REVIEW

CURRENT OPINION

Anaesthesia in outer space: the ultimate ambulatory setting?

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Purpose of review

Missions to the Moon or more distant planets are planned in the next future, and will push back the limits of our experience in providing medical support in remote environments. Medical preparedness is ongoing, and involves planning for emergency surgical interventions and anaesthetic procedures. This review will summarize what principles of ambulatory anaesthesia on Earth could benefit the environment of a space mission with its unique constraints.

Recent findings

Ambulatory anaesthesia relies on several principles such as improved patient pathway, correct patient selection, optimized procedural strategies to hasten recovery and active prevention of postoperative complications. Severe limitations in the equipment available and the skills of the crew members represent the key factors to be taken into account when designing the on-board medical system for future interplanetary space missions.

Summary

The application of some of the key principles of ambulatory anaesthesia, as well as recent advances in anaesthetic techniques and better understanding of human adaptation to the space environment might allow nonanaesthesiologist physicians to perform common anaesthetic procedures, whilst maximizing crew safety and minimizing the impact of medical events on the mission.

Keywords

ambulatory anaesthesia, anaesthetics, anaesthesiology, space exploration, space medicine

INTRODUCTION

Space exploration missions to the Moon or Mars are planned in the near future, and will push back the limits of our experience of medical support in remote settings [1▪]. During those flights, severe medical events are a major concern as they could lead to loss of crew life and jeopardize the mission. Reports have estimated that at least one major medical event requiring advanced and invasive care should be expected during a 900-day mission to Mars [2,3▪▪].

Our experience of complex anaesthetic procedures in space is very limited, as no general anaesthetic was ever performed on humans in space [4]. The current medical capabilities on the International Space Station (ISS) does not allow sustained invasive medical care and organ support [5], and any serious medical event would require evacuating the astronaut back to Earth. This has happened on at least three instances in the past, in the 1970s and 1980s [6]. During future deep space missions, such as flights to Mars, the isolation of the crew will be total with communication delays of up to 20 min in each direction and no possibility to evacuate an incapacitated crew member. Autonomy in medical care will therefore be a requirement [6].

When preparing for medical contingencies, it is important to consider what factors and constraints complicate the delivery of advanced medical care. These factors are related to physiological changes

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KEY POINTS

- Thorough preparation is a key element for maximizing the safety of medical care during future space exploration missions to Mars or the Moon.
- Limitations in the equipment available and the skills of the crew members represent important factors to take into account when designing the on-board medical system and protocols.
- The application of some of the principles of ambulatory anaesthesia to the environment of a deep space mission will improve crew safety and minimize the impact of medical events on the mission.

Table 1. General principles and advantages of ambulatory anaesthesia

Principles	Advantages
Correct patient selection	Minimized recovery time
Improved patient pathway	Reduced PACU and hospital stay
Prevention of postoperative complications: pain, PONV	Better pain control
Appropriate procedural strategies	Reduced PONV
Improved airway management	Avoidance of hospital admission
	Improved cost-effectiveness
	Enhanced patient satisfaction
	Reduced wound infection

PACU: postanaesthesia care unit, PONV: postoperative nausea and vomiting. Adapted with permission from [12▪▪].

induced by spaceflight, limited equipment and training of the crew members [1▪,7]. Surprisingly, the delivery of an anaesthetic procedure at the outpatient clinic and during a space exploration share many common features and goals.

This review will first summarize what major principles underlie the delivery of ambulatory anaesthesia on Earth. Next, the challenges of the space environment will be described, and we will discuss how the application of the principles of ambulatory anaesthesia can benefit the unique setting of a space exploration mission.

PRINCIPLES AND ADVANTAGES OF AMBULATORY ANAESTHESIA ON EARTH

The number of anaesthetic procedures in the ambulatory setting has increased steadily over the past years [8]. Today, in most developed countries, the majority of surgical procedures are done on an ambulatory basis [8,9]. Healthcare providers are facing the challenge of creating a safe, efficient, cost-effective and patient-centred environment when dealing with patients with more and more complex comorbidities [10,11]. The successful implementation of ambulatory anaesthesia relies on a few key principles, which are summarized in Table 1.

General considerations

Successful ambulatory care relies on both medical and organizational aspects [13▪]. Improved patient pathways reduce the number of hospital visits and usage of hospital facilities [12▪▪,13▪]. Appropriate patient selection is an important aspect of ambulatory anaesthesia. Classically, patients with advanced comorbidities were excluded, but this picture is changing, for example for patients with obstructive sleep apnoea [9] or other well controlled cardiovascular or respiratory conditions [12▪▪]. In recent years, pressure for cost-effectiveness as well as other economic considerations gained increasing importance in healthcare, including the outpatient clinic [14]. By reducing usage of hospital facilities and avoiding overnight admissions, ambulatory anaesthesia has proven to be a cost-effective process associated with good patient satisfaction, and has been therefore widely implemented [8,12▪▪].

