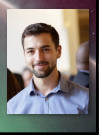
Imperial College London

MIT

2018 Society for Technology in Anesthesia

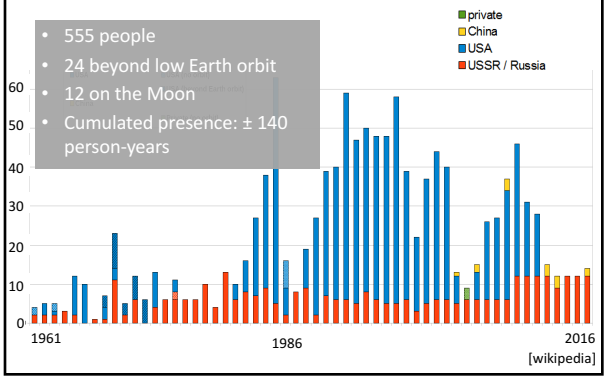
Challenges of Anesthesia & Intensive Care During Future Interplanetary Space Missions

Matthieu Komorowski MD, MRes
Attending in Anesthesia & Intensive Care, PhD student, Imperial College London
Affiliate, European Astronaut Centre, European Space Agency
Visiting Scholar, MIT Health Sciences and Technology
Co-instructor, CS282 course, Harvard University
matthieu.komorowski@gmail.com @matkomorowski



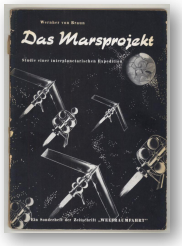
Human spaceflight

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



[wikipedia]

Missions to Mars



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

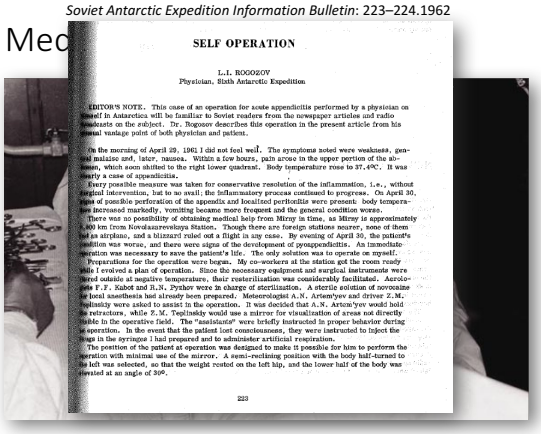
2009 Constellation program: crew of 6 for 900 days.

SPACEX

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

Soviet Antarctic Expedition Information Bulletin: 223–224.1962

Med



SELF OPERATION

L.L. ROGOZOV
Physician, Sixth Antarctic Expedition

EDITOR'S NOTE. This case of an operation for acute appendicitis performed by a physician on himself in Antarctica will be familiar to Soviet readers from the newspaper articles and radio broadcasts on the subject. Dr. Rogozov describes this operation in the present article from his personal vantage point of both physician and patient.

On the morning of April 29, 1961 I did not feel well. The symptoms noted were weakness, general malaise and, later, nausea. Within a few hours, pain arose in the upper portion of the abdomen, which soon shifted to the right lower quadrant. Body temperature rose to 37.4°C. It was clearly a case of appendicitis.

Every possible measure was taken for conservative resolution of the inflammation, i.e., without surgical intervention, but to no avail; the inflammatory process continued to progress. On April 30, signs of possible perforation of the appendix and localized peritonitis were present: body temperature increased markedly, vomiting became more frequent and the general condition worse.

There was no possibility of obtaining medical help from Mirny in time, as Mirny is approximately 1,400 km from Novolazarevskaya Station. Though there are foreign stations nearer, none of them had an airplane, and a blizzard ruled out a flight in any case. By evening of April 30, the patient's condition was worse, and there were signs of the development of pyoappendicitis. An immediate operation was necessary to save the patient's life. The only solution was to operate on myself.

