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Addressing the Space-Based Medical Facility Capability Gap with Project SOLACE: Space Orbiting Lifeboat And medical Care during Evacuation

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[Abstract] Planners for future manned deep space missions frequently address the possibility of a medical emergency far from the sanctuary of Earth. Project SOLACE is a high-fidelity simulation of just such an emergency, beginning on the lunar surface and culminating in return to Earth. Central to the project is a medical ship designed to keep station in lunar orbit, readily available to retrieve injured astronauts from the surface, provide onboard medical care and transport them back to Earth. Per US military medical doctrine and its definition of "roles," the medical ship is designed to provide role 2 and 3 care. Specifically, role 2 is defined as primary care, trauma management, and emergency medicine; role 3 encompasses resuscitation, initial wound surgery, damage control surgery, and postoperative treatment. Role 1, or first responder treatment, would be simulated on the lunar surface. This would stabilize the patient for ascent and provide as much critical care as possible during the "golden hour" of emergency medicine using portable diagnostic equipment, medication and basic hemostatic agents for trauma treatment. After lunar ascent and vehicle docking, the vehicle would begin Trans Earth Injection. During the postoperative period and transit, autonomous monitoring and responsive Total Parenteral Nutrition (TPN) would keep incapacitated crew stabilized and adequately nourished. SOLACE would ultimately return the crew to Earth, conducting simulations of role 2 and 3 care in transit. Using NASA's Human Exploration of Mars Design Reference Architecture (DRA) 5.0 as a blueprint for future manned missions to deep space destinations, Project SOLACE would address acknowledged capability gaps, namely a "lifeboat" capability, artificial gravity, and remote medical care for astronauts. It would capitalize on the proximity of the Moon and cislunar space to provide a high-fidelity simulation of a deep space mission, resulting in critical system evaluation and feedback to better address those gaps. Further, SOLACE is designed as a "plug and play" module compatible with NASA's interplanetary spacecraft architecture that supports interoperability and reusability, themes central to future missions. It uses the proposed Hercules lander to retrieve injured crew and the Trans Earth Injection (TEI) module resident in the Mars Transfer Vehicle design. Onboard medical equipment would be autonomous or teleoperated, with a gradual phase-out of the latter in favor of the former as technology matures. Finally, SOLACE design would incorporate a Lifting Body Reentry Vehicle to minimize g-forces on injured crew during Earth atmospheric reentry.

Nomenclature

a_c = centripetal acceleration
g_0 = Earth gravitational force

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R = radius
RPM = revolutions per minute
T = rotational period
V_t = tangential velocity

I. Introduction and Background

THE common sentiment among human spaceflight professionals is that nothing is more important than the safety and well-being of the crew. How much are we willing to invest in maximizing the chances of their safe return to Earth? Accidents have occurred in the past, attributable to human error, system malfunctions, or anomalies. Emergencies can precipitate quickly and have catastrophic consequences, making crew safety an overriding priority. Knowing that administrators and program managers have invested significant resources in contingency planning for crew safety will likely have a positive effect on astronaut health and psychological well-being. On multi-year deep space missions, this could mean the difference between an optimally performing crew providing maximum return on investment versus both a physically and psychologically impaired crew and a sub-optimal mission end state.

Though several minimally invasive procedures have been conducted aboard the International Space Station (ISS) and certain surgical interventions have been demonstrated in simulated microgravity environments aboard aircraft, procedures and facilities for medical care on a body's surface and in deep space represent a capability gap that could result in such an end state.[1-4] Mars Design Reference Architecture 5.0 explores the possibility of a lifeboat mode for the spacecraft, e.g. Apollo 13.[5] Project SOLACE builds upon that concept and suggests not just a mode of operation, but a separate spacecraft which could serve not only as a lifeboat, but also as a space-based emergency room, surgical facility, and post-operation recovery room. The SOLACE lifeboat presents a concept architecture designed to provide transit to Earth independent of the primary transit spacecraft. It is also a medical facility that can provide required care immediately upon receiving the crew and during the transit home. Advanced technologies including state of the art and recent advances in telemedicine and robotic surgery in particular hold promise for surgical intervention during space missions.[6]

