs a burr hole decompression.
- What would you do? (all equipment available)
  1. Local infiltration ± sedation
  2. GA with intubation
  3. Medical management
  4. Palliation?
Scenario 2

- Inside spacecraft, crew medical doctor exposed to fire, severe smoke inhalation, minor burns.
- ARDS, SpO2 80% on 100% O2, Resp rate 35/m.
- Requiring intubation.
- **What would you do?** (No equipment for NIV)
  1. Intubation and management by non physician
  2. Continue medical treatment alone
  3. Palliation?

Scenario 4

- On Mars surface.
- **What would you do?** (all equipment available)
  1. Intubation and surgical management by non physician
  2. Percutaneous biliary drainage under local anesthesia
  3. Continue medical treatment
  4. Palliation?

[Gurusamy Cochrane Database Syst Rev 2013]