Preparations for the operation were begun. My co-workers at the station got the room ready while I evolved a plan of operation. Since the necessary equipment and surgical instruments were stored outside at negative temperature, their resterilization was considerably facilitated. Aerologists F.F. Zubov and R.N. Pyzhov were in charge of sterilization. A sterile solution of novocaine for local anesthesia had already been prepared. Meteorologist A.N. Artem'yev and driver Z.M. Tsiplinsky were asked to assist in the operation. It was decided that A.N. Artem'yev would hold the retractors, while Z.M. Tsiplinsky would use a mirror for visualization of areas not directly visible in the operative field. The "assistants" were briefly instructed in proper behavior during the operation. In the event that the patient lost consciousness, they were instructed to inject the drugs in the syringes I had prepared and to administer artificial respiration.

The position of the patient at operation was designed to make it possible for him to perform the operation with minimal use of the mirror. A semi-reclining position with the body half-turned to the left was selected, so that the weight rested on the left hip, and the lower half of the body was elevated at an angle of 30°.

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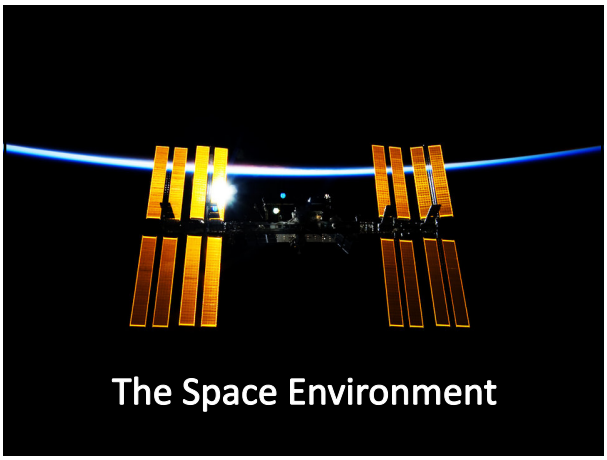
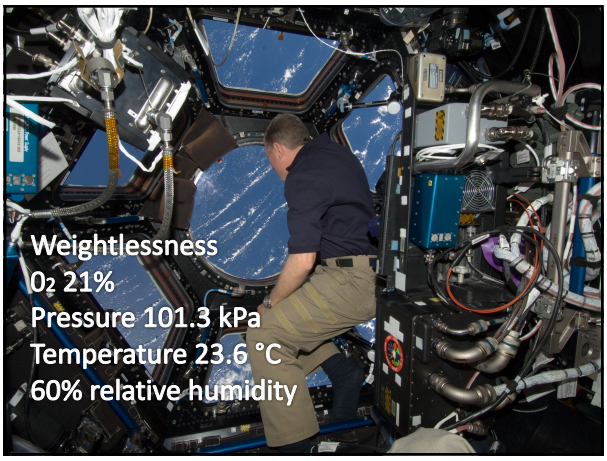
Challenges for healthcare delivery in space

	On Earth	In space
Patient's physiological status	Pathological state	Perfect fitness before launch Alterations in microgravity
Technical constraints	No	Major
Medical skills limitations	No	Important

[Norfleet 2000, Comet 2002, Agnew 2004, Campbell 2008, Ball 2012, Komorowski 2016]





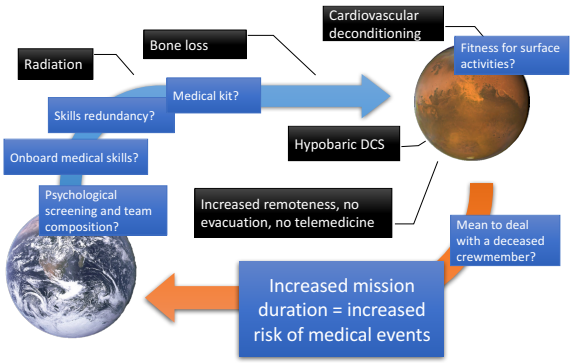
Barometric pressure: 0 kPa
Temperature: -120 to +150 °C
Solar and galactic radiation
Space debris

Spaceflight dynamics

Space analogue environments

Low Earth Orbit	LMIC / humanitarian	Combat	Isolated & Confined Envir.
Use of LEO as analogue for interplanetary travel research.	Resource-poor setting with lack of equipment and medical expertise.	Out of hospital austere setting, high prevalence of severe trauma.	Expeditions in environments such as: mountain, high altitude, polar, jungle, desert.