The Roles of medical care per United States military doctrine are numbered 1-4, with each category requiring more advanced facilities and treatment methods than the one that precedes it.[7] Role 1 is required immediately after an injury to stabilize a patient for transport to an appropriate facility. The military counterparts of paramedics – hospital corpsmen and medics – are trained to provide this care. Role 2 care is best provided by the emergency room, and is followed by Role 3 care for surgical treatment, if required. Role 4 is best thought of as physical and emotional therapy required for long-term treatment and eventual return to duty status. The Roles that SOLACE would perform are 2 and 3, with Role 4 care provided at capable facilities on Earth once the transit is complete. In short, SOLACE replicates many of the capabilities of a navy hospital ship that serves as emergency room, surgical facility, and in-patient care center while sailing to friendly areas of operation – capabilities that are currently lacking in the U.S. space program.

The premise for Project SOLACE is that the Moon and cislunar space provide the setting for an excellent high-fidelity simulation of future deep space missions. The lessons learned, as well as much of the hardware, can be recycled and potentially used in missions to Mars and other proposed destinations. SOLACE tackles the challenges of crew health and human-robotic and autonomous mission operations as outlined by NASA, and it complies with the agency's vision to use Earth orbit and cislunar space as a proving ground.[8]

II. The Scenario

Consider a crew of 4-6 astronauts on a lunar mission, established on the Moon's surface. This moon mission is a high-fidelity simulation testing procedures, hardware, and software that will be used in deep space. One or more of the crew would simulate an injury requiring triage, trauma treatment, and surgery. Surface medical facilities are not available due to one of a number of reasons. They might not be established yet due to a mission being in its early stages with no medical facility prepositioned. If they did exist on the surface, the facilities could have suffered from mechanical malfunction or damage from an environmental disaster. They may be inadequate for treating the level of injury sustained. If the injury occurs late in the mission timeline, a Trans Earth Injection (TEI) window may be approaching that necessitates immediate departure even if adequate medical care is possible on the surface. For example, the crew could be on a conjunction class mission per current planning recommendations.[5,8,9] In this type of mission, Earth return windows occur roughly once every 26 months due to Earth-Mars relative positioning and reliance

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on chemical propulsion methods.[8,9] Missing a return window to remain on the surface to provide medical care might put a crew in a position to outlast their supplies, not to mention the psychological burden incurred.

Regardless of reason, mission control will simulate a mission abort and the crew will need relatively rapid evacuation from the surface to begin a return journey to Earth. The injured crew would require trauma treatment and advanced medical care during the transit.

III. The Simulation

The crew initially transits to lunar orbit and makes its way to the surface using established methodology not described in this paper. There would likely be additional objectives associated with the overall lunar mission, but the simulation would capitalize on the opportunity to test SOLACE procedures and hardware by making them the primary method for returning the crew safely to Earth.

The simulation would begin with one or more of the crewmembers enacting a traumatic injury on the lunar surface. The healthy crewmembers would provide Role 1, or first responder, care to the patient. To accomplish this, all crew would need to receive advanced medical training to stabilize a patient for transport. Given the number of physician-astronauts in the current cadre at Johnson Space Center, at least one could be in the crew composition on such a simulated deep space mission. If the physician is not incapacitated, this crew member could lead the medical effort throughout the simulation. If the medical professional is simulating an injured crewmember, he or she could provide procedural advice and coaching – assuming the injury does not preclude ability to act in this role.

