Anaesthesia 2022, 77, 384–388 doi:10.1111/anae.15580

Editorial

Anaesthetists and aerospace medicine in a new era of human spaceflight

T. G. Smith[1,2] and **J. C. Buckey Jr**[3,4]

1 Head of Aerospace Medicine Research, Centre for Human and Applied Physiological Sciences, King's College London, UK
2 Consultant, Department of Anaesthesia, Guy's and St Thomas' NHS Foundation Trust, London, UK
3 Professor, Space Medicine Innovations Laboratory, Geisel School of Medicine, Dartmouth College, Hanover, NH, USA
4 Chief of Hyperbaric Medicine, Dartmouth-Hitchcock Medical Center, Lebanon, NH, USA

Corresponding author: T. G. Smith
Email: thomas.g.smith@kcl.ac.uk
Accepted: 14 August 2021
Keywords: commercial suborbital spaceflight; astronauts; microgravity; anaesthesia; peri-operative medicine

Fewer than 600 people have been to space, mostly very fit and healthy professional astronauts who have undergone careful medical screening and selection, but this is about to change. Two billionaires recently took maiden flights on their companies' respective suborbital spacecraft (Fig. 1), opening the way for private citizens to fly as paying customers. How will they cope with spaceflight? What should the medical approach to passengers involve? What does this have to do with anaesthetists?

Commercial suborbital spaceflight and aerospace medicine

Sir Richard Branson (Virgin Galactic) and Jeff Bezos (Blue Origin) flew on suborbital trajectories that reach space without reaching orbit and provide several minutes of microgravity ('weightlessness') in between the high G acceleration ('G forces' or 'G') of launch and atmospheric re-entry. Many members of the public have already purchased tickets for short suborbital tourist flights, which are eventually expected to develop into incredibly fast point-to-point travel – for example, London to Australia in 2 h. SpaceX, which is already ferrying astronauts to the International Space Station on contract, also has ambitions for suborbital space travel, and major investment banks anticipate suborbital travel will be 'cannibalising' long-haul air routes within a decade, with $800 billion in forecast annual sales by 2040. This may seem far-fetched, and the time frame is of course unknown, but it is worth considering the spectacular and rapid progress to date. Remarkably, the entire history of powered aviation and spaceflight has happened within a single human lifespan, specifically that of Kane Tanaka of Japan, who is the oldest person in the world (aged 118 y) and was born before the Wright brothers' first flight in 1903.

Suborbital spaceflight is a new frontier within the established field of aviation and space medicine, which is collectively known as aerospace medicine and was formally recognised as a medical specialty in the UK in 2016 [1]. Aerospace medicine is concerned with the physiological and medical challenges associated with aviation and space flight. Several anaesthetists were among the multidisciplinary group who worked to achieve regulatory approval of the specialty and its training programme, which includes core training in anaesthetics as one of the entry pathways [1]. There is considerable overlap and synergy between aerospace medicine and our specialties of anaesthesia and hyperbaric medicine, and growing scope for anaesthetists to engage with this unusual branch of medicine.

Interface between aerospace medicine and anaesthesia/peri-operative medicine

Most fundamentally, these domains share a common bedrock of applied physiology, including hypoxia (whether

Figure 1 Suborbital spacecraft. Blue Origin's 'New Shepard' (left) uses a reusable rocket to launch a crew capsule that lands via parachute (photo credit: Blue Origin). Virgin Galactic's 'SpaceShipTwo' spaceplane (right) is launched from a carrier aircraft and lands as a glider (photo credit: Virgin Galactic).

peri-operative or in-flight) and the effects of gravity (whether in the operating theatre, in ICU or in space). Mild hypoxia is routinely experienced during commercial air travel due to the reduced cabin pressure, with arterial oxygen saturation typically falling to 90–95% in airline passengers and often lower in those who are older or have respiratory disease. Mild cabin hypoxia is sufficient to stimulate classic physiological responses in passengers, including erythropoietin secretion and hypoxic pulmonary vasoconstriction [2], and probably contributes to medical emergencies in air travellers by exacerbating or precipitating cardiopulmonary disease [3, 4]. These findings are relevant to the peri-operative setting, where comparable mild-moderate oxygen desaturation is often dismissed as unimportant but is common and seriously underestimated [5], and may be contributing to peri-operative morbidity and mortality [6, 7].

Another area of overlap is gravitational physiology, which is clearly relevant to astronauts experiencing profound physiological disturbances in space [1], but is actually much more broadly important to life on Earth. Whenever we change our posture there is a change in gravitational forces on the body, with the possible exception of early gestation when the buoyancy of in-utero life somewhat mimics weightlessness. Gravity is our constant companion, and because it is ubiquitous we do not always consider its influence on everything from fluid distribution in the body to how we insert an intravenous cannula. The effects of gravity/posture can become particularly important in the operating theatre and in ICU, such as steep Trendelenburg positioning during prolonged robotic surgery and the use of prone positioning in critically ill patients.