Mission to Mars: concerns for medical operations



[Barratt & Pool, 2008 ; Safe Passage, 2001]

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]

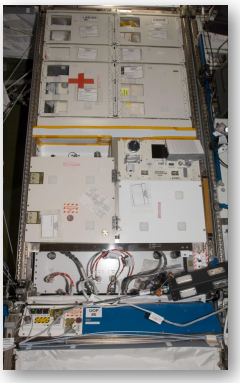
Medical skills on board

- 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

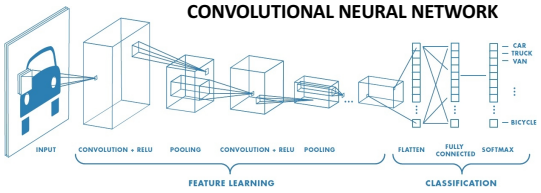
Respiratory Support Pack (RSP)

[Life Support Products Inc]

Ultrasound

Keyboard overlay

Automated diagnostic systems



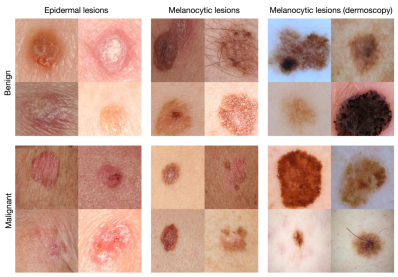
[MathWorks.com]

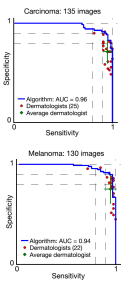
Dermatologist-level classification of skin cancer with deep neural networks

Andre Esteva[1*], Brett Kuprel[1*], Roberto A. Novoa[2,3], Justin Ko[2], Susan M. Swetter[2,4], Helen M. Blau[5] & Sebastian Thrun[6]

nature

[Feb 2017]





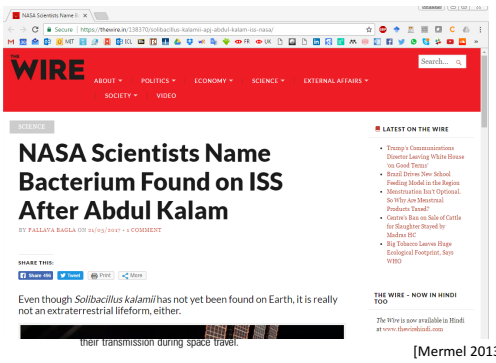
[On the ISS,] “we can stabilize someone who has a dramatic injury but we can’t sustain a patient for long”

– Dr Michael Barratt

Ethical dilemma of severe medical conditions during future interplanetary flights

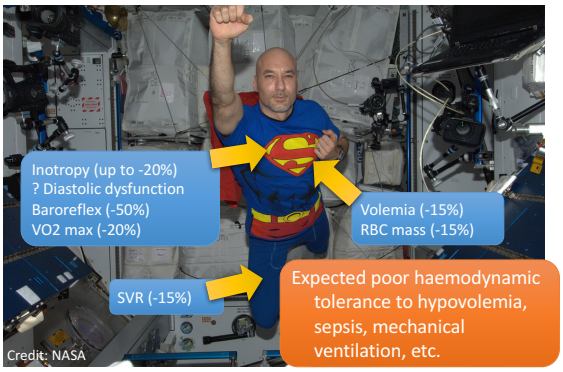
- Non survivable conditions → no ethical issue
- Condition that could be survivable but would require using all available resources → decision?
- Ethically very difficult:
  - Maximum treatment?
  - Substandard treatment?
  - Palliation?

