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A guide to Anaesthesia during Space Flight

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INTRODUCTION

Space travel has been an exciting aspect of human exploration since the early 1800's. It began with rocket launches, the use of animals to test physiological changes, the first human to enter space occurred in 1961, the first orbit of Earth in 1962, the moon landing in 1969, and unmanned probes reaching as far as Jupiter and Uranus.

Extensive experiments and studies have been carried out on both animals and humans to better understand the effect of anti-gravity on human physiology; as well as the adaptation to the hostile environment of space. These findings will be used to guide future medical care on board, to ensure safety of crew and the eventual success of long distance missions.

This has culminated in a project to inhabit Mars, a mission that is predicted to occur within this decade.

The proposed mission to Mars has taken into consideration that the crew will be exposed to the space environment over a few years and at a far enough distance from Earth. Any medical emergency would have to be dealt with promptly, as opposed to the option of an emergency evacuation as would have occurred with a mission closer to Earth's orbit. Telecommunications for expert medical advice would also be affected, as there is a significant radiofrequency delay of up to 60 minutes. This results in isolation of the crew and implies total autonomy in regards to the management of medical emergencies. Thus the crew would not only be expected to have scientific, mathematical and engineering knowledge, but also medical and surgical training.

One might question how the subject of anaesthesia in space may be applicable to us, a third world country without a developed national space program. However, studies around the anaesthetic management of traumatic injuries in remote or low-income environments have produced interesting and unique protocols that could be used to overcome the limitations to anaesthesia during space flight. Also, anaesthesia during space travel furthers our understanding of how the human body responds to certain physiologic stressors.

To date, no complete anaesthetic or surgical procedure has been carried out on humans in space. Procedures on humans have been limited to suturing minor wounds under local anaesthesia. Anaesthesia and surgical techniques have been applied to animal based studies to gain some insight into probable outcomes. So far, protocols are produced according to the emergencies that are most likely to occur, or most likely to incapacitate the crew.[2] The probability of medical emergencies has been calculated based on emergencies that have occurred under Mars-like simulations, submarine missions and polar bases.

Before creating relevant protocols, one has to understand the change in human physiology during the different aspects of space flight, as well as the physics of space travel and the complexities of these costly missions.

THE SPACE ENVIRONMENT

A flight is considered a space flight if it occurs 100 km's or more above the level of the sea.[1, 4] Different levels of flight have been created to accommodate the change in the distance from the level of sea, and in relation to Earth's orbit. Three such levels have been described: [1]

1. Suborbital flight refers to flights that reach a trajectory beyond 100 km's above sea, but do not complete an orbit of the gravitating body i.e. Earth. These flights are short in nature and occupants of the vehicle are not subjected to microgravity for a prolonged duration. Occupants can be exposed to the effects of G-force acceleration and deceleration.

2. Low Earth Orbit (LOE) refers to flights that orbit the Earth at altitudes of 200 – 450 km's and at a velocity strong enough to counterbalance the Earth's gravity resulting in microgravity. This is where the International Space Station is situated currently.

3. Exploration Class Missions (ECM) are flights that extend further than LOE i.e. missions to locations such as the Moon or other planetary bodies. These flights are characterised by prolonged exposure to microgravity and long duration of flight.

Physiological disturbances occur during entry of the Earth's orbit from acceleration forces, during re-entry of the atmosphere and landing due to deceleration forces. These disturbances can persist beyond the travel period and affect how astronauts function once the mission is completed.

