On the Challenges of Anesthesia and Surgery during Interplanetary Spaceflight

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Two months after landing on Mars, an astronaut suffers from a fall during an extravehicular activity, resulting in a fractured femur. Because it is impossible to return home, the remaining crew must manage the injury.

Imray *et al.*[1] argued that modern day explorers will encounter "environments where physiologic and geographical extremes necessitate prompt and innovative approaches to rescue, medical care, and transportation." A human settlement in deep space perfectly illustrates this statement, particularly when considering the challenges of providing emergency medical and trauma care.

Experts have estimated that the most significant risks for space exploration missions are trauma, hemorrhagic shock, and infections.[2–4] To some extent, the likelihood of medical events can be estimated from analog ground populations, both military and civilian, and data gathered during human spaceflight experience.[2,5,6] For example, the risk of lower limb fracture has been estimated at 0.046 event per Mars mission (950-day mission for a crew of six).[2] A recent consensus of experts estimated that such trauma would have one of the highest impacts on the mission (ranked fifth out of 30 severe medical conditions).[7]

Moon exploration missions leading to the establishment of a permanent settlement are planned in the coming years, as early as 2024 (National Aeronautics and Space Administration [Washington, D.C.] NASA Artemis program), and will be followed by Mars missions. The private sector, spearheaded by the efforts of the company SpaceX (Hawthorne, California), is also shifting its focus from low-Earth orbit to the colonization of Mars, with the first manned missions planned for the mid-2020s. The duration, remoteness, and type of activities involved on a Moon or Mars settlement lead to hazard exposure different than would be expected in low Earth orbit.[6–8] Specifically, challenges of the unique lunar environment include exposure to reduced gravity (about one sixth of Earth's gravity on the Moon and one third on Mars), ionizing radiations, meteoroids, planetary dust, hypobaric decompression sickness, and extreme temperatures.[7–9]

The vast number of extravehicular activities planned during surface exploration will expose the astronauts to a high cumulative risk of traumatic accidents and hypobaric decompression sickness.[2,3,8,10] Exposure to weightlessness (and possibly even to partial gravity) reduces bone density to osteoporotic levels after a few months without countermeasures and exposes astronauts to an increased risk of pathologic fractures.[10–12]

In this focused narrative review, we sought to identify key challenges for a crew on the surface of Mars or the Moon facing a severe surgical emergency such as a major trauma. In particular, we examined the existing literature for factors related to medical evacuation, telemedicine, the delivery of anesthesia and surgery, and behavioral health and performance. Finally, we analyze what technologies and futuristic concepts could be useful in both the setting of a space mission and the practice of anesthesia on Earth.

Results

"Stay and Play or Scoop and Fly?"

Medical Evacuation from Deep Space. A trip to Mars is likely to take 200 days in each direction, which precludes any option for an urgent return back to Earth, leaving the crew truly self-reliant.[7] In case of an emergency, immediate evacuation from the Moon ("scoop and fly") may not be possible either.[13] In the best case scenario, the delay between the decision to evacuate and reaching a medical facility on Earth will be more than 4 days.[8] A rescue aeromedical operation coming from Earth would not impact the initial management of the casualties since it would realistically take several weeks for a team to arrive on site.

Issue of Medical Supplies and Resupply

In London, austere environments, the ideal scenario for medical support is to match the equipment and personnel

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competencies to the most likely medical conditions.[1,14,15] The design of the medical kit must balance crew skills with constraints in volume; weight; power requirements against the load of expected medical conditions, which partly depend on the mission profile (*e.g.*, mission duration, number of extravehicular activities); and crew size.[2,7,14,15]

Table 1 shows the content of the medical kit of early space programs and the current International Space Station, and what would be desirable onboard future space exploration missions. The current International Space Station medical kit does not allow for invasive procedures or prolonged organ support and will need to be significantly updated for future missions.[5,7,13] The care of a severely ill patient requires a range of support services and equipment that extend well beyond clinical skills, such as running water, electricity, surgical equipment and sterilization means, personal protective equipment, and ideally laboratory work, imaging equipment, blood products, and continuous oxygen.[16,17] This quantity of equipment is not compatible with the currently envisioned storage capability for early interplanetary exploration missions (*e.g.*, in the Orion capsule for a Moon mission). At the National Aeronautics and Space Administration, the "Integrated Medical Model" was specifically created with the objective of resource and kit optimization. It relies on Monte Carlo simulations of various mission outcomes under different conditions (*e.g.*, crew size, mission duration, content of the medical kit).[15] Resupply options will be extremely limited for a Moon base, and impossible for Mars, so the assumption is that the crew will only have available what they bring onboard, making reliability and airworthiness requirements of the equipment incredibly stringent.