Scenario: sepsis during the transit



[Mermel 2013]

Cardiovascular system in microgravity



[Komorowski 2016]

Intravenous fluids?

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

Prototype: Clearwater IV-Grade Water Filtration System.

[Checinska IJSEM 2017]

Fluid administration in microgravity

[Norfleet, 2000]

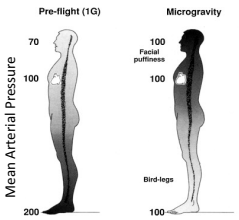
ISS Drugs Pack

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

Scenario: orthostatic hypotension

- Off-nominal Mars landing
- Capsule capsized
- Require emergency egress

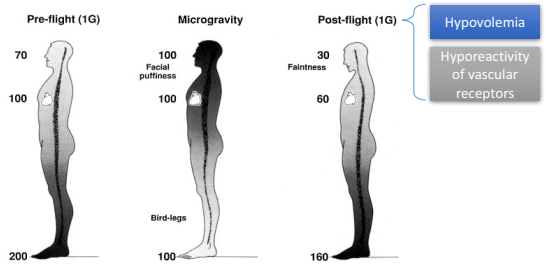
Fluid shift

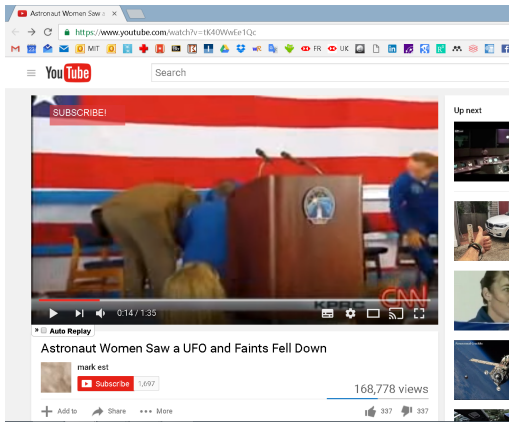


[Gunga 2016, Hargens 2007
Convertino 2005]

Orthostatic hypotension on return to gravity

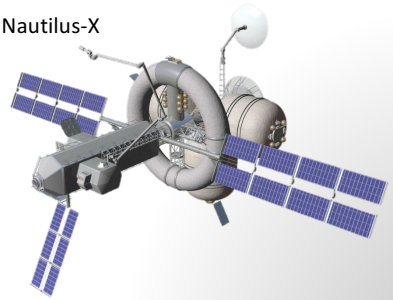
"The most significant operational risk associated with the cardiovascular system of astronauts."





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

Rinehart et al. Critical Care (2015) 19:94
DOI: 10.1186/s13054-015-0827-7

CRITICAL CARE

RESEARCH Open Access

Closed-loop assisted versus manual goal-directed fluid therapy during high-risk abdominal surgery: a case–control study with propensity matching

Joseph Rinehart[1*], Marc Liloit[2], Christine Lee[1], Alexandre Joosten[1], Trish Huynh[1], Cecilia Canales[1], David Imagawa[3], Aram Demirjian[4] and Maxime Cannesson[1]

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

Rinehart J, et al. J Clin Monit Comput. 2018.
Show full citation

British Journal of Anaesthesia 114 (5): 886–92 (2015)
Advance Access publication 17 February 2015 · doi:10.1093/bja/aev002

BJA

Goal-Directed fluid therapy with closed-loop assistance during moderate risk surgery using noninvasive cardiac output monitoring: A pilot study

A. Joosten[1,2], T. Huynh[1], K. Suehiro[1,3], C. Canales[1], M. Cannesson[1] and J. Rinehart[1*]

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

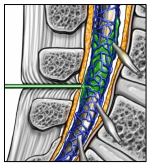
- Limit to a small number of safe, widely applicable techniques
- General anesthesia use should be minimized whenever possible

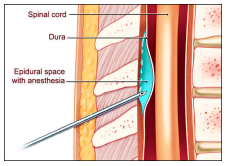
Limited surgery?	Painful quick procedure?	Peripheral (limb) surgery?	Invasive head or torso surgery?
Local infiltraton	**Conscious sedation = no apnea, no intubation**	**Regional blocks**	**General anesthesia with intubation**

[Dobson/WHO 2000, Jawa 2012, Komorowski 2016]

Perimedullar anesthesia?