The space environment is inadequate to sustain human life due to a lack of barometric pressure and oxygen, severe extremes of temperature, and dangerous levels of radiation.[4] Spacecraft are equipped with Environmental Control and Life Support Systems (ECLSS) to ensure survival. These systems can become a source of medical risk to the crew in the form of explosions, fires, toxic carbon dioxide levels, diminished oxygen levels, artificial lighting and confined environment that can affect neurocognitive functioning resulting in mental illness, and decompression illness when transitioning from differently pressurized environments.[4]

PHYSIOLOGICAL CHANGES

- **Cardiovascular system**

  Microgravity causes fluid shifts towards the upper half of the body producing facial oedema and diuresis ("perceived hypovolemia").[1, 4] (Fig. 1) Plasma volumes tend to fall by approximately 10-15%,[1] and intracellular volumes increase after 7 days of weightlessness. Red cell mass increases possibly due to erythropoietin inhibition due to increased renal oxygen partial pressures or hemolysis. An initial increase in cardiac output and stroke volume is followed by an increased ejection fraction, and consequently a decreased stroke volume, after adaptation. There is a decrease in systemic vascular resistance from vasodilatation of about 14%.[4] Left ventricular mass is decreased by 8-14% with retained ventricular systolic function.[4] Arrhythmias can occur secondary to catecholamine discharge. Baroreceptor responses are inhibited with prolonged spaceflight and these changes can persist on return to Earth for up to 14 days, resulting in autonomic dysfunction and orthostatic hypotension.

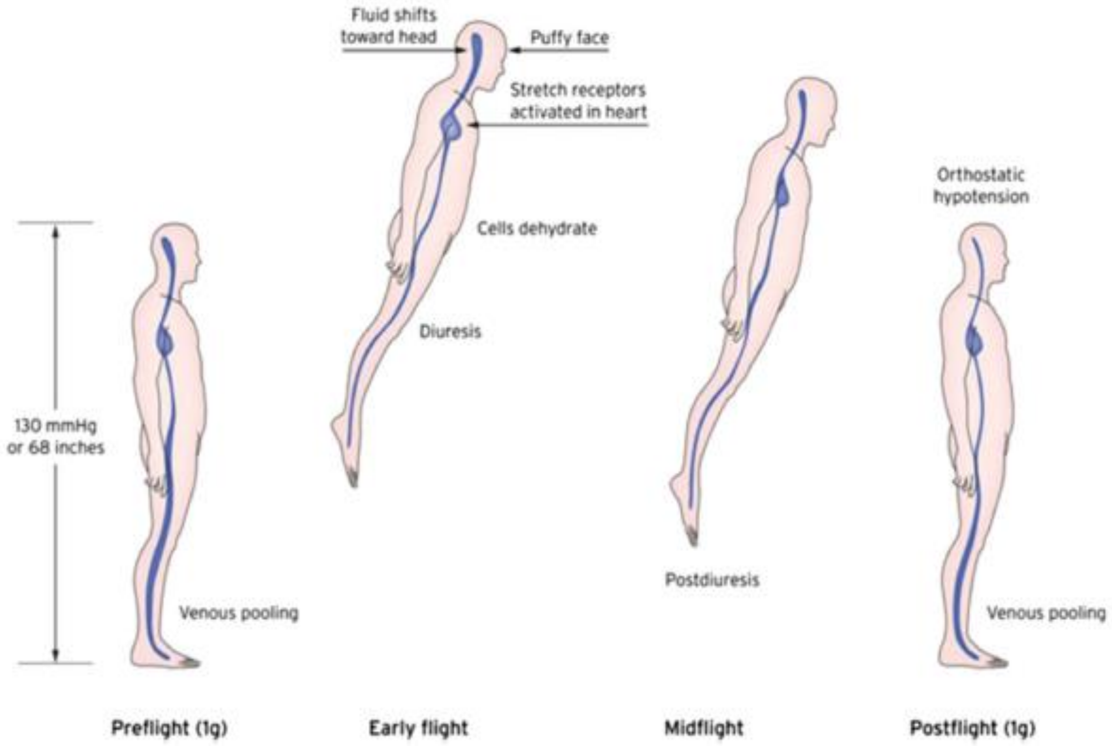

Figure 1. Illustration demonstrating the different fluid shifts that occur before, during, and after microgravity.[5]

- **Respiratory system**

  An increase in respiratory rate and a decrease in tidal volume have been observed in study subjects, resulting in preserved alveolar ventilation. Overall, pulmonary function is favoured in microgravity via an increase in functional residual capacity and an increase in diffusing capacity from an increased alveolar capillary surface.[4]

- **Neurological system**

  The lack of gravity interferes with sensory organs causing disturbances in spatial orientation, balance, gaze control and vestibular function. This results in motion sickness until acclimation occurs within the first week of space flight. Constant exposure to artificial lighting alters circadian and sleep rhythms predisposing crew to impaired mental acuity and depression.

