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An overview of space medicine

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Abstract

Space medicine is fundamental to the human exploration of space. It supports survival, function and performance in this challenging and potentially lethal environment. It is international, intercultural and interdisciplinary, operating at the boundaries of exploration, science, technology and medicine. Space medicine is also the latest UK specialty to be recognized by the Royal College of Physicians in the UK and the General Medical Council. This review introduces the field of space medicine and describes the different types of spaceflight, environmental challenges, associated medical and physiological effects, and operational medical considerations. It will describe the varied roles of the space medicine doctor, including the conduct of surgery and anaesthesia, and concludes with a vision of the future for space medicine in the UK.
Space medicine doctors have a responsibility to space workers and spaceflight participants. These 'flight surgeons' are key in developing mitigation strategies to ensure the safety, health and performance of space travellers in what is an extreme and hazardous environment. This includes all phases from selection, training and spaceflight itself to post-flight rehabilitation and long-term health. The recent recognition of the speciality provides a pathway to train in this fascinating field of medicine and is a key enabler for the UK Government's commercial spaceflight ambition.

Key words: aerospace medicine; space flight; weightlessness

In 2017, the Royal College of Anaesthetists celebrated its 25th anniversary; it was also the 60th anniversary of the Russian launch of Sputnik 1 (first artificial satellite in space), and the 50th anniversary of the launch of Ariel 3, the first UK designed and constructed artificial satellite. It is fitting, therefore, that these anniversaries are marked with this review describing the recently recognised UK specialty of Aviation and Space Medicine.

The establishment of this specialty was achieved through the efforts of individuals from across a broad spectrum of medical disciplines – including several anaesthetists – reflecting its multidisciplinary character. While the discipline features elements drawn from occupational health, primary care, emergency and aviation medicine, a core feature of operational space medicine entails the support and protection of human life and physiology using state of the art life support systems. This, along with the need to consider the challenges of critical care in austere environments, makes this newest of specialties familiar in many ways to those in anaesthetic practice and one to which anaesthetists will be required to make direct contributions in the future.

Space medicine can broadly be defined as: "The practice of all aspects of preventative medicine including screening, health care delivery, and maintaining human performance in the extreme environment of space and preserving the long-term health of space travellers".[1] Here we introduce the core concepts that underpin the theory and practice of space medicine ranging from crew selection and clinical considerations to the interface between life support systems, engineering and human factors (Fig. 1).

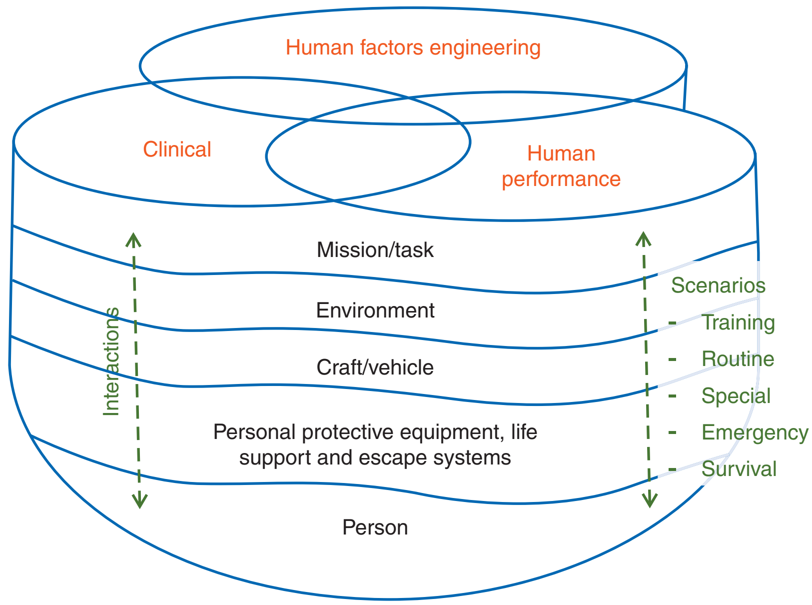

Fig 1 Overview of space medicine. This diagram is inspired by the human factors SHELL model, which was first proposed by Edwards in 1972 and subsequently modified by Hawkins in 1975. The SHELL abbreviation stands for: Software (e.g. standard operating procedures), Hardware (e.g. equipment, systems, vehicles), Environment, Liveware (individual) and Liveware (other people). The SHELL model highlights the importance of interfaces and interactions (along with the inherent variability in each of these) between different components of a manned system.

Types of spaceflight

Spaceflight refers to those journeys that take place more than 100 km above sea level. This internationally recognised altitude boundary is known as the Karman line. In broad terms the Karman line is the altitude above which the atmosphere is insufficiently dense for the aerodynamic control surfaces of conventional aircraft to be effective; beyond that lies space. For the purpose of this article there are three categories of human spaceflight: i) suborbital, ii) low Earth orbit (LEO; e.g. the International Space Station), and iii) exploration class missions (e.g. missions to the Moon and Mars).