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





[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?

Fundamentals of Anesthesiology for Spaceflight

Matthieu Komorowski, MD, MRes,*†‡ Sarah Fleming, BSc (Hons),§ and Andrew W. Kirkpatrick, CD, MD, MHSc, FRCSC, FACS‖#**

Journal of Cardiothoracic and Vascular Anesthesia, Vol 30, No 3 (June), 2016: pp 781–790

Closed-loop anesthesia?

Society for Technology in Anesthesia

Section Editor: **Maxime Cannesson**

A Multicenter Evaluation of a Closed-Loop Anesthesia Delivery System: A Randomized Controlled Trial

Goverdhan D. Puri, MD, PhD,* Preethy J. Mathew, MD,* Indranil Biswas, MD,* Amitabh Dutta, MD,† Jayashree Sood, PGDHHM, FFARCS, MD, MBBS, FICA,† Satinder Gombar, MD,‡ Sanjeev Palta, MD,‖ Morup Tsering, MD,§ P. L. Gautam, MD,‖ Aveek Jayant, MD, DM,* Inderjeet Arora, MSc,* Vishal Bajaj, MD,¶ T. S. Punia, MD,¶ and Gurjit Singh, MSc#

www.anesthesia-analgesia.org January 2016 • Volume 122 • Number 1

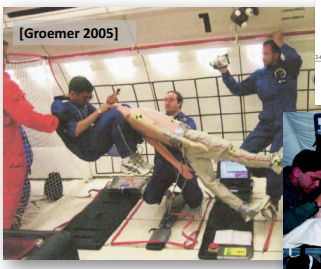
Feasibility of Closed-loop Titration of Propofol and Remifentanil Guided by the Bispectral Monitor in Pediatric and Adolescent Patients

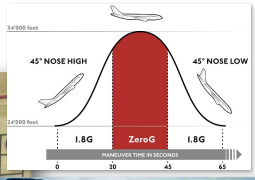
A Prospective Randomized Study

Gilles A. Orliaguet, M.D., Ph.D., Fatema Benabbes Lambert, M.D., Thierry Chazot, M.D., Pauline Glasman, M.D., Marc Fischler, M.D., Ngai Liu, M.D., Ph.D.

Anesthesiology, V 122 • No 4 759 April 2015

Intubating in weightlessness

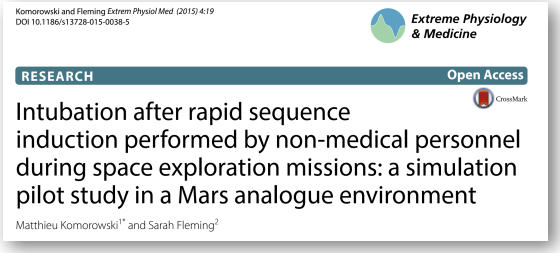




Videolaryngoscopy?

March 2018 ESA/CNES parabolic flight campaign

What if the crew doctor is the patient?



Komorowski and Fleming *Extrem Physiol Med* (2015) 4:19
DOI 10.1186/s13728-015-0038-5

Extreme Physiology & Medicine

RESEARCH Open Access

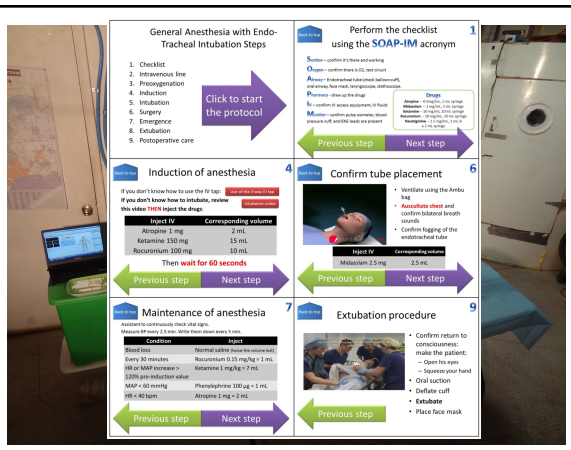
Intubation after rapid sequence induction performed by non-medical personnel during space exploration missions: a simulation pilot study in a Mars analogue environment