- **Musculoskeletal**

  Weightlessness and subsequent inactivity with decreased loading forces on bones results in an increase in bone resorption, with bone density loss averaging about 1% per month.[4] This produces a twofold effect of predisposing astronauts to fractures and renal stones secondary to increased calcium excretion. Both of these scenarios constitute a medical emergency requiring immediate medical and surgical management.

  Muscle atrophy is more pronounced in the lower body due to weightlessness, causing a loss in muscle mass and power.

- **Gastrointestinal system**

  A combination of decreased gastric motility and increased gastric acidity in the first week of flight can pose an aspiration risk.[4, 6]

  Due to bone resorption, renal calculi can occur.

- **Immune system**

  Dysregulation of the immune system occurs with a combination of factors – nutritional changes, mental affectation from confinement and altered circadian rhythms, and cell destruction secondary to radiation exposure. This has been evidenced by an increase incidence of infections in the Apollo crew.[4]

- **Occupational health hazards**

  Radiation exposure – the Earth's atmosphere and magnetic field serve as a shield against radiation. On an Exploration Class Mission, there is a notable lack of protection. For comparison, a standard chest radiograph has a radiation exposure of 0.2mSV. A postulated 2.5 year mission to Mars may carry up to 1000mSv of radiation exposure.[4]

  Water storage or treatment system malfunction can cause contamination of water.

  Extravehicular Activities (EVA) – repairs may need to be carried out on the outer surface of the space craft, necessitating the need for pressurized and oxygenated space suits. These suits must also have protective factors against the temperature extremes, high levels of radiation and debris in space. The space suits are pressurized to less than atmospheric pressure, approximately 222 mmHg, with high concentrations of oxygen carrying the risk of decompression sickness.