Once stabilized, the crew would board an ascent vehicle for transit to the medical module in the SOLACE spacecraft prepositioned in lunar orbit. Once docking is complete, the crew would utilize onboard medical equipment to test emergency room and surgical procedures and capability, simulating Role 2 and 3 care. The SOLACE spacecraft will simultaneously begin its TEI burn and progress toward Earth orbit. During the transit, postoperative recovery procedures would be evaluated. When safely in Low Earth Orbit (LEO), the crew will board a lifting body reentry vehicle for minimum debilitating g-forces on atmospheric reentry. Role 4 care will be in the hands of the sophisticated medical teams and facilities on Earth. As spacecraft technologies and systems evolve and new generation of reusable vehicles becomes operational, it may be possible to design scenarios in which the emergency may be handled without the need to dock and transfer incapacitated crew at various stages of return flight.

IV. The Hardware

The hardware capable of performing Roles 1-3 must be capable, in some cases portable, and reusable. Themes such as modularity and reusability permeate the landscape of modern space mission planning as we migrate away from the “Flags and Footprints” model of the Apollo era toward more effective economies of scale.[9] Without such a migration, enticing lawmakers to appropriate more funds to NASA for the development of deep space capabilities will continue to be challenging. Our goals as we design the architecture and associated hardware for missions should follow certain heuristics to ensure project sustainability, notably keeping the design relatively simple and building components with good “bones” to support growth, upgradability, and utilization of evolving Commercial Off The Shelf (COTS) technology.[10]

An important consideration is that space agencies need not go it alone when developing hardware for these tasks. There is ongoing research and work that NASA can leverage to combine efforts and save costs. The U.S. Army’s Telemedicine and Advanced Technology Research Center (TATRC) and the Defense Advanced Research Projects Agency (DARPA), the main research and development arm of the U.S. Department of Defense, are two such entities that have overseen development of hardware that can translate directly to capabilities needed for Project SOLACE and beyond.[11,12] Additionally, individuals and private companies would be able to supply much of the smaller hardware items that are no less important, but are required for medical procedures in an environment where volumetric space and mass are at a premium.[13]

A. First Response and Ascent

Trauma patients run increased risk of permanent injury or death within the first hour after infliction if they do not receive timely care.[14] Many patients could have been saved had first responders with appropriate training and

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equipment been on the scene. Project SOLACE addresses this concern with two parallel lines of effort: first responder training for astronauts and sophisticated portable equipment.

Current NASA astronaut training imbues its spaceflight crews with first responder skills appropriate to LEO missions, where constant communication with mission control and quick atmospheric reentry are possible. Mission crews would need more in-depth first responder training to deal with the myriad emergencies presented in a SOLACE lunar simulation. In each ISS crew, one astronaut is designated the Crew Medical Officer (CMO). If not a physician, the CMO receives the closest approximation to the training needed for SOLACE and other deep space sojourns. In the event the CMO and/or crew physician is injured (assuming there is a physician in the crew), training depth for all crew members would have to be increased to optimize chances of success with SOLACE protocols. Emergency Medical Technician (EMT) courses can take several months to complete and teach skills such as general pharmacology, musculoskeletal care, intravenous procedures, dealing with injuries to the head and spine, as well as respiratory, cardiovascular, and environmental emergencies.[15] Additionally, students can complete clinical rotations to gain hands-on experience in real world situations. Paramedic training is even more detailed and is a closer approximation to required SOLACE training. This level of expertise would promote greater autonomy and increase safety margins on deep space missions, and SOLACE is an ideal setting to practice while preserving the ability to rapidly communicate with flight surgeons and other medical specialists on Earth. While several NASA and International Partner astronauts are physicians, those with other backgrounds such as pilots, scientists, and engineers can provide redundancy of expertise if the medical professional is an injured crewmember.

To assist in the practical application of this training, astronauts can use devices such as the L-STAT (Life Support for Trauma and Transport), Lightweight Trauma Module (LTM), and Med-Ex 1000.[11] Already tested in ground combat situations, L-STAT is a 15-cm thick stretcher-like device that serves as a highly portable intensive care unit with minor surgical capability.[16] Combined with diagnostic capabilities provided by the LTM,[17] L-STAT can help astronauts triage and treat injuries prior to transporting the patient to more capable facilities – in this case, to the orbiting medical module (the main SOLACE spacecraft). There are, however, limitations to using portable trauma care devices when the injured crew require an Extra-Vehicular Activity (EVA) suit for survival. In many cases, EVA suit removal would be required to ensure access to injuries. Thus, the first responders on the lunar surface might need to move the patient to a pressurized environment, remove the suit, and treat the injuries to stabilize the patient for ascent to orbit. To preclude having to put the patient back in the suit for ascent, L-STAT could be modified to provide a closed atmospheric environment once work on the patient is complete. The patient could then be transported to the ascent vehicle and remain in the closed environment until ambient atmosphere precludes the need for a pressure suit.