Suborbital spaceflights are short, generally lasting no more than a few hrs of which only a few min are spent experiencing the weightlessness of microgravity. The flights involve exposure to increased acceleration in the vertical (Gz) and horizontal (front-to-back; Gx) planes, which can affect the cardiorespiratory systems. The degree of acceleration experienced is typically referenced to the acceleration as a result of gravity near the Earth's surface (g; 9.8 m s^{-2}), for example, +6 Gz is head-to-toe acceleration equal to six times g. Cabin pressures are likely to be equivalent to commercial aircraft cabins (~6–8000 ft pressure altitude).

Low Earth orbit implies vehicles in orbit around Earth at an altitude of 200–400 km. This is where almost all of human space exploration has occurred; from Russia's Vostok 1 through to the US Space Shuttle program and today's International Space Station (ISS).

Exploration class space flight refers to missions beyond low Earth orbit. These encompass expeditions to the Moon, Mars and other celestial objects and locations including Lagrange points and near Earth objects such as asteroids. Lagrange points are locations where gravitational forces between two large bodies (e.g. the Sun and Earth or the Moon and Earth), are balanced such that a smaller body, such as a space station, can effectively be 'parked' in space and is maintained in a stationary position relative to the two larger bodies. The remoteness of these missions from Earth and their comparatively long duration distinguishes them from the vast majority of our experience in human space flight to date.

Medical standards for spaceflight

Human space flight takes place in an austere, remote and physiologically challenging environment with medical provision severely limited by considerations of power, weight and volume and the available skill mix of the crew. Additionally, it represents an environment in which the incapacitation of an individual with a critical role in a mission may threaten the health and safety of the whole crew.

The most successful method of mitigating against the significant physiological risks imposed by spaceflight lies in adequate prevention through screening.[2 3] Therefore medical standards for spaceflight have traditionally played an important role; the aim being to select out any pre-existing medical conditions that might threaten either the safety of the crew or the goals of the mission. Medical standards for spaceflight must be considered in relation to the intended sortie profile and role of the individual within the wider crew.

Professional astronaut medical standards

Standards are stricter for astronauts than for professional aviators. Exclusions are for conditions that; i) may cause acute incapacitation (e.g. coronary artery disease, renal stones, epilepsy), ii) may interact with the space environment or life support systems (e.g. bullous lung disease or asthma; incompatible with