Another consideration is the accelerated degradation of drugs in the space environment, which will require specially designed packaging.[18] Ultrasonography is likely to remain the leading imaging modality.[6,19,20] It can be used for a variety of clinical tasks and procedures, such as focused assessment for trauma, diagnosis of a pneumothorax or pulmonary condensation, assessment of volemia and cardiac function, line placement, regional blocks, or assisting external fixation of fractures.[6,14,20,21]

On-board Medical Skills

The current International Space Station program requires the on-board presence of a crew medical officer, who is not necessarily a physician.[6,13] The best physician profile for a space exploration mission would be an emergency medicine doctor with additional training in surgery and wilderness medicine.[6,23] Table 2 presents an overview of the skills and techniques relevant to acute medical care that have been adapted and tested in spaceflight or space analog environments. Importantly, the crew physician will spend most of their time on nonmedical tasks, in which they must be proficient.[6,24] The crew doctor will need to have a broad knowledge base and to be competent in basic surgical skills and in the management of the critically ill and injured.[6] Most likely, a single crew physician will oversee all aspects of patient care, possibly endorsing several roles such as being both the surgeon and the anesthesiologist.[14,17]

Skills redundancy will be critical to enhance crew safety, particularly if the designated crew physician becomes incapacitated or dies.[13,14,25] In this situation, it has been suggested that nonphysicians could perform advanced medical care.[14,25,26] It therefore appears advisable to train several crew members to manage the most common emergencies, for example, matching the first level of competency of the World Health Organization (Geneva, Switzerland) medical competency models, which correspond to basic resuscitative and primary trauma care that do not require extensive equipment or skills.[14,17]

Table 1. Comparison of the Content of Medical Kits for Early Space Missions, the International Space Station, and Proposed Medical Kit for a Deep Space Mission[13,22]

	Early Space Programs (1960s–1980s)	Current International Space Station Medical Kit	Proposed Space Exploration Kit for the Moon and Mars
Diagnostic tools	Clinical signs and vital signs (heart rate, blood pressure, respiratory rate, temperature) monitored by physicians on the ground	+ Monitor, electrocardiogram, ultrasound machine, point-of-care limited laboratory tests	+ Artificial intelligence–embedded ultrasound, extensive laboratory tests including microbiology
Medications	A few oral and IM medications	Extended list of oral medications, some IV including IV morphine and ketamine	Extended oral/IV medications, including antibiotics, sedatives, vasopressors, inotropes
Surgical tools	None	Minor surgery	Advanced surgical kit including endoscopic surgery, three-dimensional printing of tools and implants
Organ support	None	Automated external defibrillator, simple ventilator	+Video-laryngoscope, advanced ventilator, syringe drivers, hyperbaric chamber
Support facilities	None	Foldable stretcher IV fluids: 4–5 l oxygen and nitrogen tanks	Medical bay or module, on-site IV fluid generation, oxygen concentrator
Hardware/Information Technology	Standard audio communications	Real-time telemedical link with audio/video	Artificial intelligence–based decision support tools

IM, intramuscular; IV, intravenous.

Table 2. Skills and Procedures Related to the Care of a Surgical Critical Patient, Tested in Spaceflight and Spaceflight Analogs, along with a Few Selected Relevant References

Skill	Setting of the Research	References
Ultrasound	Spaceflight	19
Rapid sequence induction	Mars analog environment	25
Airway management	Parabolic flight, neutral buoyancy (submerged) facility, Mars analog environment	25–27
Surgery	Parabolic flight, spaceflight	5,28
Cardiopulmonary resuscitation	Parabolic flight, neutral buoyancy (submerged) facility, body suspension device, spaceflight	29

Telemedicine

Telemedicine relies on remote communication technologies to facilitate specialist provision of diagnostic and/or therapeutic advice for patients in an isolated place.[30–32] It is used extensively in current spaceflight operations for remote monitoring, training, diagnosis, and treatment of astronauts.[13,30,33] Near real-time communications are possible between the Moon and Earth, with delays around 2 s in each direction. This latency will allow voice and video communication, but most likely not remote operation of hazardous equipment like a surgical robot. However, in the case of Mars, delays in communications of 4 to 20 min in each direction will preclude real-time communications and remote control of equipment. This leaves the option to use asynchronous remote support, which was demonstrated, for example, in a simulated appendectomy on Mars.[31]