The ascent vehicle will be modeled after the Single Stage Reusable Lander (SSRL) referred to as “Hercules” by Arney et al.[18] It will provide Single Stage To Orbit (SSTO) capability and, as technology matures, later versions will manufacture fuel on the surface using In Situ Resource Utilization (ISRU) methods. ISRU would allow for reduced mass during transit and initial descent. Less propellant is needed for the descent, and the lander can “top off” on the surface. Benefits of SSTO include decreased complexity as well as reliability due to eliminating the risk of second stage failure.[19]

The ascent vehicle will launch with the full crew, rendezvous, and dock with the orbiting SOLACE spacecraft. Analysis of previous Mars Ascent Vehicle (MAV) designs indicate maximum g-forces on the crew during an ascent from the Martian surface would be little over 1.5 Earth-g (g_0).[20] Acceleration experienced on an ascent from the lunar surface would be even less. In either case, crew injuries are subjected to manageable levels of stress. Once docked, the injured crew would be moved to the medical module for Roles 2 and 3 care.

B. The Spacecraft

The SOLACE spacecraft itself is composed of several modules, one each for propulsion, medical, artificial gravity, and crew habitat. Of these, only one is intended to be truly unique to the SOLACE spacecraft – that which houses the medical facility. The other modules are common to the design architecture proposed in DRA 5.0,[5] except for the artificial gravity module, or “spin module,” which can be initially tested on a SOLACE lunar simulation and adapted to be compatible with future spacecraft designs. This concept supports the themes of reusability and commonality. All modules can be launched separately and assembled in LEO, then propelled by the propulsion module to lunar orbit where the spacecraft waits as a lifeboat to transport injured crew back to Earth. The components of follow-on deep space mission versions could be towed to the target planet's orbit using solar electric powered tugs, thus preserving all propulsion module propellant for TEI, trajectory corrections, and Earth orbit insertion.

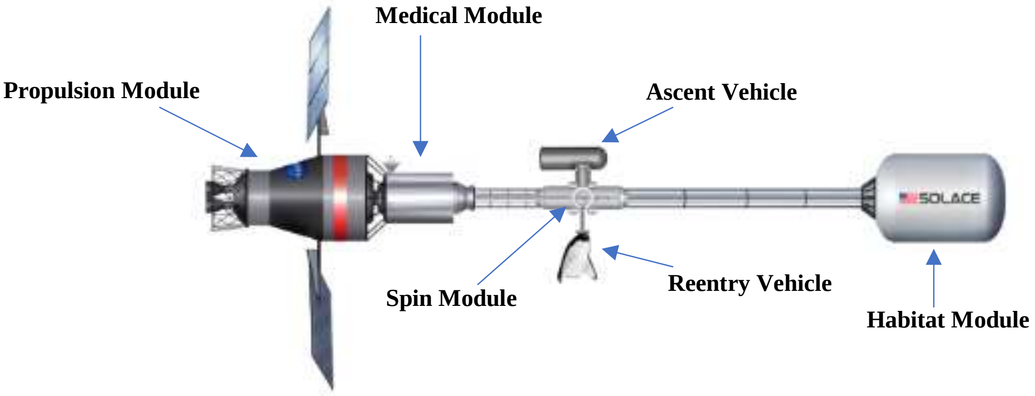

Figure 1. The SOLACE Spacecraft
Illustration credit: Lorin Zide, ca. 2017

The medical module is connected to the same type of propulsion module that propels the primary deep space crew transfer vehicle. If commonality with DRA spacecraft is required, the propulsion module must be large enough for a return journey to Earth via conjunction class transfer and have sufficient fuel for propulsion braking. Given the injuries sustained by the crew, Earth orbit insertion would need to be accomplished entirely by fuel burn. This method, while costly from a propulsion standpoint, is preferred over the much more g-intensive aero-assist method in which the spacecraft decelerates by partially entering Earth's atmosphere.[5,21,22]