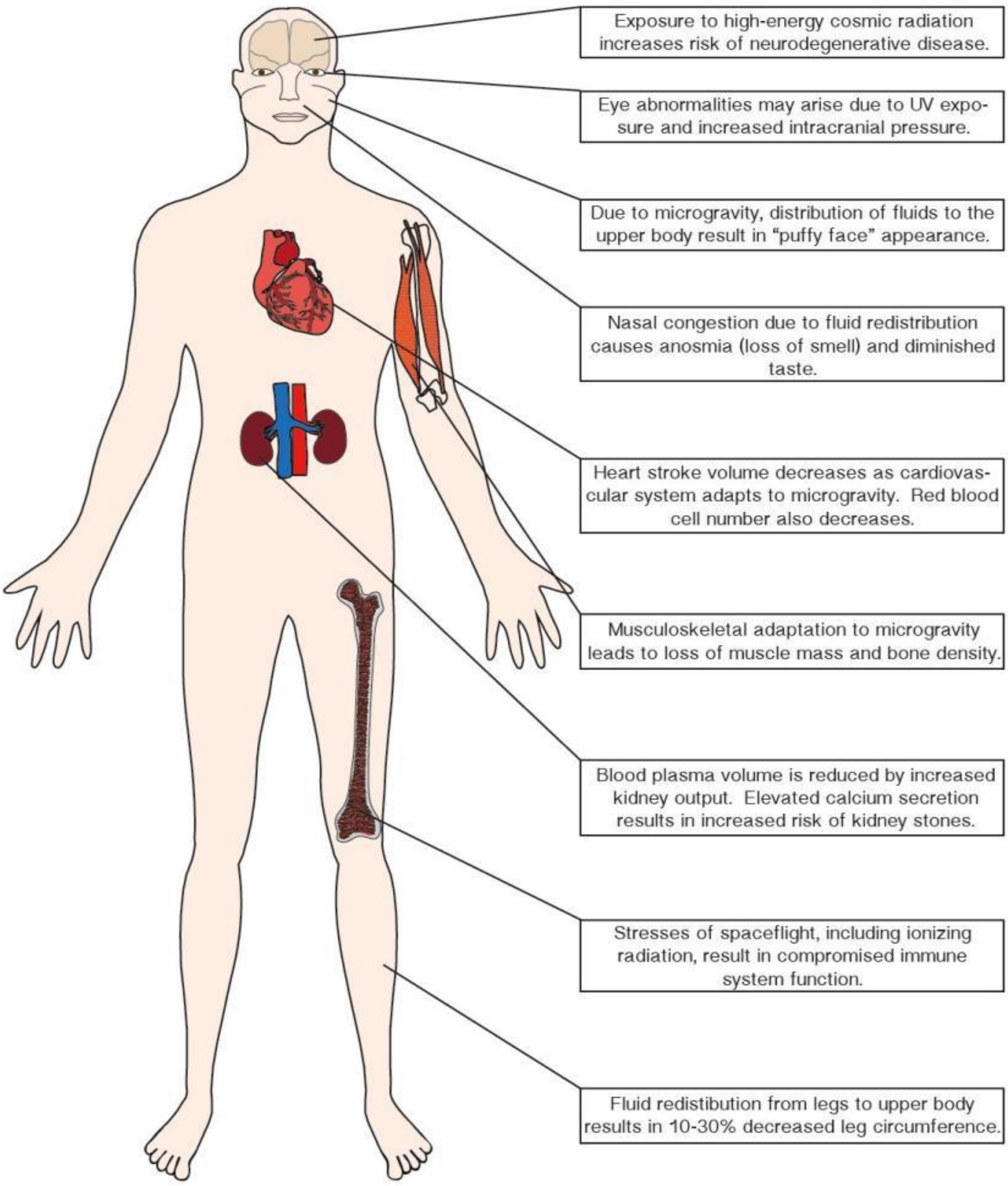

Figure 2. Summary of the physiologic effects of microgravity on the human body.

MINIMISING THE RISK OF MEDICAL OR SURGICAL EMERGENCIES

Serious medical risks stratification begins before the flight occurs. Careful astronaut selection programs pick out healthy and mentally fit candidates able to withstand the stresses of microgravity. Medical and genetic conditions are excluded to prevent adverse outcomes. Exclusion criteria include incapacitating diseases that can complicate acutely (e.g. cardiovascular disease, renal disease, epilepsy), lung disease that is not compatible with scuba diving or extravehicular activity, and any pathology requiring chronic medication as availability may be limited during long distance travel.[1]

Astronauts undergo rigorous training for medical emergencies. This is done with the help of simulated intubations in microgravity, the development of simplified anaesthetic protocols for basic surgical conditions, and diagnostic use of ultrasound and ultrasound guided regional anaesthesia training.[3, 6] (Fig. 6)

Availability of a medical doctor as one of the crew can potentially minimize the risk of permanent incapacitation of other crewmembers.

MEDICAL AND SURGICAL EMERGENCIES

The risk of serious injury occurring on an expedition to Mars with a 6-person crew is estimated at 1 event per 2.8 years.[2, 4] Figure 3 tabulates the medical conditions that could occur on space flight.

1- Surgical conditions and procedures	2-Non-surgical conditions
1.1- Trauma	2.1- General medical conditions
Suturing laceration Tube thoracostomy Fracture reduction Irrigation and debridement of open fractures Fractures: external and internal fixation; use of traction Trauma laparotomy or Eescharotomy/fasciotomy Trauma-related amputations Skin grafting Burr hole Surgical airway	Minor trauma, sprains and strains Infections: pneumonia, cellulitis, gastroenteritis, urinary tract infection, corneal infection, latent viral reactivation Cardiovascular diseases: myocardial infarction, cardiac dysrhythmias Renal stones Psychiatric: depression, anxiety, sleep disorders Cancer
1.2- General surgical	2.2- Space-specific conditions
Drainage of superficial abscess Dental extraction, drainage of dental abscess Repair of perforations: for example, perforated peptic ulcer Appendectomy Bowel obstruction, colostomy Gall bladder disease, including emergency surgery Relief of urinary obstruction: catheterisation, suprapubic cystostomy Treatment of renal stone including nephrostomy Hernia, including incarceration Drainage of septic arthritis Biopsy	Cardiovascular deconditioning, orthostatic intolerance Radiation exposure Visual impairment and intracranial pressure syndrome Space motion sickness Environmental exposure including hypobaric decompression sickness, toxic atmosphere, hypothermia/heat stroke, planetary dust