Anesthetic and Surgical Management

Physiologic Considerations

In space, microgravity affects most physiologic systems.[34,35] The main cardiovascular features of the zero-gravity adaptation include a fluid shift toward the head; a reduction in blood volume, cardiac function, and volume; an increase in lower-extremity venous compliance; and an alteration of the arterial systemic resistance and the baroreflex response (fig. 1).[35–37] The system rapidly becomes unable to respond efficiently to challenges such as orthostatism after return to normogravity, or blood loss.[35,38] A return to gravity is increasingly difficult with longer time spent in weightlessness.[35] The extent of the cardiovascular alterations in partial gravity (on the Moon or Mars surface) and the level of gravity required to prevent these effects are currently unknown, so more research on these fundamental questions is needed.[35]

Besides alterations of the cardiovascular system, the anesthesiologist will also be concerned about the increased risk of sepsis that threatens astronauts. Indeed, many factors exacerbate infectious risk, including confinement, restricted hygiene, altered immune system, decreased antibiotic activity and potentially increased bacterial resistance, as well as newly identified dynamic changes in the microbiome of subjects and the environment.[4]

Choice of Anesthetic Technique

The general approach for choosing an anesthetic technique in a difficult environment depends on several factors including the patient's condition, experience of the care providers, availability of drugs and equipment, degree of urgency, presence of a full stomach, and patient's preference.[14,16,17] Anesthesia providers with limited experience should restrict themselves to a small number of safe, widely applicable techniques, in which they should be competent. It has been suggested that in case of limited skills and supplies, general anesthetic use should be minimized whenever possible.[16,24]

To this day, no anesthetic procedure was ever required during or shortly after a spaceflight. For space exploration missions, in the absence of strong evidence, it appears sensible to formulate choices based on a worst case scenario approach. Astronauts requiring surgery should therefore be considered to be severely deconditioned, hypovolemic, difficult to intubate, and intolerant to succinylcholine; have a full stomach; and be managed by nonmedical personnel with limited training.[14,24,25] Overall, we argue that regional anesthesia should be attempted whenever possible.[24,39] A combination of short training before the mission with on-the-spot refresher should give crewmembers a good chance of succeeding at their regional block. When not suitable or in case of failure, general anesthetic will be necessary. We recommend the implementation of a limited number of simplified intravenous anesthesia protocols: conscious sedation (for procedural anesthesia, peripheral surgery, and superficial trunk surgery) and general anesthetic with endotracheal intubation (for head, face, and deep trunk surgery).[14,24] Using volatile anesthetic agents would generally be ill advised in such small, enclosed environment. Finally, no research was ever conducted on the safety and efficacy of perimedullary anesthesia in weightlessness or partial gravity, but concerns have been expressed over the effect of the sympathetic block on a microgravity-exposed patient.[14]

Surgical Considerations

The provision of surgery on the lunar surface will be restricted to procedures that are absolutely essential for the saving of life or limb.[5,12,17,28] Nonoperative treatment may be preferred, for example, for uncomplicated appendicitis.[28] In the case of a femur fracture, one may consider temporary stabilization such as long leg plastering or an external fixator.[10,21] These temporizing measures, while technically less challenging, would be clinically suboptimal for bone healing and would make evacuation impossible due to a very cramped vehicle and the seated position.[10]