One of the major challenges to conducting surgery in space is the microgravity environment. Project SOLACE is an excellent platform to help solve the artificial gravity problem. Not only would artificial gravity facilitate medical procedures, it would also alleviate conditions caused by prolonged exposure to microgravity such as changing eyesight, deteriorating bones and muscles, loss of weight, and redistribution of fluids.[23] This measure becomes increasingly important as space travel progresses to more distant destinations. For example, a Mars mission requires an approximate transit time of six to nine months, requiring prolonged exposure to microgravity.[5,24]

A habitat module, potentially inflatable, for uninjured crew would provide adequate facilities and stores for the transit. To provide artificial gravity, SOLACE would adopt part of a design concept proposed by Benton for a Mars exploration vehicle.[25] The crew habitat would be on the opposite end of the spacecraft from the medical module, connected by a spin module – a telescoping cylindrical bridge that rotates about a platform. The bridge serves as a crew transit tunnel and extends or retracts to vary its length from either side of the spin platform as the spacecraft expends fuel and decreases its propellant mass. Thus, despite decreasing mass during the transit, the spacecraft is always spinning about its center of mass for constant outward acceleration to simulate gravity. As Benton writes, "the literature suggests a minimum of $0.2g_{0E}$ to provide a minimum level of traction for the crew to perform useful tasks, and a maximum … of 4 RPM [Revolutions Per Minute] to prevent undesirable effects caused by Coriolis forces."[25]

Table 1. Approximate spacecraft radii and RPM required for artificial gravity. *As spacecraft rpm and tangential velocity increase, the radius, measured from the center of rotation, increases. The SOLACE spacecraft can simulate up to Earth gravity by varying the length of the spin module to achieve the desired radius.*

a_c (m/s^2)	g_0	RPM	V_t (m/s)	R (m)
1.6	0.17	2	7.54	36
3.7	0.38	2.7	12.99	46
9.8	1	4	23.03	55

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Research indicates that simulating lunar gravity at approximately 1.6 m/s^2 would produce no adverse Coriolis effects.[26] Simulating Martian gravity at 3.7 m/s^2 would be nearly as benign, as Coriolis effects are considered negligible until about 2 RPM. Simulating Earth gravity requires a minimum radius of 55 m, but Eq. (1) shows that lower spin rates to reduce risk of adverse Coriolis effects require longer radii. Using target centripetal acceleration values to simulate desired gravitational force, and converting RPM to seconds to determine the rotational period, we can calculate required radius of spin as measured from the center of rotation.

$$R = \frac{(a_c T^2)}{4\pi^2} \tag{1}$$

Since a crewed mission to bodies with higher gravity than Earth is beyond serious planning for the next several decades, and simulating lunar and Martian gravity would be beneficial for deep space mission simulation, SOLACE will limit radius length to approximately 55 m for the first iteration of the spin module. Further, if simulating Earth gravity is desired, astronauts can be trained to move in ways that mitigate disorientation, dizziness, and nausea that are considered side-effects of Coriolis forces.[26]

The drawback of the design is additional moving parts and a more complicated vehicle from an engineering standpoint, potentially decreasing long-term reliability. An alternate design would incorporate a centrifuge in the medical module to create artificial gravity, precluding the need for a spinning spacecraft.[23] Centrifuges, however, are untested in space.