Figure 3. A list of the likely surgical or medical emergencies that could occur based on emergencies that have occurred in analogue environments.[5]

ANAESTHETIC LIMITATIONS

Pharmacologic factors

The storage and shelf life of drugs: prolonged storage and exposure to the extreme temperatures and radiation of space can cause drugs to become toxic or ineffective. Also, certain intravenous fluids and drugs can produce an unusable foam in space, as the gas and liquid contents do not separate according to their specific densities as they do with gravity. (Fig. 4)

Due to physical space limitations, storage of intravenous fluid can become expensive and if not used could represent precious wasted space. It is estimated that carrying 1 kilogram of material into Earth’s orbit can cost apporximately 22000 USD.

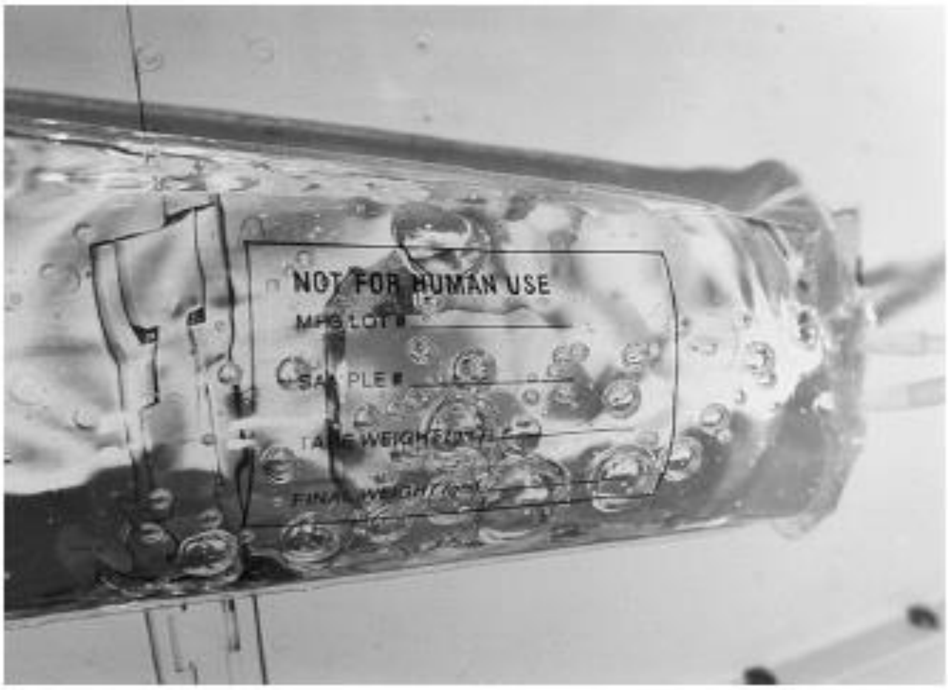

Figure 4. This photo displays an intravenous fluid bag on board the ISS. Gas and fluid do not separate according to their densities in microgravity.[4]

The storage of blood has a limited shelf life, which makes it unfeasible on a prolonged flight; however, the lack of available blood can present a problem in the event of severe haemorrhage.

Volatile gases can leak and contaminate the cabin environment, while oxygen leakages pose a significant fire hazard. The build up of gases can result in an explosion. Vaporisers do not appear to function in microgravity. Hence, volatiles are not permitted on board space craft. Maintenance of anaesthesia will solely rely on intravenous infusion methods.