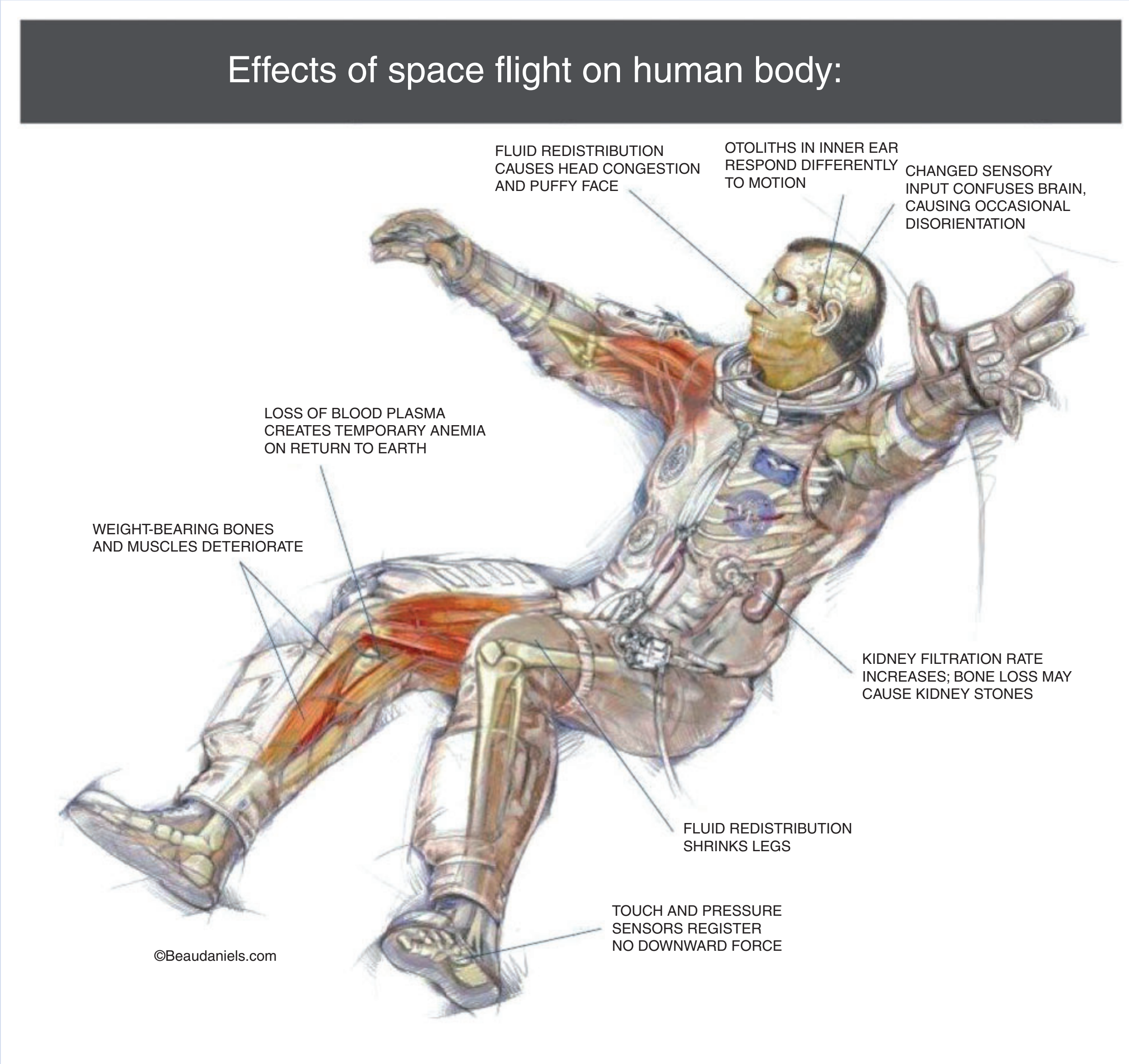

Fig 2 Effects of spaceflight on the human body. Copyright Daniels and Daniels.

sub-aqua diving or spacewalks), and iii) are incompatible with a long duration deep space mission (e.g. may need to exclude stable chronic conditions requiring regular medication).[4 5]

Commercial spaceflight and 'space tourist' medical standards

The Aerospace Medical Association (AsMA) has published medical guidelines for space passengers[6] and for 'Space Flight Participants'[7] who are likely to be older and exhibit more in the way of co-morbidity. These standards are "substantially less stringent than those for professional astronauts and/or crewmembers on long-duration missions to the ISS".[7]

One case study in particular illustrates what is possible with regard to participation in space flight activities in the context of multiple pre-existing medical conditions. In 2005, a 60 yr old male flew onboard the ISS with a history of moderately severe bullous emphysema, previous spontaneous pneumothorax, a lung parenchymal mass and ventricular and atrial ectopy.[8] These medical conditions would have disqualified any professional astronaut from selection. However, after prophylactic bilateral pleurodesis and extensive medical evaluations, which recreated, as closely as possible, the challenges of spaceflight, including high-G centrifuge and altitude chamber runs, this spaceflight participant was approved for flight.

Preliminary studies of potential suborbital spaceflight participants have been conducted to understand the likely tolerance of this new population of space travellers to the rigours of suborbital flight. Extremes of age and controlled chronic medical conditions, including hypertension, cardiovascular disease, diabetes mellitus, lung disease and back or neck problems have been shown to tolerate suborbital flight profile centrifuge training.[9 10] At the extreme, even a 23-yr-old man with a history of multiple congenital cardiac malformations (including aortic insufficiency, pulmonary atresia, pulmonary valve replacement, repaired ventricular septal defect, and pulmonary artery stenosis [post-dilation]) tolerated a centrifuge assessment to +6Gx.[11] This suggests that potential spaceflight participants with well-controlled medical conditions are likely to tolerate the launch and re-entry acceleration profiles of typical suborbital spaceflight profiles. Medical standards will continue to be informed by future research in combination with medical incident data from flights as numbers increase.

Physiological and medical effects of spaceflight

Early effects of deployment in the space environment

Microgravity refers to the near weightlessness environment associated with space flight. It arises as a consequence of the free-fall motion of the vehicle as it orbits the Earth or travels through space on a ballistic trajectory. The human body undergoes profound changes in response to microgravity (see Figure 2). Most are beneficial and aid adaptation to the space environment but some are maladaptive.

The most immediately noticeable effect is sensory disturbance involving the vestibular system. Overall, 60% to 80% of astronauts experience space adaptation syndrome[12] within the first three days (e.g. nausea, pallor and vomiting). These symptoms can be disabling. Mitigating strategies predominantly consist of avoiding provocative head manoeuvres and deferring critical activities during the initial days in space.[13] For future short duration commercial flights, individuals may take prophylactic treatment to minimise the risk of being affected. I.M. promethazine has been shown to be an effective treatment.[13]

The most visible early physiological change is the redistribution of body fluid from the lower to upper body,[14] resulting from the elimination of the gravitational loading experienced on Earth. This manifests as the so-called 'puffy face' associated with facial oedema[14] and reduced leg volume giving the characteristic 'chicken legs' appearance.[15] Accompanying the fluid shift, plasma volume reduces by 10–15% as intravascular fluids shift into the extracellular space because of increased capillary permeability.[16] This relative hypovolaemia, along with reduced sensitivity of the baroreflexes[17] contributes significantly to the orthostatic intolerance experienced by most astronauts on return to a 1 G environment.[18]

Over half of all US astronauts reported suffering back pain in the first few days in space.[19] Other examples of commonly reported symptoms that may have space specific differential diagnoses are given in Table 1.