In addition to underlying physiological parallels, anaesthesia and aerospace medicine have a common focus on human factors. Anaesthetists, and more particularly patients, have benefited greatly from aviation concepts such as crew resource management, simulation training and safety checklists. There is also technology crossover between peri-operative medicine and military aviation and spaceflight, including the role of sophisticated life support systems and advanced physiological monitoring.

Clinically, these disciplines directly converge in the areas of aeromedical critical care and hyperbaric medicine, in which many anaesthetists sub-specialise. Core physiological concepts of altitude, depth and pressure link these clinical fields and connect such varied activities as transferring a critically unwell patient by air ambulance; treating a hospital patient with hyperbaric oxygen therapy; sustaining a military pilot pushing an advanced aircraft to its limits; and protecting a space-walking astronaut from the vacuum of space. With the advent of commercial suborbital flights, potential involvement of anaesthetists in space medicine is expanding to encompass a broader role in peri-flight care.

'When astronauts become patients' vs. 'when patients become astronauts'

In theory, an astronaut could be injured or develop a medical condition ('become a patient') requiring anaesthesia in space. This has not yet occurred but would present unique challenges, not least microgravity-induced physiological changes such as a large head-ward fluid shift, reduced blood volume and possibly cardiovascular deconditioning [1, 8]. The closed cabin environment is a contraindication to inhalational anaesthesia, while weightlessness complicates even routine technical procedures. We have yet to answer the question of how best to provide anaesthesia in space [8], although multiple studies in the anaesthetic literature have investigated relevant techniques on parabolic aircraft flights that provide repeated ~20-s periods of microgravity; for example, recent work supports the use of videolaryngoscopy for intubation in microgravity [9].

Commercial suborbital spaceflight flips the astronaut/patient paradigm by replacing rigorously screened and selected professionals with everyday citizens. With a little licence, this can be conceptualised as 'normal' people, who we might meet every day as patients, flying to space ('patients becoming astronauts'). Many people who are elderly (some aged >90 y) or have significant medical problems have already booked flights. Tickets are very expensive (as in the early days of air travel) and thus more likely to be affordable for older individuals, who tend to have a higher prevalence of comorbidities [10]. Prospective suborbital passengers will require pre-flight evaluation and appropriate peri-flight interventions to maximise access while minimising morbidity. These concepts are likely to sound familiar to anaesthetists.

Anaesthetists as peri-flight physicians

The development of the specialty of anaesthesia into peri-operative medicine, and of anaesthetists into peri-operative physicians, is now well established. Anaesthetists are experts in evaluating and optimising a patient's capacity to withstand a major physiological challenge, and similar principles of pre-assessment and optimisation apply to private citizens facing the stressors of spaceflight, which could one day include all of us. In both cases, the aim is to improve outcomes by stratifying physiological risk and then intervening to modify this risk as required, whether through widespread pre-operative tools like cardiopulmonary exercise testing and prehabilitation, or by targeting in-flight support with a pre-flight 'G challenge test' on a human centrifuge [11]. Alongside colleagues in aerospace medicine and other specialties, anaesthetists are well placed to apply their skills and experience in pre-assessment and optimisation as 'peri-flight physicians'.

Challenges in suborbital physiology and medicine

It has not yet been possible to develop medical fitness-to-fly criteria for suborbital flights – very few people have ever experienced such a dynamic high/zero/high-G profile, and the physiological effects need to be determined in relevant passenger groups [12]. Reassuringly, high G peaks on launch and re-entry are brief, and simulating these G profiles on a centrifuge has been tolerated by many people of varying ages (up to 88 y) and with various stable medical conditions [10, 13, 14]. However, these high G exposures are not trivial, potentially reaching a transient peak of up to 6 Gs in the chest-to-back direction on re-entry [14]. At 6 Gs, bodyweight is multiplied six-fold, which is half a tonne for an 85-kg person, and the experience has colloquially been likened to an 'elephant sitting on the chest'. Recent anaesthetist-led research in the UK has characterised the pulmonary response to these magnitudes of G on a centrifuge, demonstrating ventilation/perfusion mismatching and hypoxaemia; reversal of regional lung ventilation with associated gas trapping; impaired breathing mechanics; and breathlessness [11]. These effects were well tolerated by young healthy participants, but studies are required to investigate their potential to become clinically meaningful in medically susceptible passengers, such as those with lung pathology, cardiac conditions or higher BMI [11].