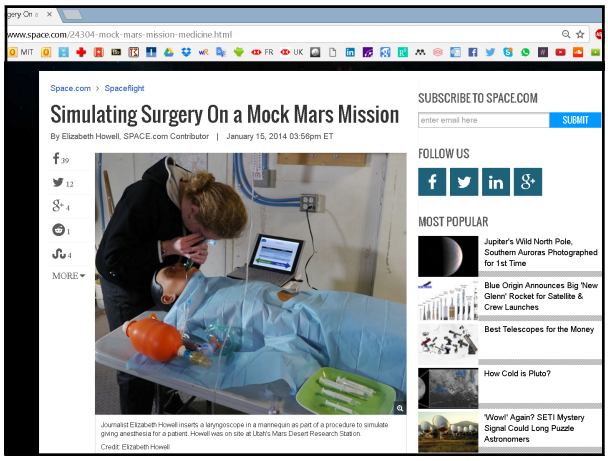
Matthieu Komorowski[1*] and Sarah Fleming[2]

The Mars Society Desert Research Station

[Credit: James Urquhart]


Desert Research Station
SEARCH GOALS
Devon Island Joint EVA Room
Long term isolation studies
Closed biosphere studies
Greenhouse food growth


General Anesthesia with Endo-Tracheal Intubation Steps
1. Checklist
2. Intravenous line
3. Preoxygenation
4. Induction
5. Intubation
6. Surgery
7. Emergence
8. Extubation
9. Postoperative care
Click to start the protocol
Back to top
Perform the checklist using the SOAP-IM acronym
1
Suction – confirm it's there and working
Oxygen – confirm there is O2, test circuit
Airway – Endotracheal tube (check balloon cuff), oral airway, face mask, laryngoscope, stethoscope
Pharmacy – draw up the drugs
IV – confirm IV access equipment, IV fluids
Monitor – confirm pulse oximeter, blood pressure cuff, and EKG leads are present
Drugs
Atropine – 1 mg/mL, 2 mL syringe
Midazolam – 5 mg/mL, 3 mL syringe
Ketamine – 50 mg/mL, 10 mL syringe
Rocuronium – 10 mg/mL, 10 mL syringe
Neostigmine – 0.5 mg/mL, 5 mL or 2.5 mL syringe
Previous step
Next step
Back to top
Induction of anesthesia
4
If you don't know how to use the IV tap:
One of the 3 ways O2 tap
Circuit and ventilator
If you don't know how to intubate, review this video THEN inject the drugs:
Inject IV | Corresponding volume
Atropine 1 mg | 2 mL
Ketamine 150 mg | 15 mL
Rocuronium 100 mg | 10 mL
Then wait for 60 seconds
Previous step
Next step
Back to top
Confirm tube placement
6
Ventilate using the Ambu bag
Auscultate chest and confirm bilateral breath sounds
Confirm fogging of the endotracheal tube
Inject IV | Corresponding volume
Midazolam 2.5 mg | 2.5 mL
Previous step
Next step
Back to top
Maintenance of anesthesia
7
Assistant to continuously check vital signs.
Measure BP every 2.5 min. Write them down every 5 min.
Condition | Inject
Blood loss | Normal saline (twice the volume lost)
Every 30 minutes | Rocuronium 0.15 mg/kg = 1 mL
HR or MAP increase > 120% pre-induction value | Ketamine 1 mg/kg = 7 mL
MAP < 60 mmHg | Phenylephrine 100 µg = 1 mL
HR < 40 bpm | Atropine 1 mg = 2 mL
Previous step
Next step
Back to top
Extubation procedure
9
Confirm return to consciousness: make the patient:
– Open his eyes
– Squeeze your hand
Oral suction
Deflate cuff
Extubate
Place face mask
Previous step