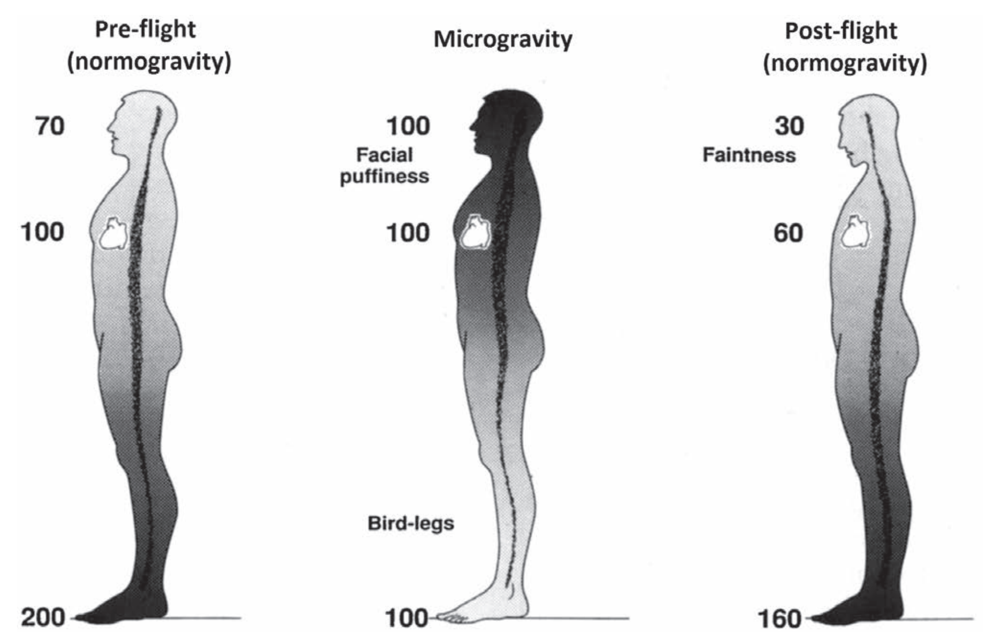

Fig. 1. Illustrated mean arterial blood pressure and fluid shifts before, during, and after microgravity exposure. Reprinted from Hargens AR, Richardson S: Cardiovascular adaptations, fluid shifts, and countermeasures related to space flight. Respir Physiol Neurobiol 2009; 169(suppl 1):S30–3, with permission from Elsevier.

Early stabilization using anterograde intramedullary nailing remains the accepted standard intervention for isolated diaphyseal femoral shaft fractures. It involves insertion of an intramedullary nail at the medial tip of the greater trochanter that is secured by a proximal and a distal locking screw. Given the situational impracticalities of x-ray films during spaceflight, ultrasonography is a compact and readily learnable technique that can delineate fracture anatomy and guide intervention with good diagnostic accuracy.[10,21] It is expected that ultrasound would be able to demonstrate intramedullary placement of the nail, although confirmation of distal locking screws would be very difficult. Effective non–image-guided techniques for distal locking screws have been described[40] and may need to be employed in this scenario but would require greater surgical exposure. Larger incisions then require appropriate closure methods and demand biologic healing, for which conflicting evidence exists regarding the impact of reduced gravity.[41,42]

The rehabilitation aim of intramedullary stabilization is full weight-bearing on postoperative day 1, and early mobilization of the hip and knee. This is likely to be possible in the reduced gravity environment; however, the biologic impact on fracture healing will be profound.[10] Computational and *in vivo* models have highlighted this impact,[11] suggesting the need for follow-up imaging and assessment for the risk of fracture non-union. The risk of venous stasis and thromboembolism may be increased in space, so appropriate thromboprophylaxis will be required.[43]

Human Factors and Behavioral Health and Performance

Human Factors and Nontechnical Skills

Isolated and confined extreme environments are independent physiologic and psychologic stressors that affect behavioral health and performance, due to prolonged exposure to factors such as stress, workload, fatigue, social isolation, altered lighting conditions, and circadian cues.[14,44] The negative psychologic responses to living in isolated and confined environments include mild cognitive impairment, time-sense disturbances, motivational decline, sleep disorders, psychosomatic symptoms, anxiety, depression, and social conflicts.[44–46] All these factors will impair the crew's ability to respond to medical emergencies, increase the risk of errors including cognitive errors, and represent added threats to the patient's safety.[7,28,44] An expert consensus publication identified key nontechnical skills for the management of severe medical emergencies during long-duration spaceflight, which included correct information exchange, supporting behavior, and team leadership/followership.[7]

Another factor to consider is that medical emergencies would represent rare events during the course of a long mission, so that maintaining sufficient basic technical and nontechnical skills for several months or years will be difficult.[44,46]

Next, emergencies are intrinsically a source of errors including cognitive errors, as they are high-demanding in terms of cognitive resources.[47,48] Cognitive errors are "thought-process errors, or thinking mistakes, which lead to incorrect diagnoses, treatments, or both."[47] The most common types of cognitive errors and biases in anesthesia include anchoring ("focusing on one issue at the expense of understanding the whole situation"), availability bias ("choosing a diagnosis because it is in the forefront of your mind due to an emotionally charged memory of a bad experience"), premature closure ("accepting a diagnosis prematurely, failure to consider reasonable differential of possibilities"), or confirmation bias ("seeking or acknowledging only information that confirms the desired or suspected diagnosis"). These cognitive errors (and other common ones) were found to occur in between 50 and 80% of medical emergencies in anesthesia.[47,48]