The crew's Earth reentry vehicle would be docked to the exterior of the spacecraft. This vehicle would be much like the X-38 developed during NASA's Crew Return Vehicle (CRV) program of the 1990s – a lifting body reentry vehicle capable of transferring the entire crew to the surface autonomously in case of crew incapacitation.[27] The CRV was designed to accommodate evacuation of all 6-7 crew members onboard the ISS, providing enough room for the crew of a deep space mission. Importantly, it would do this while subjecting them to the relatively light load factor of 1.5-g_0 as, much like the Space Shuttle, it could roll to change lift direction throughout reentry.[22] And it could do this while enroute to a precision landing using GPS guidance and steerable via a parafoil that deploys at approximately 40,000 feet above mean sea level. While a blunt body reentry vehicle could return the crew as well, it would expose injured crew to much higher g-forces during the heart of reentry. Additionally, the hypersonic lifting body reentry vehicle is a reusable concept which could be a common component on various space vehicles, further supporting themes of SOLACE's design.

Figure 2. X-38 Lifting Body Reentry Vehicle
By NASA/Carla Thomas – Armstrong Photo Gallery

C. Emergency Medicine and Surgery

The main SOLACE spacecraft will need to begin rotating to produce the desired level of artificial gravity as soon as the ascent vehicle has safely docked. This procedure creates an environment conducive to emergency medicine and surgery. Once onboard, the crew can utilize the medical module's unique hardware to continue to diagnose, treat, and, if necessary, prepare the injured crew for surgery. Fortunately, medical equipment suited to the spacecraft environment currently exists. As early as 2005, Mounir Laroussi, a professor at Old Dominion University, invented a cold plasma pencil measuring less than a foot long that can kill bacteria in wounds.[13] Researchers at the University of Saskatchewan developed a compact Magnetic Resonance Imager (MRI) with space applications in mind.[28] It weighs less than ten percent of a traditional MRI and is a fraction of the cost. It consumes less energy and relies on a Halbech magnet instead of superconducting coils to reduce weight and preclude creation of stray magnetic fields. Also, devices such as Virtual Incision's 0.4 kg robotic arms designed for surgical work can provide rapid and precise emergency room assistance to crewmembers.[13]

The robotic surgical hardware will be semi-autonomous in its original design. Advances from SRI International's trauma pod project, funded by DARPA, could lead to such hardware.[11] In fact, surgical robots are currently in use in hospitals,[12] but the current challenges of limited bandwidth and latency inherent in deep space missions have yet to be fully overcome. The LLCD payload aboard the LADEE spacecraft orbiting the Moon successfully tested optical communications, providing a link between 40-622 Mbps.[29] Interplanetary optical communications may offer promise for broadband teleoperations during deep space missions. Incorporating semi-autonomous robots in the initial medical module design should facilitate realistic testing of the equipment in two scenarios. In the first, the equipment is operated by trained personnel onboard the spacecraft. In the second, remote teleoperation by doctors on Earth is tested, albeit subject to a time lag depending on speed of connectivity. If the Earth operator is manipulating the surgical equipment via a master console using direct inputs – how we traditionally think of teleoperation – we can test the space network connectivity speeds, particularly those of the Disruption Tolerant Network (DTN) or its successor, to determine if they are sufficient for this application.

Figure 3. The SRI-led Trauma Pod, developed for DARPA as a next-generation mobile robotic surgery platform for the military

DTN is a form of space internet in which the protocol stores commands if a signal is lost and then forwards them once a reliable connection is regained. This practice is different than Transfer Control Protocol/Internet Protocol (TCP/IP) which relies on a low latency and Bit Error Rates (BER). However, space networks experience the opposite effect. High latency and BER rely on DTN methodology to overcome inevitable connectivity disruption. Even when optimally performing, the time lag for one-way transmission to the Moon is approximately 1.7 seconds. Another possibility for remote operation is to design the hardware and software such that the equipment is responsive to voice commands. However, voice communications suffer from a similar time lag. An additional disadvantage to this approach is that fine surgical procedures may require more precision than a remote operator is able to convey with verbal commands alone. The surgical robots would have to be autonomous enough to perform exact surgical procedures with voice commands that do not always specifically delineate a high level of granularity. In other words, they would have to overcome human imprecision to be successful.