Table 1 Space related differential diagnoses for a few common presenting symptoms. In addition to the usual Earth-based differentials, these additional space specific potential causes must also be considered

Symptom	Differential diagnoses when in space
Headache	Space Adaptation Syndrome (SAS), cephalad fluid shift, raised CO_2, carbon monoxide, dehydration, caffeine withdrawal
Nausea/ Vomiting	SAS, raised CO_2, hypoxia, radiation illness
Cough	Infections, inhaled foreign bodies, inhaled irritants- hydrazine, ammonia, ethylene glycol fumes, pulmonary oedema, low humidity
Joint pain	Musculoskeletal injury, Decompression sickness, trauma

Longer duration spaceflight

The longest continuous human exposure to microgravity to date is 438 days. However the vast majority of our experience in space flight involves flight durations measured in days and weeks rather than months and yr. The challenges of long-term deployment will have to be properly addressed to facilitate exploration class missions. Two of the most important effects to consider are the increased radiation exposure and physiological alterations caused by microgravity.

Radiation

Radiation is a critical barrier to manned exploration of Mars based on current spacecraft and radiation shielding options.[20] The four types of ionising space radiation are: i) galactic cosmic radiation (GCR), ii) solar particle events (SPE), iii) solar protons and iv) trapped radiation.[21 22] On Earth we are protected from ionising space radiation by the atmosphere and Earth's geomagnetic field. Current low Earth orbit (LEO) missions still benefit from the protection offered by Earth's magnetic field. This magnetic field greatly reduces the radiation exposure but some additional exposure occurs on transit through the 'South Atlantic Anomaly' (SAA), which is part of the inner van Allen belt. The van Allen belts are layers of radiation (charged high-energy particles) trapped by the Earth's magnetic field that form donut-like rings around Earth. The SAA is an extension of the inner belt down into low Earth orbit over the South Atlantic, reaching the orbital altitudes of the International Space Station.

Outside of the protection of the Earth's atmosphere, cosmic radiation damages cellular DNA, impeding response to cytokines and increasing the risk of certain cancers. Career exposure limits for astronauts are set at 1500 mSv for a 45 yr old man and 900 mSv for a 45 yr old woman.[23] For comparison, typical radiation exposures in aviation and space are summarised in Table 2.

Galactic cosmic radiation originates from outside our solar system; it is a 'background' radiation of highly energetic protons and alpha particles. In contrast, Solar particle events (SPEs) are sudden events associated with acute high radiation exposure which present an immediate risk to crew health. It is difficult to predict the occurrence, the magnitude or the length of SPEs as the arrival time from the Sun to low Earth orbit is only a few mins. Monitoring solar weather is vital in informing spacecraft operations and spacewalk schedules, to minimize the degree of solar radiation crew are exposed to. Mitigation strategies for radiation exposure on long duration spaceflights are challenging as a result of the complexity of the radiation environments.[25] They include scheduling missions to when solar activity is at a minimum, improving radiation shielding by using materials of low atomic mass and high hydrogen content (i.e. water), and even potentially biological countermeasures such as chemoprevention medication.[26 27]

Musculoskeletal system

In the context of prolonged microgravity exposure, gravitational unloading and deconditioning of the musculoskeletal system is

Table 2 Typical aviation and space radiation exposures. Adapted from Chancellor and colleagues[24]

Mission/Scenario	Dose equivalent (cosmic ray exposure)
Average U.S background	2.2 mSv yr^{-1}
Standard chest radiograph	0.2 mSv
Airline Crew (annual limit)	2 mSv yr^{-1} (6 mSv yr^{-1})
Apollo average dose	12 mSv
Apollo 14 (highest skin dose)	14 mSv
Shuttle (average skin dose)	4 mSv
Shuttle (highest skin dose)	79 mSv
MOL nominal skin dose	41.7-64.6 mSv
Skylab 4 (highest skin dose)	178 mSv
ISS (avg. 6 month dose)	75 mSv
ISS (approx. 1-yr mission dose)	215-310 mSv
2.5yr Mission to Mars Surface	~1000 mSv

of particular concern. Bone demineralisation occurs with increased excretion of calcium, predisposing to an increased risk of suffering a fracture or developing a calcified stone in the renal tract.[28 29] Mean losses of bone are in the order of 1%–1.6% per month in the spine, femur neck, trochanter and pelvis.[30] Medical countermeasures to limit bone loss have been considered such as bisphosphonates[31 32] and diet[33] but the main countermeasure has been exercise. Resistive exercise, in particular, is thought to stimulate osteogenesis.[34]