Collective Cognition: Teamwork and Communication Issues

Emergencies will force the whole team to adapt, to coordinate complex tasks, and to detect and to correct system instability, often by integrating multiple discordant information.[49] Minor cognitive or organizational unrecognized errors can rapidly escalate to catastrophic failures.[47,48]

In the event of an overwhelming medical event, the crew will request emergency assistance from Earth-based medical experts.[7,8,13] Exchanging timely and pertinent information between the two parties will pose considerable challenges, which will only be aggravated in case of communication instability or latency. In telemedicine, the establishment of a shared mental model and correct cross-understanding is mandatory to avoid poor coordination, leadership issues, and conflicts.[30,32,49] Teams on Earth and in space may have trouble coordinating because of different interaction models leading to members behaving contrary to the other team's expectations.

From Space to Earth: Translation of Space Technologies to Enhance Terrestrial Anesthesia

In this section, we highlight a number of innovations that are either readily available or still in development and would find valuable applications both for spaceflight and on Earth, to either expand the capabilities of experts or assist healthcare providers who may lack expertise (for example, in rural or remote settings).

Many technologies and concepts developed initially in the space sector have benefitted terrestrial medicine, anesthesiology in particular. To begin with, space agencies are known for their vast emphasis on risk assessment and culture of safety.[50] The National Aeronautics and Space Administration was the first to propose the concept of the safety matrix, which quantifies the impact of potential threats by combining their likelihood and severity.[51] Related approaches of risk quantification stemming from the aerospace industry have been applied to health care and anesthesiology. For example, the failure mode and effects analysis was shown to reduce medication errors in anesthesia.[52]

Telemedicine technology and biotelemetry developed for space missions have been used to support the management of medical and surgical emergencies in remote locations on Earth.[32] A striking example was the repair of a ruptured patellar tendon under spinal anesthesia in Antarctica, assisted by surgeons and anesthesiologists located in Boston, Massachusetts.[53] Access to video data enhances the value of telemedical support. For example, a remote expert can have access to real-time images generated by a novice operator holding an ultrasound probe.[19,20,32] This approach could be used, for example, to remotely guide doctors on Earth or crewmembers on the Moon surface to perform regional blocks. In situations of low communication latencies, image quality could be improved with remotely operated robotic ultrasound machines, which were tested in low Earth orbit.[54] Since artificial intelligence–embedded ultrasound machines can now localize important structures such as vessels or nerves, it will not be long before the loop is closed, and we have fully autonomous ultrasound machines capable of carrying out examinations, automatically achieving high image quality, suggesting diagnoses, and potentially carrying out procedures such as a central line placement or a nerve block.[55]

Airway and cardiovascular issues remain the two leading causes of morbidity and mortality related to anesthesia.[14] Here again, artificial intelligence–fueled innovations may provide precious help. While remote controlled robotic laryngoscopes have been described, a few prototypes exist that attempt to provide automated intubation, by identifying relevant anatomical landmarks and manipulating an endoscope for intubation.[56] Closed-loop systems capable of optimizing the delivery of anesthetic drugs, fluids, and vasopressors have been described by various teams, with positive effects on care quality and safety.[57,58] Such systems could prove extremely useful both in remote settings and during spaceflight, for example, if the crew physician himself was incapacitated.

Discussion

In this focused review, we highlighted the physiologic, logistical, medical, and environmental factors that would impact the management of a serious medical emergency on a deep space settlement. Medical challenges are a key issue that limits to this day the establishment of human colonies on foreign planetary bodies. Providing advanced medical care beyond Earth's vicinity and evacuating a patient remain open challenges due to extreme environmental factors and issues of medical skills and supplies.[7,8] Another consideration is that the overriding priority during a mission is flight safety: Caring for the injured crew member must not endanger the others.

During future space exploration missions, the challenges of matching the available kit and on-board medical skills to the expected medical and surgical conditions are immense. The uniqueness of this environment may lead to situations requiring extreme measures. In the worst case scenario, it is possible that it will simply be a glorified remote expedition, with only the most limited kit, and that any severe medical event will mean the demise of the crewmember. In this situation, there may not even be the need for a medical doctor among the crew, the argument being that a test pilot, an astronomer, or a geologist would bring more valuable skills.[6,23] Similar to what was common in the early ages of Earth's exploration, serious medical conditions with a low probability of survival or which are resource-heavy may not be actively treated, and instead, the only option may involve palliation or withdrawal of care.