Speculative cardiovascular effects of suborbital flights also raise interesting questions. Like head-down tilt on Earth, the large head-ward fluid shift in microgravity causes bulging neck veins, facial congestion and increased stroke volume. For many years, this fluid shift was assumed to increase central venous pressure, until direct measurements in Space Shuttle astronauts found that CVP actually falls in microgravity, apparently due to loss of compressive forces associated with tissue mass [15–18]. In the suborbital context, does a sudden transition to a bigger heart at a lower pressure present concerns for older people with 'stiff' hearts? Are contingencies required for development of arrhythmias in predisposed individuals [19, 20]? Could microgravity actually improve cardiac function by reducing afterload? There is no way to replicate the high/zero/high-G profile of suborbital flights, and definitive answers will require flight experience and in-flight research. It is notable that microgravity has only rarely been experienced by individuals with significant medical conditions [21], such as the late Professor Stephen Hawking, who famously undertook a parabolic aircraft flight but was closely monitored by accompanying doctors and received glycopyrrolate and supplementary oxygen [22].

The potential for nausea and vomiting during suborbital flights is another challenge that falls well within the professional expertise of anaesthetists. A form of motion sickness afflicts most astronauts during early spaceflight and is common on parabolic aircraft flights (of 'vomit comet' fame), although not usually on the first parabola [23]. A suborbital trajectory is essentially one big parabola, but passengers will presumably be undertaking highly provocative manoeuvres such as somersaults, and sickness could be problematic [23].

Suborbital research opportunities

There is a long history of anaesthetists and hyperbaric medicine specialists exploring physiological extremes, whether at high altitude, undersea or in aerospace environments, often involving invasive or otherwise advanced measurements. Already more than 1000 publications listed on PubMed touch on both aerospace medicine and anaesthesia in some form, and commercial spaceflight brings a new imperative for studies supporting the medical approach to prospective passengers.

More generally, suborbital flights also enable fundamental biomedical research that has not been possible before, as they provide an intermediate platform that bridges the gap between parabolic flights (which are limited by the very short duration of microgravity) and orbital missions (which are limited by accessibility and cost). While suborbital tourist flights receive most of the media attention, scientists are another important market for suborbital operators. Research seats have already been reserved by academic institutions, the military and NASA, and access to suborbital human spaceflight for researchers should be a priority for the UK Space Agency and European Space Agency. This is important not only for space medicine research per se, but because research in space also enlightens life on Earth. The Space Shuttle CVP studies mentioned above are a prime example – this work unveiled novel aspects of terrestrial cardiovascular physiology and overturned our prevailing understanding of what 'should' happen, while providing a reminder of the importance of scientific humility. Space medicine is not lacking in unexplained pathophysiological phenomena, which currently include the visual impairment experienced by long-duration astronauts and the recent development of an internal jugular vein thrombosis in space [24].

Anaesthetists in the new space age

Commercial space exploration offers many exciting and important possibilities, notably including Jeff Bezos' ultimate ambition of saving the Earth by moving all heavy industry off-planet. Although it sounds like science fiction, just 5 y before NASA landed astronauts on the Moon, the betting odds for achieving that feat were 1000 to 1 [25]. The UK aims to be the European centre of commercial suborbital spaceflight and is driving forward the necessary regulatory framework, including medical policies, in parallel with UK spaceport development. We are at a historical inflection point and there is a growing opportunity, and indeed necessity, for anaesthetists to exploit the specialty's close alignment with aerospace medicine and make direct contributions to clinical practice and research in the new space age.

Acknowledgements

TS is an advisor in aerospace medicine to the Medical Research Council and a Member of Council of the Aerospace Medical Association (USA). He has received research grants or in-kind support from the UK Space Agency, UK Civil Aviation Authority, Royal Air Force and NASA, and has received payments from Caeli Nova for consultancy work. JB is a former payload specialist astronaut and has received funding from NASA, the Office of Naval Research, DARPA and the US National Institutes of Health. No other competing interests declared.