Physiologic factors

Changes associated with microgravity can predispose a potential patient to aspiration risk, hypovolemia with autonomic dysfunction, and the risk of hyperkalemia with succinylcholine use. Hence, should a general anesthetic be indicated, it would likely require a rapid sequence induction with cardiostable drugs and endotracheal intubation. Fluid shifts associated with weightlessness cause unpredictable drug distribution.

Physical factors

It is important to consider that the patient may be a difficult intubation in the setting of microgravity and confined spacing, and managed by crew members who have limited anaesthetic experience. Microgravity will require restraints to keep the patient immobile for intubation. (Fig. 5)

Draping and sterile technique may be difficult to attain. In addition, it has been noted that microbial growth is accelerated in microgravity[2] with bacteria displaying an increased resistance to antibiotics. Laparoscopic procedures have been investigated to limit contamination and bleeding with some success.[1]

Figure 5. This photo demonstrates how intubation can be achieved during weightlessness. It is suggested to stabilise the patient's head between the operator's knees and draw the knees up to the chest to optimise visualisation and minimise movement.[7]

REGIONAL ANAESTHESIA VERSUS GENERAL ANAESTHESIA

Regional Anaesthesia

Regional techniques are preferable over general anaesthesia as they require less resources and have less complications, however they are not without limitations:

1. To carry out a successful regional technique requires skill, experience, training and regular use of such skills. Studies show that an average of 20 procedures are required to reach a learning curve plateau.[6] The minimum blocks available to treat the majority of conditions expected to be encountered in space include femoral, sciatic, brachial plexus, transversus abdominus plane, obturator and lateral cutaneous nerve blocks.

2. Regional anaesthesia takes longer to perform than a general anaesthetic, especially in an emergency with inexperienced staff. Injury to a lower limb requires knowledge of three blocks: femoral, sciatic and lateral femoral cutaneous nerve blocks. The likelihood of all three blocks being successful is low, and failure of any one would require conversion to a general anaesthetic.[6]

3. The use of local anaesthetic for regional techniques carries the inherent risk of local anaesthetic toxicity. The antidote for local anaesthetic toxicity is lipid emulsion, which requires stringent storage, has a shelf life of 24 months, and is required in large amounts, which could occupy valuable space on board.

4. Regional blocks can mask the signs and symptoms of compartment syndrome and can result in an acutely threatened limb.

5. Hyperbaric local anaesthesia use has not been investigated in microgravity as yet, and it is considered to have an unpredictable outcome.

General Anaesthesia

General anaesthesia should have the benefit of a quick successful onset, achieved with short and effective protocols while being easy to replicate, and preserving the patient's hemodynamic and physiologic state. Factors to consider include:

- **Environment**

  Medical checklists ensure patient safety, and familiarity with equipment and drugs. It also ensures that a safe procedure can be completed. The provision of basic medical kits that include a basic monitor and mechanical ventilator, suction, intraosseous access kit, airway equipment and a limited range of drugs with attached protocols.

  Availability of emergency drugs but also limiting the amount of drugs available for use to avoid drug mistakes and produce easy to follow protocols with little required training.

  The availability of functional infusion pumps.

  Limited space and restraints to intubate.

  Significant radio communication delays.

  Knowledge of ultrasound guided diagnostics.

  Cabin contamination with microbials can place the patient at risk of infection at a later stage.

- **Monitoring**

  Standard baseline monitoring includes ECG, non-invasive blood pressure, temperature, oxygen saturation, and capnography.

  Ultrasound use has many applications in this environment including diagnostic use, assessment of cardiac function and fluid status, peripheral or central line placement, and nerve localization for regional techniques.

- **Patient factors**

  The deconditioning of microgravity results in a patient prone to cardiovascular collapse and aspiration on induction. It is suggested to load the patient with fluids prior to induction. Large bore IV cannulae are recommended. Astronauts are trained in insertion of intravenous cannulae and blood sampling for diagnostic use.

- **Induction**

Ketamine has been described as the preferred drug of choice for induction, as it causes minimal myocardial or respiratory depression.[1, 6] It is currently successfully used in remote locations with limited equipment and monitoring (i.e. combat anaesthesia in high conflict regions and low-income countries).