However, a survey among active astronauts confirmed that they would—understandably—be more confident with a doctor on board.[23] On the bright side, progress in medical education (*e.g.*, on-the-spot training) and the excellent dispositions of astronauts make it realistic to envision that they could carry out medical procedures, including advanced ones such as a limb block, a general anesthetic, even if they are not medically trained.[14,25,26] We showed in relevant simulated settings that novice operators may be able to perform tasks usually carried out by anesthesiologists, including rapid-sequence induction and orotracheal intubation.[25,26] Ultrasound will likely be the imaging modality of choice for these missions. Acquisition of several critical skills appears shorter with ultrasound, even in novices. For example, ultrasound-guided central venous catheter insertion and brachial plexus block can be learned by nonexperts after fewer than 10 procedures.[14,59,60] Advances in artificial intelligence–based medical technologies (such as augmented reality devices, smart ultrasound machines, or closed-loop systems for hemodynamic optimization or general anesthetic delivery) also offer the hope of assistive tools capable of supporting crewmembers diagnosing diseases and performing medical procedures.

Even the best-trained physician will be rendered helpless with no medical equipment, and limitations in payload mass and storage will mean that the medical kit for early Moon and Mars exploration missions may be even more compact than on the International Space Station. We have highlighted the role of computer models in assisting the design of a medical kit that satisfies strict mission constraints.[15] The crew may also rely on using resources on site, for example for construction and power,[61] IV fluid generation,[62] three-dimensional printing of surgical equipment,[63] or even blood transfusion! The expected lack of blood products could be mitigated using fresh whole blood transfusion, similar to the concept of a "walking blood bank" in combat medicine, which would imply the addition of blood compatibility into crew selection criteria.[64]

Particularly of concern for long-duration space missions is the degradation of behavioral health and performance, which is one of the most challenging aspects of prolonged stays in isolated confined environments.[44,45] This will require dedicated research (*e.g.*, long-duration isolation experiments) and development and testing of new countermeasures.[8,44,46]

Conclusions

As the ambitions of human space travel expand, the risk to health and the probability of severe medical events intensify.[7,8] While exemplary planning can go so far as to mitigate risk with provision of necessary skills and equipment, the heterogeneity of medical/surgical emergencies demands consideration of in-mission uncertainties, personnel training, and on-site synthesis of equipment.

The medical community will no doubt play an essential role in planning future space exploration. Provision of acute care remains a key barrier, although one that, through improved understanding and technology, can potentially be overcome. Finally, the lessons learned and material and protocols developed in that process are likely to benefit physicians and patients on Earth, in resource-limited, isolated, and austere environments, but also potentially at scale in very conventional hospital settings.

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The authors declare no competing interests.

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ANESTHESIOLOGY REFLECTIONS FROM THE WOOD LIBRARY-MUSEUM

George Harley's Triple Threat: The A.C.E. of Anesthetic Mixtures

Many agents that rendered insensibility also promised transcendence, euphoria, even a touch of the sublime. Christened "*spiritus aethereus*" in 1730 by German mathematician F. G. Frobenius, ether, by its very name, evoked the heavens. One century later, neighbors of chloroform's American co-discoverer, physician Samuel Guthrie, nicknamed his nectar-like substance "sweet whiskey." After W. T. G. Morton's 1846 demonstration, Americans exalted ether as the ace of anesthetics; however, the next year, Europeans deemed chloroform supreme. Although more cardiodepressive and arrhythmogenic than ether, chloroform afforded fragrant potency to achieve swift anesthetic depth. Nonetheless, rising deaths spurred the Royal Medico-Chirurgical (Surgical) Society of London to form an 1864 commission to examine chloroform's physiological effects. A Scottish commissioner, physician George Harley, championed his A.C.E. mixture (*lower left*): a star-studded 1:2:3 ratio of alcohol (*upper middle*), chloroform (*upper left*), and ether (*upper right*). Combining the trio's superlative properties—the (initial) stimulation of alcohol, the strength of chloroform, and the stability of ether—A.C.E. enjoyed first-rate popularity for decades to come. (Copyright © the American Society of Anesthesiologists' Wood Library-Museum of Anesthesiology, Schaumburg, Illinois.)

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