Without the loading forces exerted by gravity, skeletal muscle atrophy occurs, most markedly in the lower body as the legs become effectively redundant.[35] In the absence of exercise, lower leg muscle volume reduces[36] and despite focused exercise, muscle mass and power is still lost.[37] ISS crew have individually tailored exercise programmes and access to a variety of aerobic and resistive exercise devices, which operate over a wide range of motions to mimic those in the terrestrial 1 G environment.[38] A meta-analysis of countermeasure exercises conducted in analogue bed rest studies demonstrated that no specific exercise was completely successful in preventing all musculoskeletal changes.[39] An adjunct to exercise is the 'SkinSuit', which applies compressive axial loading in an attempt to replicate the loading caused by terrestrial gravity.[40]

Another proposed strategy to prevent deconditioning is to create artificial on-board gravity, either continuously by spinning the entire spacecraft, or with an on-board short arm centrifuge to intermittently spin individual astronauts. The latter in particular can cause motion sickness but studies suggest humans can satisfactorily adapt to cope with this.[41] Currently the optimum level and duration of gravity exposure has not been determined. The main factors limiting implementation are the sheer size, cost and logistics of creating such devices.

Neurological system

Acute changes occur in the neurological system upon deployment in the space environment. These contribute to Space Adaptation Syndrome and to impairments of visuomotor tracking tasks and the vestibulo-ocular reflex. The impairments of the neurovestibular system appear to become more pronounced with extended mission duration.

A relatively recent and concerning finding is the degradation in visual acuity; a post-flight questionnaire of 300 astronauts found 28% and 60% experienced degradation in distant and near visual acuity on short and long-duration missions respectively.[42] An associated pre and post-flight study of seven astronauts found all had some ophthalmic abnormality including optic disc oedema, globe flattening, choroidal folds and cotton wool spots.[42] The physiological response is variable and not all astronauts experience visual symptoms despite objective findings.[43] This collection of findings is termed Spaceflight Associated Neuro-ocular Syndrome (SANS), previously known as visual impairment and intracranial pressure syndrome (VIIP). The aetiology is unknown but postulated causes include cephalad fluid shifts,[42] radiation and inspired CO_2 levels.[43]

Multisystem considerations

The effects of space flight and the space environment upon the human body are widespread, affecting every system that has been studied in any detail (Fig. 2). For example spaceflight affects the regulation of the immune system, with elevated granulocytes, decreased lymphocytes, elevated B cells and decreased natural killer (NK) cells.[44 45] Haemopoiesis also appears to be affected with reductions in red cell mass leading to a so-called "space anaemia'.[46] Spaceflight also leads to significant sleep disruption[47] as a result of gross alterations in light and dark cycles, illumination and crew workload.[48 49] For the respiratory system there are alterations in both static and dynamic lung volumes and despite ventilation and perfusion being more uniform in spaceflight, gas exchange appears to be no more efficient than on Earth.[50] For the renal system, cases of renal stones have been reported in flight, in one instance disabling a crew member who was then unable to carry out their primary duty and nearly required an urgent deorbit.[29] In addition to hypercalcuria, other factors contributing to renal stones include decreased urinary output and changes in the concentration of urine, with increased urinary phosphate[51] and sodium.

The effects of space flight and microgravity extend well beyond the discrete systems listed above and our future exploration of space will demand a parallel, continued exploration of its effects on the human body.

Re-entry, landing and post-flight considerations

The medical concerns of re-entry relate to risk of: i) spacecraft depressurisation, ii) crash iii) fire, iv) trauma of a normal landing (e.g. loose articles and impact forces) and v) post-landing survival, which may include risk of water ingress if landing in sea or winter land survival if off-nominal landing away from rescue services. Immediately post-landing astronauts may experience a generalised weakness, orthostatic intolerance and neurosensory disturbance, including pitch sensitivity which may affect an individual's abilities to walk.[52] Once able, astronauts undergo a prolonged period of physical re-conditioning to improve both musculoskeletal and cardiovascular systems.[53] Similar considerations may be necessary on arrival at the surface of Mars before commencing active surface exploration activities.

Occupational health hazards

Spaceflight involves many potentially hazardous substances. Water is treated with trialkylamines to reduce iodine content as failure of the water treatment system has permitted contamination of the drinking water.[54] Despite significant ingestion it was without adverse health impact but highlighted the potential risks vehicle systems can pose to astronauts. Another example is exposure to hydrazines, which have been widely used as rocket fuels. Although there is limited evidence regarding suggested therapies for human exposure[55] and serious exposures are rare, this may have increasing relevance to UK based healthcare workers if the proposed UK Spaceport(s) transpire. Further afield, biohazards were considered a serious risk when the Apollo astronauts landed on the lunar surface itself and back on Earth once they had returned. Equivalent risks and mitigation options have also been considered for Mars missions.[56]

Extra-vehicular activity

'Extra-Vehicular Activity' (EVA; aka spacewalks) refers to human activities occurring outside the spacecraft or habitat whilst in space and are uniquely hazardous activities. They are typically undertaken to install new equipment, or to carry out repairs, maintenance or fault investigation. They are physically demanding and generate significant metabolic heat that is challenging to manage. For spacewalks astronauts must don special clothing and equipment (space suits) that protect against environmental threats including thermal stress, micrometeoroids, radiation hazards and hard vacuum, while maintaining a breathable, habitable atmosphere. These space suits are pressurised, but to lower than normal atmospheric pressures in order to reduce suit rigidity and maintain mobility. The ISS is pressurised to sea level, whereas NASA space suits provide only 29.5 kPa (4.3 psi). This pressure difference, however, creates the possibility of decompression sickness (DCS).