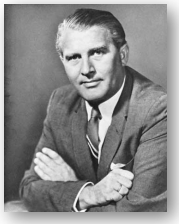


Results

- 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. "

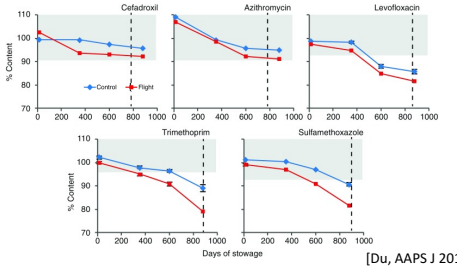
Komorowski and Fleming *Extrem Physiol Med (2015) 4:19*
DOI 10.1186/s13728-015-0038-5

"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



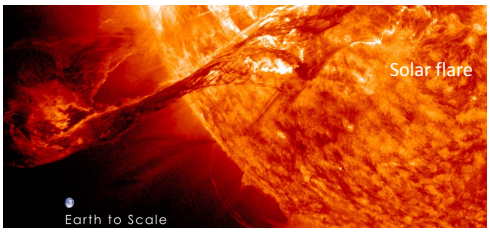
[Du, AAPS J 2011]

→ Need of space-hardy pharmaceuticals packaging technologies

Scenario: acute radiation sickness

3 naturally occurring sources:

- Trapped radiation
- Galactic cosmic radiation
- Solar particle events



RADIATION RESEARCH **185**, 349–358 (2016)
0033-7587/16 $15.00

DOI: 10.1667/RR14311.1

Space Radiation and Human Exposures, A Primer

Gregory A. Nelson

- 3-year return trip to Mars
- Total individual doses: 1 to 1.2 Sv
  - = ±**330 times** terrestrial dose for 3 years
  - = ±**10,000 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

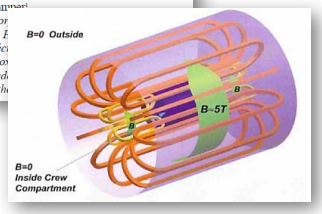
[Epelman & Hamilton 2006]

Magnetic shielding

The interaction of a flowing plasma with a dipole magnetic field: measurements and modelling of a diamagnetic cavity relevant to spacecraft protection

R. Bamford[1], K. J. Gibson[2], A. J. Thornton[2], J. Bradford[1], R Bingham[1,4], L. Gargate[1,3], L..O. Silva[5],. R.A. Fonseca[5], M. Hapgood[1], C. Norberg[4], T. Todd[1], R. Stanw

[1]*Space Plasmas, Rutherford Appleton Laborator*
[2] *Department of Physics, University of York, E*
[3]*Centro de Fisica dos Plasmas, Inst Superior Téc*
[4]*Dept of Space Physics, Umea University, Box*
[5] *EFDA-JET, Culham Science Centre, Abingd*
[6]*Physics Department, University of Strath*



Management of massive blood loss?

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

[Kirkpatrick 2009, combatmedicalsystems.com]

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!

[Mansuri 2017, Sakhuja 2015, Doyle 2016, image: nephrotec.com]

Peritoneal Dialysis?

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

EQUIPMENT NEEDED FOR PD

- DPL catheter (chest tube or any other tube device with distal portholes may also be used)
- Drainage bag (emptied IVF bag, blood collection bag)
- IV tubing with roller clamp
- Mask/gown/cap
- Disinfectant

Recipe:

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

[Annals of Emerg Navy Medicine 2010]

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 $PaO_2/FIO_2 < 150$ [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 $Pa_{O2}/FI_{O2} < 150$ [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% O_2, 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.
- Crew medical doctor develops acute cholecystitis. Medical treatment fails and gallbladder perforates on day 8. Needs urgent surgical intervention.
- **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]