As deep space missions become a reality, SOLACE surgical equipment will require full autonomy to be of optimal use beyond the cislunar environment. On a mission to Mars, for example, time lag increases to at least 8 minutes for a one-way data burst. Obviously, this is an unacceptable time lag for semi-autonomous teleoperation with a real-time operator on Earth providing commands to the surgical unit. As robotic surgical technology matures, largely to support applications on Earth, future iterations of SOLACE hardware can capitalize on such improvements so that fully autonomous robotic surgery becomes the standard procedure. The medical module would need to be designed so that upgrading the internal hardware is a manageable process. Hence, the "good bones" heuristic.

D. Post-Operative Care during Transit

Caring for multiple crew injuries around the clock on a long duration mission also presents significant challenges. Postoperative recovery equipment would need a level of autonomy beyond what is normally seen with inpatient care. While current medical technology can sustain patients requiring life support, anyone who has visited an Intensive Care Unit (ICU) in a hospital has seen medical professionals focused on patient care operate in shifts to ensure no gaps in coverage. They actively monitor life support equipment, make adjustments as required, and periodically consult with other professionals. Astronauts on a deep space mission are encumbered with many other tasks, and a crew of 4-6 would be busy operating the spacecraft and dealing with other duties as required. Round trip communications would require approximately 16 minutes if consulting with flight surgeons in mission control. The crew's attention might be redirected to malfunctions and emergencies as they arise, and patients in deep space will not enjoy the full resources of a hospital when a flight crew is stretched thin.

Much of the patient monitoring that is done by ICU nurses and doctors will need to be done by medical equipment, and these machines will need to provide treatment autonomously if required. Radisens Diagnostics developed

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technology that can run batteries of tests in minutes using a tiny sample of blood from a finger. This technology has been tested on the ISS. The basis of the technology is a mini-disc device embedded with a variety of test procedures. The disc is inserted into a device and spun to spread the sample evenly. In minutes, the device delivers automated results to determine patient health. The idea is that devices like this can feed data on astronaut health to equipment that can adjust automated treatment depending specific needs revealed by the testing.

Total Parenteral Nutrition (TPN) is a possible method for keeping incapacitated crew properly nourished during the transit. Nutritional requirements can also be determined by diagnostic devices, whereupon the equipment can adjust supplements depending on the patient's needs.[30]

V. Conclusion

Project SOLACE is a high-fidelity simulation of a medical emergency on a deep space mission, and by conducting the simulation the crew would be able to test and evolve many systems and technologies. Spacecraft hardware such as the medical module and the artificial gravity-generating spin module would be developed, tested, and subsequently refined. Engineering lessons learned could be applied to future iterations of the SOLACE spacecraft and would translate well to the construction of other spacecraft components in the Mars DRA 5.0 architecture. Teleoperated medical hardware and procedures could be tested for feasibility beyond LEO where communications time lag is a factor. If designed properly, the medical module could be upgraded with fully autonomous surgical robots as that technology matures. Spacefaring nations have or could soon have the ability to construct a spacecraft such as that required for a first iteration of project SOLACE, and in the time required to build and test such a vehicle, autonomous medical hardware could well become a reality. As themes of modularity and reusability translate to affordability, more lifeboats like the SOLACE vehicle can be built. Several in orbit around the Moon or a planet could provide a fast transit ambulance system, moving injured surface inhabitants from one side of the body to another in a matter of hours via ascent, appropriate orbital trajectory, and landing at the desired location. Finally, we need not go to the Moon to run a partial SOLACE simulation. Assuming we programmed an appropriate communications time lag into the scenario, all but the ascent and reentry vehicles could be tested in LEO, providing an even more cost-effective way to assess deep space medical hardware and procedures. But like Apollo 10 was the dress rehearsal for the first lunar landing in 1969, the lunar simulation proposed with Project SOLACE would be an excellent way to prepare for a deep space medical emergency – something that could very well happen in the next few decades as we once again expand our reach beyond Earth orbit.

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