Decompression sickness in the space environment

Decompression sickness is caused by evolution of nitrogen gas from tissue or body fluids when an individual is exposed to reduced ambient pressure. Symptoms range from joint pain (the bends) to, more seriously, the incapacitating neurological effects of confusion, motor incoordination and loss of consciousness.[57] Many factors can increase the risk of DCS during hypobaric exposure including individual susceptibility and physical activity.[57] Before spacewalks astronauts breathe 100% oxygen to off-load the body's nitrogen stores and reduce the risk of DCS; currently this is enhanced with In-Suit Light Exercise (ISLE).[58]

Medical planning, emergencies, anaesthesia and surgery in space

The Shuttle-era health care system focused on maintaining crew health and performance, primarily using prevention strategies.[59] International Space Station (ISS) medical planning takes into consideration the international and intercultural nature of medical standards and practice, medical hardware constraints, with reviews of clinical events in space, medical kit contents and crew medical training.[60] Together these examples provide a basis from which medical support plans for spaceflight can be made; examples and anticipated conditions are summarised in Table 3.

While prevention is the cornerstone of crew health maintenance and protection, the risk of illness or injury remains an inherent risk in spaceflight, and is considered by NASA to increase with exploration beyond low Earth orbit (LEO).[66] The risk of a serious medical emergency has been estimated at approximately 0.06 per person-yr of flight, or one event per 68 person months.[67] Thus, for a crew of six on a 900-day mission to Mars at least one emergency should be expected.[68]

Stringent volume, power and mass limitations on board are a significant consideration when configuring medical capability for human space exploration.[64] The challenges associated with the carriage and storage of common medications serves as an example of the unique challenges in this environment. Medications should be chemically stable, thermally robust, and have an adequate shelf life,[64] while the radiation environment may lead to more rapid degradation of these medicines than on Earth.[69] Powdered medications can provide the stability desired. However, re-constitution with fluids can be challenging in microgravity as bubbles do not gravitate to the top of the solution. Examples of included medication in typical kits on board are: analgesics, antibiotics, anxiolytics, anti-emetics, antidepressants, hypnotics and benzodiazepines.[70] Medical diagnostic imaging capabilities are currently limited to ultrasound on the ISS.[71] Multipurpose ultrasound has been successfully used both on-board the ISS and, in conjunction with telemedicine, to support medical provision in remote areas.[72]

It should be noted that on a Mars mission time delays for communication and therefore telemedical support can be significant; from eight up to 56 min depending on the orbital alignments of Mars and Earth.[2] Thus, for Mars exploration missions medical care provisions may need to be autonomous and self-sufficient. As such the presence of a physician in the crew may provide greater flexibility and capability enhancement to meet some of these anticipated and unanticipated medical or emergency requirements.

Anaesthesia in space

In the space environment, microgravity and the extremely limited availability of space, power and equipment present unique challenges for the conduct of anaesthesia.[73] The closed environment of a spacecraft renders inhaled techniques problematic. Vapours could contaminate the cabin, affecting other crew members, while oxygen leakage in the cabin environment would increase the fire risk.[73]

In addition the myriad alterations in physiology that accompany deployment in microgravity – and in particular those affecting the cardiovascular system – are likely to alter the response to anaesthetic agents and other vasoactive drugs. These changes were postulated to have played a role in an unexpected death and the "less-than-optimal" physiological condition of primates anaesthetized shortly after return to Earth.[74] Nevertheless general anaesthesia has been successfully administered using i.v. agents in a variety of animal models on orbit.[75] Many of the discrete skills and procedures associated with general anaesthesia have been performed either on orbit or during simulation studies on parabolic flights.[73]

Ketamine has been proposed by some as the preferred i.v. agent for sedation, induction and maintenance of anaesthesia, in part because of the growing experience with its use in the prehospital environment, in the hands of clinicians with a range of backgrounds. Ketamine has a wider therapeutic ratio with regard to cardiovascular stability when compared with other i.v. anaesthetic agents and has less profound effects on airway reflexes and respiratory depression than i.v. anaesthetic drugs or opioid analgesics of similar potency.[76]

Some commentators have proposed regional techniques as a preferred method of delivering anaesthesia in the space environment.[77] This approach is attractive in this setting because it leaves the patient conscious with a reduced dependence upon additional physiological support and the equipment associated with general anaesthesia. However, regional techniques are not