Ketamine has the advantage of inducing a dissociative state and producing analgesia. It has many routes of administration, it has an extended shelf life in powder form of around 20 years, it displays a high therapeutic index, airway reflexes are maintained and cerebral blood flow is preserved, and it produces bronchodilatation while maintaining spontaneous ventilation.

The psychomimetic side effects of ketamine can be negated with the use of a benzodiazepine 3 - 5 minutes prior to induction. The suggested dose of benzodiazepine is intravenous diazepam at 0.05-0.1mg/kg.[6] Atropine is recommended on induction to minimise the increased secretions produced by ketamine.[6]

The use of muscle relaxants for intubation is recommended. Succinylcholine should be avoided for its ability to cause hyperkalemia. Non-depolarizing muscle blocking agents suggested include rocuronium at a modified rapid sequence dose (1mg/kg). Sugammadex is available as one of the onboard drugs to rapidly reverse neuromuscular blockage once the procedure is completed.

- **Maintenance**

Ketamine is again recommended for maintenance of anaesthesia via an intravenous infusion of 0.5mg/kg/min for spontaneous ventilation, or 1mg/kg/min for controlled ventilation.[6]

Opioids are not recommended in situations where cardiovascular instability could occur. It is suggested that the analgesic effect of ketamine is sufficient.[6]

- **Extubation and recovery**

Sugammadex is available to reverse prolonged neuromuscular blockade from high dose rocuronium. Neuromuscular monitoring is advised prior to extubation.

Recovery protocols are similar to those on Earth with importance placed on limitation of resource utilization. It will place extra demand on staff during the recovery period. Pain control is an important factor of recovery and local or regional anaesthesia is suggested, with the caution that regional anaesthesia may mask the signs and symptoms of compartment syndrome.[5]

Based on the capabilities currently installed on the International Space Station, it is presumed that long-term ventilation and organ support may not be an option following resuscitation or surgical intervention.[5]