Procedural strategies

The choice between general anaesthesia or regional anaesthesia in the ambulatory setting remains debated [12▪▪]. Whereas regional anaesthesia allows shorter recovery times, provides better postoperative pain management and requires less monitoring, it is significantly more complicated to perform, requires more training and is limited to certain body parts [3▪▪,15]. The use of ultrasound has accelerated the training of residents and improved success rates [16,17]. On the other hand, general anaesthesia requires handling dangerous drugs and managing the airway, which remains a significant cause of anaesthesia-related morbidity and mortality [18▪▪]. Interestingly, nonmedical doctors in a Mars analogue simulation were shown to be capable of inducing a general anaesthesia and performing endotracheal intubation (ETI) [19▪]. Drugs used in the ambulatory setting should have specific profiles to facilitate patient management and prevent complications. The profile of interest typically involves drugs with a wide therapeutic range, a quick onset and a short half-life, which allow swift procedures, short recovery time and timely discharge [12▪▪]. Ambulatory anaesthesia puts an emphasis on the prevention of common postoperative side-effects and complications such as pain and postoperative nausea and vomiting (PONV) [12▪▪].

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Airway management

Supraglottic airway devices have almost eliminated the need of routine ETI in ambulatory anaesthesia [20,21▪]. In the last years, manufacturers presented many new models of laryngeal masks. When compared with conventional ETI, insertion of a laryngeal mask is usually easier (no need for laryngoscopy), faster and safer (no need for muscle relaxation) and does not involve the risk of oesophageal intubation. Furthermore, ETI requires significantly more training [22]. In the recent years, the use of videolaryngoscopes has become widespread, after some benefit was demonstrated, in particular in novice hands [18▪▪,23,24]. Current publications evaluating videolaryngoscopy in the outpatient setting are lacking. Overall, both laryngeal masks and videolaryngoscopes may be interesting for the space environment, wherein they may be used by nonphysicians [19▪].

Telemedicine

Telemedicine is a useful tool in remote or rural areas and has been employed for medical consultations, physical examinations (including preoperative airway assessment) and remote monitoring of patients [25,26]. It is extensively used in spaceflight for remote diagnosis and treatment, monitoring and training of astronauts [27▪].

The following section will introduce the reader to some key aspects of the space environment and detail which constraints will complicate the delivery of a safe anaesthesia. These limitations dictate how some of the principles of a day surgery could be applied to the unique environment of a space mission.

THE SPACE ENVIRONMENT

Overview of pathogenesis in space

Beyond the protection of the Earth's atmosphere, astronauts can only survive space's harsh environment inside the shelter of a space vehicle which provides the right conditions to sustain human life: a normoxic normobaric environment relatively free from pollutants, a comfortable temperature and level of humidity [2]. In low Earth orbit, most space stations transit at an altitude of around 400 km (about 250 miles). At this altitude, Earth's gravity is still 88% of that at sea level, thus space vehicles have to travel at very high velocities to generate a centrifugal force capable of mirroring Earth's gravity (about 17 500 mph), leading to the state of apparent weightlessness in stable orbit [2].

The exposure to weightlessness leads to physiological deconditioning and shifts of bodily systems' equilibrium [28]. This altered physiological state must be taken into account when considering urgent medical care. In particular, the cardiovascular system displays profound changes and remodelling, marked by a decrease in circulatory volume, systemic vascular resistances, baroreflex and diastolic function [3▪▪]. The systolic function seems preserved, likely thanks to the intense resistive and endurance exercise currently performed by crewmembers on board the ISS [29,30].

Outside the space vehicle, the barometric pressure is zero and the temperature varies from −150 to +120°C [2]. When performing extravehicular activities (EVAs or spacewalks), astronauts transition from a normoxic normobaric environment in the spacecraft into a hypobaric pure oxygen atmosphere in their EVA suit [31]. This transition exposes them to the risk of hypobaric decompression sickness, which however has never been officially reported [32].

The 2015 National Aeronautics and Space Administration (NASA) Mars mission design is based around a crew of '4 or more', for 'up to 1100 days' [33]. Concerns over the psychological well-being of the crew have been expressed, as it is clearly established that living in an enclosed and isolated environment for such a prolonged duration commonly induces sleep and mood disturbances, and decrease in cognitive performance [34]. Prevention and mitigation strategies have been proposed by various committees, and are based around correct crew selection and improved crew dynamics [35].