Table 3 Overview of medical conditions that have occurred or may occur during spaceflight. Adapted from Barratt and Pool[61] and Watkins[62] with other additions.[29 63] Space Exploration Medical Condition List sets out conditions that could affect crew and are prioritised according to incidence, effect, and ability to mitigate against, based on a three-crew 13 month return journey with one month on surface of another planet (no planned spacewalks). 'Not addressed' conditions are defined as highly unlikely to occur, are unable to be treated with limited medical training or require too many resources to feasibly treat[62 64 65]

Common/anticipated	Occasional incidences	Space Exploration Medical Condition List capability	Not addressed
• Space Motion Sickness • Nasal/sinus congestion • Constipation • Headache • Back pain • Upper Respiratory tract infection • Minor Abrasion • Musculo-skeletal trauma • Corneal irritation • Insomnia	• Renal stone formation • Acute urinary retention • Cardiac Dysrrhythmias - Extrasystoles - Bigeminy - SVT - Sustained VT (asymptomatic) • Urinary tract infection • Gastroenteritis • Prostatitis • Serous otitis media • Contact dermatitis • Decompression sickness (joint pain) • Near drowning after spacesuit failure • Aspiration of foreign body	• Radiation sickness • Severe Decompression illness • Barotrauma • Osteoporosis • Seizure • Anaphylaxis • Anxiety • Depression • Medication overdose/misuse • Palliative treatment • Diverticulitis • Appendicitis • Sepsis • Herpes reactivation Cellulitis • Otitis media/externa • Dental - Cavity - Pulpitis, - Toothache, - Avulsion, Loss • Eye penetration • Limb amputation (lifesaving) • Chest trauma/Pneumothorax • Obstructed airway • Haemorrhage • Burns (thermal or chemical) • Smoke inhalation	• Cardiogenic shock • Malignancy • Acute Glaucoma • Compartment syndrome • Head Injury • Hypovolaemic shock • Lumbar spine fracture • Shoulder/elbow dislocation

suitable for a number of surgical procedures and require significant skill and training in order to be used effectively. Furthermore it is likely that central neuraxial blockade, with its dependence on gravitational forces to facilitate the appropriate spread of local anaesthetic agent, would behave too unpredictably in the microgravity environment to be useful.[77]

Surgery in space

Surgery has been carried out in simulated parabolic flights.[78] Microgravity necessitates a secure system of restraint for both the patient and clinician and, because of the large number of weightless, non-sterile particles suspended in the cabin, careful consideration needs to be given to the means of containing the surgical field in an effort to prevent contamination of the wound. Sponges and suction have been shown to adequately prevent cabin contamination from bleeding, with the exception of arterial bleeds.[79] A variety of techniques have been demonstrated in parabolic flight animal studies including laparoscopic surgery[80] and percutaneous aspiration of intra-peritoneal fluid under sonographic guidance, in the event of peritonitis not being amenable to medical management.[81] In anticipation of International Space Station operations requiring stabilisation of crew members before evacuation to Earth, advanced trauma life support (ATLS) procedures during parabolic flights were shown to be feasible.[82] Furthermore the potential to perform complex surgical procedures was demonstrated in animal models during the STS-90 Neurolab Shuttle mission.[75] The degree of training and experience of the crew medical officer on board will greatly affect the surgical and anaesthetic capabilities of the crew. A compromise may be to offer specific and focused surgical training to the designated crew officer, who can operate in the event of a common surgical emergency in collaboration with terrestrial telemedical support.[83]

Cardiopulmonary resuscitation in space

Cardiopulmonary resuscitation is an emergency intervention used to maintain blood circulation and oxygenation in the event of acute loss of cardiac output. If required during spaceflight there are various methods of CPR that have been adapted to microgravity.[84–86] Alternatively a mechanical device could be useful when considering the effects of deconditioning on the CPR operator.[87] However, even if successful resuscitation was achieved, the complex supportive critical care generally required after a cardiac arrest is unlikely to be available or sustainable over any extended period in the space environment.

Table 4 The aerospace medicine sieve, divided into three overarching categories, illustrating a systematic approach to space medicine considerations and the holistic nature of the speciality. For each aspect we must also consider each population of interest: i) ground personnel, ii) pilots, iii) other crew, iv) passengers (or spaceflight participants) and v) patients