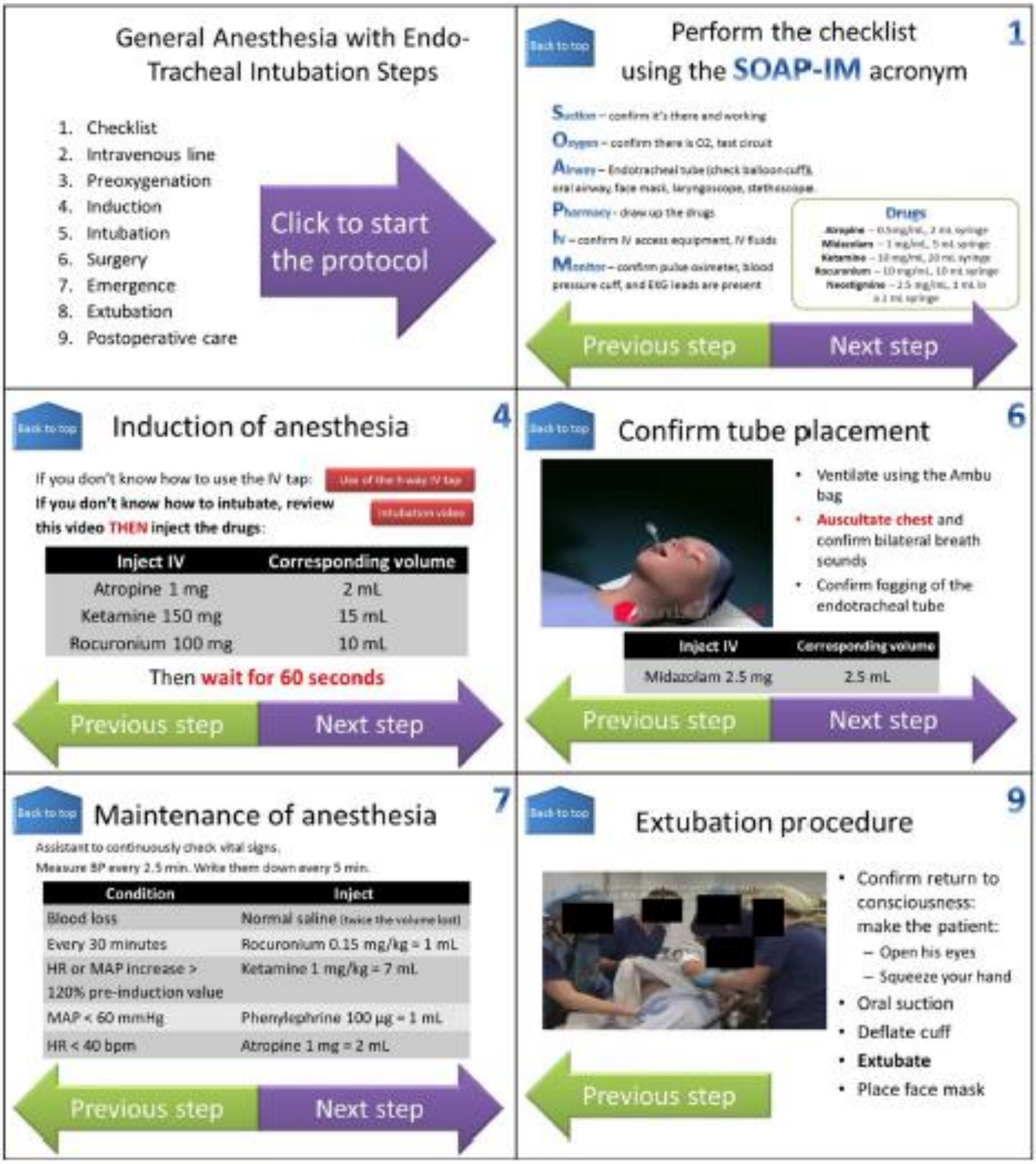

Figure 6. A simplified protocol developed by Komorowksi and Fleming to approach intubation and general anaesthesia for a patient during a simulation. Their study "Intubaion after rapid sequence induction performed by non-medical personnel during space exploration missions: a simulation pilot study in a Mars analogue environment," demonstrates that intubation can be done by non-medical staff with little or no training via instructions from Powerpoint slides.[3]

DEVELOPING TECHNOLOGIES

- Continued studies into simulations provide further insight into how safe anaesthesia may be achievable on long duration flights.

- 3D printing is an innovative way of creating supplies where storage space is restricted.[5]

- The possibility of producing intravenous fluid from drinking water is under review, in conjunction with technologies to remove air bubbles from fluids is being further explored.[4]

- Laparoscopic surgery with robotics is being explored to minimise the risk of infection and contamination as well as decrease the risk of blood loss.[2]

- Improvements in telemedical communication.

- A trend has been noted in the development of privately funded space programs. Members of the general public are now offered the opportunity to experience space travel. Previously, only the elite that passed vigorous physical and mental testing were afforded the status of an astronaut. Young, healthy scientists and pilots were considered ideal candidates. Further experimentation is pushing the boundaries on optimisation of undesirable candidates to undergo space missions. This is evidenced by a patient with the confounding factors of bullous lung disease, spontaneous pneumothoraces, ventricular and atrial ectopy who underwent optimisation and was thereafter able to tolerate simulations similar to suborbital flight (i.e. centrifugal forces) and was subsequently approved for space flight.

CONCLUSION

Comparing the delivery of anaesthesia in Exploration Class Missions to that being achieved in limited resource environments has gathered vital information to overcome limitations to anaesthesia in space travel. The protocols devised are not optimal as yet, but further studies and developments can achieve near optimal guidelines. Significant findings from studies centered on improving anaesthesia delivery on space flights can consequently impact how anaesthesia is performed currently in low resource settings.

There is much information and planning required before a mission to Mars can be considered safe and likely to succeed. The possibility of a medical professional as one of the crew members is desirable, but not an option currently. Scientific developments, and privately funded programs are ensuring that new technologies will improve the health of crew members and ensure the mission's eventual success. The human need to explore and colonise distant planets is strong enough to ensure that this will become a reality in the near future.

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