References

1. Hodkinson PD, Anderton RA, Posselt BN, Fong KJ. An overview of space medicine. *British Journal of Anaesthesia* 2017; **119**: i143–i53.
2. Turner BE, Hodkinson PD, Timperley AC, Smith TG. Pulmonary artery pressure response to simulated air travel in a hypobaric chamber. *Aerospace Medicine and Human Performance* 2015; **86**: 529–34.
3. Smith TG, Chang RW, Robbins PA, Dorrington KL. Commercial air travel and in-flight pulmonary hypertension. *Aviation, Space and Environmental Medicine* 2013; **84**: 65–7.
4. Smith TG, Talbot NP. Aircraft cabin hypoxia and adverse medical events. *Journal of the American Medical Association* 2019; **321**: 2030.
5. Sun Z, Sessler DI, Dalton JE, et al. Postoperative hypoxemia is common and persistent: a prospective blinded observational study. *Anesthesia and Analgesia* 2015; **121**: 709–15.
6. Bojesen RD, Fitzgerald P, Munk-Madsen P, Eriksen JR, Kehlet H, Gogenur I. Hypoxaemia during recovery after surgery for colorectal cancer: a prospective observational study. *Anaesthesia* 2019; **74**: 1009–17.
7. Ekeloef S, Alamili M, Devereaux PJ, Gogenur I. Troponin elevations after non-cardiac, non-vascular surgery are predictive of major adverse cardiac events and mortality: a systematic review and meta-analysis. *British Journal of Anaesthesia* 2016; **117**: 559–68.

8. Komorowski M, Thierry S, Stark C, Sykes M, Hinkelbein J. On the challenges of anesthesia and surgery during interplanetary spaceflight. *Anesthesiology* 2021; **135**: 155–63.
9. Starck C, Thierry S, Bernard CI, et al. Tracheal intubation in microgravity: a simulation study comparing direct laryngoscopy and videolaryngoscopy. *British Journal of Anaesthesia* 2020; **125**: e47–53.
10. Blue RS, Jennings RT, Antunano MJ, Mathers CH. Commercial spaceflight: progress and challenges in expanding human access to space. *REACH – Reviews in Human Space Exploration* 2017; **7–8**: 6–13.
11. Pollock RD, Jolley CJ, Abid N, et al. Pulmonary effects of sustained periods of high-G acceleration relevant to suborbital spaceflight. *Aerospace Medicine and Human Performance* 2021; **92**: 633–41.
12. Stepanek J, Blue RS, Parazynski S. Space medicine in the era of civilian spaceflight. *New England Journal of Medicine* 2019; **380**: 1053–60.
13. Blue RS, Riccitello JM, Tizard J, Hamilton RJ, Vanderploeg JM. Commercial spaceflight participant G-force tolerance during centrifuge-simulated suborbital flight. *Aviation, Space and Environmental Medicine* 2012; **83**: 929–34.
14. Blue RS, Pattarini JM, Reyes DP, et al. Tolerance of centrifuge-simulated suborbital spaceflight by medical condition. *Aviation, Space and Environmental Medicine* 2014; **85**: 721–9.
15. Buckey JC, Gaffney FA, Lane LD, et al. Central venous pressure in space. *Journal of Applied Physiology* 1996; **81**: 19–25.
16. Buckey JC, Phillips SD, Anderson AP, et al. Microgravity-induced ocular changes are related to body weight. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology* 2018; **315**: R496–9.
17. Buckey JC, Gaffney FA, Lane LD, Levine BD, Watenpaugh DE, Blomqvist CG. Central venous pressure in space. *New England Journal of Medicine* 1993; **328**: 1853–4.
18. Buckey JC. Central venous pressure. In: Prisk GK, West JB, Paiva M, eds. *Gravity and the Lung: Lessons from Microgravity*. New York, NY: Marcel Dekker; 2001: pp. 225–54.
19. Suresh R, Blue RS, Mathers CH, Castleberry TL, Vanderploeg JM. Dysrhythmias in laypersons during centrifuge-simulated suborbital spaceflight. *Aerospace Medicine and Human Performance* 2017; **88**: 1008–15.
20. Torphy DE, Leverett SD, Lamb LE. Cardiac arrhythmias occurring during acceleration. *Aerospace Medicine* 1966; **37**: 52–8.
21. Jennings RT, Murphy DM, Ware DL, et al. Medical qualification of a commercial spaceflight participant: not your average astronaut. *Aviation, Space and Environmental Medicine* 2006; **77**: 475–84.
22. Mackenzie I, Viirre E, Vanderploeg JM, Chilvers ER. Zero G in a patient with advanced amyotrophic lateral sclerosis. *Lancet* 2007; **370**: 566.
23. Golding JF, Paillard AC, Normand H, Besnard S, Denise P. Prevalence, predictors, and prevention of motion sickness in zero-G parabolic flights. *Aerospace Medicine and Human Performance* 2017; **88**: 3–9.
24. Limper U, Tank J, Ahnert T, et al. The thrombotic risk of spaceflight: has a serious problem been overlooked for more than half of a century? *European Heart Journal* 2021; **42**: 97–100.
25. D'Alto N. Betting on the Moon. *Air and Space/Smithsonian* 2018; **33**: 18.