Clinical	Human performance	Human systems engineering
Selection • standards • testing • psychological screening	Environmental effects on physiology, performance and survivability • Altitude/reduced pressure • Acceleration (G forces) • Microgravity • Radiation • Noise • Thermal	Personal protective equipment • clothing • space suits • personal emergency systems
Training and pre-flight • health promotion • travel health • fitness to fly • quarantine	Sleep/fatigue/circadian cycle	Vehicle/habitat • environmental control • life support systems • living and sleeping space • toileting, food, water
Launch and landing • emergency cover • public health (if point-to-point transport)	Nutrition	Medical devices
In-flight • routine medical care and telemedical support • psychological support • emergency management • evacuation advice	Human error and contribution to incidents and accidents	Human machine – interface • human factors • anthropometry • ergonomics
Accident • acute care • Major Incident Medical Managements Systems • Extreme environment medicine and survival	Incident and accident investigation	Escape systems
Post-flight • physical rehabilitation • psychological support	Training, education and simulation	Impact protection
Through life health and well-being	Performance optimisation +/- enhancement	Survival aids
Spaceflight analogues		Integration
Research		
Governance		

Spacecraft emergencies

In addition to normal medical considerations, spacecraft emergency scenarios should also be considered. The top three on board the International Space station are: i) loss of pressurisation, ii) fire, and iii) toxic leak (e.g. ammonia) all of which have occurred during real missions in the history of human space flight. Loss of pressure could be because of a small or large leak in the habitat, vehicle or spacesuit, each with differing potential causes and emergency responses.[88] The medical consequences of decompression depend upon the rate and magnitude of pressure loss. Hazards include barotrauma, arterial gas embolism, acute hypoxia, decompression sickness and ebullism (vaporisation of water in the soft tissues and low pressure areas of the circulation).

Astronauts are drilled for these scenarios, donning emergency oxygen systems to protect from hypoxia or filtering respirators for smoke or toxic fumes. Ultimately they may need to evacuate the spacecraft if the issue cannot be isolated and stabilised. These efforts are locally controlled on the spacecraft but with additional support from ground stations. For interplanetary missions abort options and real-time ground support would be severely limited compared with that available in low Earth orbit (LEO).

Medical evacuation

From LEO, an emergency return is achievable in a matter of hrs although options may be limited by the type and availability of the evacuation vehicle, the physical state of the patient and the on-going medical support required. The ISS emergency return vehicle is the Soyuz; a very reliable and capable launch and return vehicle, but one not designed for evacuation of patients requiring on-going medical support. Furthermore, little is known about the impact on an ill or injured person of microgravity or +Gx acceleration, as occurs during re-entry to Earth's atmosphere. A primate model of hypovolaemic haemorrhagic shock found re-entry may be potentially survivable without volume resuscitation but that appropriate treatment and monitoring would likely optimise clinical outcome.[89]

For missions on the Moon evacuation times would be in the order of days and for missions to Mars it would be in the order of months, if it were possible at all. Missions of this type therefore demand a greater level of provision and self-sufficiency, which in turn would be reflected in the equipment, on board pharmacopoeia and medical skills mix of the crew. Education is important to manage the expectations of astronauts or commercial space participants with regard to the medical risks of flight and limitations of the treatment options.

Roles of a space medicine doctor

The roles of a space medicine doctor (aka flight surgeon) can be considered in the context of the specialty as a whole (Fig. 1) and the range of scenarios astronauts and therefore flight surgeons may be involved in (Clinical column in Table 4). Table 4 is an 'aerospace medicine sieve' that provides a framework to approach the medical, physiological and protection system considerations for different potential spaceflight scenarios and the multiple interactions to consider (Fig. 1).

One aspect of space medicine that is particularly different from normal medical practice is the role of the flight test doctor. They are working at the interface of extreme environment medicine, engineering, and flying to help design the human into the system. This may involve system specification and design, underlying research or test and evaluation trials that may be conducted in a range of settings: the exercise laboratory, altitude chambers, man-carrying centrifuges, analogue spaceflight environments or the flight environment itself.

A mission to Mars will have to be significantly more self-sufficient than current LEO operations and may require the return of a traditional component of human exploration: the ship or expedition doctor. Indeed, NASA stipulates that a physician should be part of the crew for planetary missions longer than 210 days.[64] Their role would include acute care skills to manage trauma or emergency medical situations but traditionally, more holistically, they are also an important moral and social component of the exploration team leadership.

The future of space medicine in the UK

The UK has a strong history of aviation medicine and, with a view to the future, the General Medical Council recently recognized Aviation and Space Medicine as a specialty. The subsequent approval of the training curriculum in September 2016 has opened up the pathway in the UK to train in this fascinating field of medicine.The UK also has a long history and reputation of contributing to the design and implementation of safety and life-supporting equipment in aviation, which could be applied to the spaceflight industry. However, to support this there is a need for greater interaction between medicine and engineering. The recognition of the specialty in the UK is a positive step forward to facilitate this and is a key enabler for the UK Government's commercial spaceflight ambition.[90]

As this brief overview indicates there is much that remains unknown in the field of space medicine. It is clear that the same exploration that takes us out into the endless frontier of space will demand that we also continue to look within and explore the limits of the human body in this the most austere of all extreme environments.

Authors' contributions

Study design/planning: P.H., K.F.
Study conduct: all authors
Data analysis: all authors
Writing paper: all authors
Revising paper: all authors

Declaration of interest

None declared.

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