Beyond the protection of Earth's magnetosphere (the Van Allen belts), astronauts are exposed to the threat of radiation, in particular from solar particle events [36,37]. To date, no effective protective countermeasure exists. Experts have recommended the capacity to perform stem cells graft while *en route* to Mars [37].

Upon returning to gravity, the cardiovascular alterations previously described contribute to the onset of orthostatic intolerance in over 80% of spaceflight participants after long duration flights [38]. Current astronauts receive oral and intravenous fluids, and occasionally vasoconstrictors (ephedrine or midodrine) [38]. The risk of orthostatic hypotension after a landing on Mars (about 38% of Earth's gravity) is unknown, but would have potentially very serious effects if the crew had to perform emergency procedures, such as evacuating the module immediately after landing [29].

Table 2 summarizes what medical conditions are expected during a space exploration mission.

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Table 2. Earth-like and space-specific medical conditions in space

Earth-like conditions	Space-specific conditions
Trauma	Cardiovascular deconditioning
Infections	Radiation exposure
Cardiovascular diseases: arrhythmias, myocardial ischaemic events, stroke	Vision Impairment and Intracranial Pressure (VIIP) syndrome
Renal stone	Hypobaric decompression sickness
Psychiatric disorders	Exposure to a toxic atmosphere
Cataract	Hypothermia/heat stroke
Cancer	Exposure to planetary dust

Adapted with permission from [7].

Limitations in on-board equipment and crew medical skills

Beyond the physiological constraints, the delivery of medical care will be further complicated by limited on-board equipment and skills (Table 3).

Designing a medical kit for a space mission is a difficult optimization task involving the assessment of weight and volume of equipment against the statistical likelihood of medical events needing inflight intervention. The NASA Integrated Medical Model has been developed to optimize this task [40].

Table 3. Constraints to the delivery of advanced medical care including anaesthesia and surgery

Physiological constraints	Physiological deconditioning induced by the exposure to microgravity; changes in pharmacokinetics and pharmacodynamics of drugs; wound and bone healing possibly impaired
Technical constraints	Isolation and impossibility to evacuate; Communication delays (no real-time telemedicine); immobilization of patient, operator and equipment in weightlessness; limitations in medical device and consumables (mass and volume), including intravenous fluids; loss of stability of medications; risk of contamination of closed cabin environment by gas, fluids or biological substances; lack of blood products; management of healthcare waste
Human factors	Limitations in crew skills and training (especially if crew medical doctor is injured or ill); risk of skills fading during the mission; psychological stress

Translated and adapted with permission from [39].

As an example, the current US medical kit on the ISS weighs about 31 kg for a volume of approximately 130l. It comprises multiple sub-kits (for clinical examination, dental procedures, minor surgery, etc.), 190 medications, a foldable stretcher (the Crew Medical Restraint System), a semiautomatic defibrillator, a simple respirator (AutoVent 2000; Allied Healthcare Products, Inc., St. Louis, Missouri, USA) and a modern ultrasound machine (GE Vivid q; GE Healthcare, Little Chalfont, UK). The kit allows provision of routine minor medical procedures, as well as basic and advanced life support [5]. A separate medical kit also exists in the Russian segment of the ISS.

Nowadays, every ISS crew contains at least one crew medical officer (CMO), trained for medical contingencies but not necessarily a medical doctor. Furthermore, all NASA and ESA astronauts receive basic medical training (e.g. in Cologne for European Space Agency (ESA) astronauts). For interplanetary missions, more extensive medical knowledge and skills are required. The crew medical doctor will have to deal with any medical issue that could arise during the flight, including critical illnesses, surgical conditions and loss of crew life. According to a survey carried out among NASA astronauts, the most suitable profile for the crew physician would be one of an emergency medicine doctor with additional training in surgery and wilderness medicine [41]. It is still unclear which conditions will be accessible to treatment and which ones will require palliation [1▪,42].

APPLICABILITY TO SPACE EXPLORATION MISSIONS

To date, no anaesthetic procedure was ever performed on a human in space, beyond using local anaesthesia for infiltration [4]. In the light of all the constraints previously described (Table 3), the provision of advanced anaesthesia during a space mission will be a daunting task. Luckily, correct protocol design and training might allow safe and efficient delivery of anaesthesia, by nonanaesthesiologists and, in contingency, by nonmedical doctors [19▪]. The question of the surgical competences remains work in progress. In the event of a surgical condition happening during a distant interplanetary spaceflight, the application of some of the major principles of ambulatory anaesthesia discussed earlier could benefit the crew members and minimize the impact of the incident on the mission.

The choice of anaesthetic techniques will have to take into account the specificities of the environment, the current clinical status of the injured or ill crew member (deconditioned by microgravity or

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living on the Martian surface?) and the skill set of the individuals delivering medical care. For example, by favouring regional blocks, issues related to the risk of cardiovascular collapse or the need for advanced airway management will most likely be avoided [3▪▪]. However, proper preliminary training will be mandatory. With only three techniques (axillary brachial, femoral and subgluteal sciatic blocks), most surgery of the limbs is achievable [3▪▪]. Procedural sedation (e.g. for reduction of a shoulder dislocation) should be achieved using drugs that do not impair ventilation or the cardiovascular system, such as (s-)ketamine [3▪▪,4]. Life-saving procedures involving abdominal surgery could be attempted under general anaesthesia with ETI [3▪▪,19▪].

The agenda of astronauts during a space mission is extremely busy, with minute-by-minute activities planned from 7.30 a.m. to 7.30 p.m., 6 days a week. The actual timelines for the ISS are available on the NASA website [43]. Typical activities include science experiments, spacecraft maintenance, preparation of visiting vehicles, public relationship events and various medical tasks including 2 h of daily exercise. Crew time is extremely precious and any loss of fitness leads to major disruptions in the schedule, with potential impact on the completion of the mission objectives. By applying general principles similar to those of enhanced recovery programmes, it would be possible to ensure that the crew members return faster to their baseline level of fitness, hence reducing the impact on the mission. As discussed earlier, ambulatory anaesthesia is associated with a shorter length of stay, reduced use of hospital facilities and use of consumables, all of which will be interesting in the context of a deep space exploration mission, where consumables will be in short supply and facilities limited (e.g. no permanent facility for accommodating a lying crew member).

In order to illustrate how these principles could be applied during a space exploration mission, let us consider a possible scenario. Minor and severe trauma are among common medical conditions expected during future space missions, in particular during the exploration of a planetary surface [1▪,42]. In our scenario, the crew commander fell from a height of 10 ft onto his right side, during the exploration of a crater on the Martian surface. The astronaut, still inside his EVA suit is evacuated inside the lander habitat using a foldable stretcher. Removal of the suit is complicated by an intense right wrist pain. The initial assessment by the crew physician using ultrasound confirms a displaced distal radial fracture. Because of the degree of posterior tilt, specialists on Earth advise an operative management. Percutaneous pinning can be achieved without image intensifier and is therefore recommended for its relative simplicity and reduced risk of postoperative infection [44]. The crew medical doctor has a background of internal medicine with additional training in surgery, emergency and wilderness medicine. He is competent with the use of the ultrasound machine and has performed 10 axillary blocks as part of his preflight preparation. After reviewing the technique on the on-board medical compendium, he successfully completes on the injured crewmember an axillary block under ultrasound guidance, then performs external reduction and percutaneous pinning. The arm is further immobilized with a removable splint and a sling. Postoperative pain is controlled with nonopioid oral analgesics. Despite not being able to use his right arm, the crew commander is back to near-nominal status within a few hours after his trauma. Because no sedative drug was used, he is able to communicate with his crew and continues to fulfil his role of crew commander. Major risks associated with intravenous drugs were also avoided, such as the need to manage his airways and the risk of cardiovascular collapse. He did not experience any other side-effect of a general anaesthesia, such as PONV. He did not require to be monitored or to rest in bed after surgery. The EVAs are suspended until confirmed fracture healing. After 10 days, gentle range of motion is allowed, which helps him complete daily activities such as using a keyboard. Six weeks after surgery, healing of the fracture is confirmed. The pins are removed under local anaesthetic and the commander is back to nominal status. The impact on the mission schedule has been minimized partly by using patient management methods inspired from ambulatory anaesthesia.

CONCLUSION

Performing an anaesthetic procedure and surgery on an injured crew member during a space exploration mission, possibly by a nonphysician, unquestionably represents an exceptional challenge. Fortunately, recent advances in anaesthesia techniques and training and the application of some of the principles of ambulatory anaesthesia will improve the feasibility of such procedures, enhance patient safety and minimize the impact of major medical events on the mission.

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Conflicts of interest

J.H. is Vice President of the German Society for Aviation and Space Medicine (DGLRM) and Treasurer of the European Society of Aerospace Medicine (ESAM). He has no financial conflict of interest with any product/company/drug mentioned. The remaining authors have no conflicts of interest.

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