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The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations☆

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Abstract

Introduction: Medical requirements for the future crew exploration vehicle (CEV), lunar surface access module (LSAM), advanced extravehicular activity (EVA) suits, and Lunar habitat are currently being developed within the exploration architecture. While much is known about the vehicle and lunar surface activities during Apollo, relatively little is known about whether the hardware, systems, or environment impacted crew health or performance during these missions. Also, inherent to the proposed aggressive surface activities is the potential risk of injury to crewmembers. The Space Medicine Division at the NASA Johnson Space Center (JSC) requested a study in December 2005 to identify Apollo mission issues relevant to medical operations impacting crew health and/or performance during a lunar mission. The goals of this project were to develop or modify medical requirements for new vehicles and habitats, create a centralized database for future access, and share relevant Apollo information with various working groups participating in the exploration effort.

Methods: A review of medical operations during Apollo missions 7–17 was conducted. Ten categories of hardware, systems, or crew factors were identified during preliminary data review generating 655 data records which were captured in an Access® database. The preliminary review resulted in 285 questions. The questions were posed to surviving Apollo crewmembers using mail, face-to-face meetings, phone communications, or online interactions.

Results: Fourteen of 22 surviving Apollo astronauts (64%) participated in the project. This effort yielded 107 recommendations for future vehicles, habitats, EVA suits, and lunar surface operations.

Conclusions: To date, the Apollo Medical Operations recommendations are being incorporated into the exploration mission architecture at various levels and a centralized database has been developed. The Apollo crewmember's input has proved to be an invaluable resource. We will continue soliciting input from this group as we continue to evolve and refine requirements for the future exploration missions.
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1. Introduction

The Apollo Program, which began in January of 1966, was composed of 18 missions: 12 crewed missions (including the Apollo 204 mission with Virgil

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"Gus" Grissom, Ed White, and Roger Chaffee) and six un-crewed missions which tested the capabilities of the Saturn rocket components [1]. Of the manned missions, six flights conducted between July 1969 and December 1972 successfully landed 12 humans on the lunar surface and safely returned them to the Earth.

In January 2004, President George W. Bush committed the United States to the further exploration of space [2]. This new vision for space exploration will benefit from the cumulative knowledge and experience gained from the Apollo Program. The exploration effort will require development of new vehicles to transport crew from Earth to the lunar surface and to traverse the moon. In addition, crew will need extravehicular activity (EVA) suits and extended duration habitation elements for the lunar surface operations [3]. The crew exploration vehicle (CEV) and lunar surface access module (LSAM) will bear many similarities to the Apollo command module (CM) and lunar module (LM) though they will be slightly larger to accommodate more crewmembers and cargo. The EVA suits may serve the dual function of a launch and entry suit as well as the lunar surface suit. Lunar habitation will be the new frontier, enabling humans to live on the Moon for extended periods to conduct science experiments and use the lunar environment for in situ resource utilization (ISRU).

During the previous studies, Apollo astronauts provided input into the engineering and mechanical aspects of EVA suit system designs [4]. However, no study has specifically addressed the impact of the Apollo vehicles, hardware, and systems on crew health or performance throughout all mission phases, including lunar surface operations. The influence of that impact on the new exploration vehicles and mission architectures remains unknown.

The Space Medicine Division requested a study in December of 2005 to identify Apollo mission issues relevant to crew health and performance. The goals of this project were to develop or modify medical requirements for new vehicles and habitats, create a centralized medical operations database for future access, and provide this knowledge to the various directorates at National Astronautics Space Administration (NASA)-Johnson Space Center (JSC) participating in the exploration effort. Secondary objectives included using this information to validate and refresh knowledge regarding lunar operations in an effort to reduce both programmatic risk and risk to crew health, productivity, and safety. This study commissioned by the Space Medicine Division and this paper are not intended to be a review of information contained in the previous publications, such as Biomedical Results of Apollo [5].

This study's primary target audience is diverse: flight surgeons, engineers, and scientists responsible for developing medical requirements for exploration vehicles, habitats, and suits; mission planners developing crew timelines; and experts supporting behavioral health and performance. Various aspects of this report will be of interest to a broader readership outside the medical operations community. Therefore, the report is written in a medically non-attributable format accessible to anyone with an interest in the Apollo Program.

2. Methods

The initial task involved a review of historical data from the Apollo missions. Sources of this information included mission medical debriefs, flight surgeon logs, biomedical engineer logs, mission reports [6], lunar surface journals [7], preliminary science reports [8], the Apollo lecture series [9], videos of Apollo missions, NASA technical memoranda [4,10–14], and related papers and personal communications with Apollo astronauts and flight surgeons.

After reviewing historical data, the team identified 10 categories within the operational environment occurring during Apollo 7–17 that had impacts to crew health and/or performance. Information assembled into these categories formed the basis for the questions used to interview the Apollo astronauts. The categories included EVA mobility unit (EMU) and EVA suit issues; lunar surface operations; in-flight illnesses, medical kit, medications, or bioinstrumentation; environmental (vehicle); radiation; exercise; food and nutrition; performance, human factors, crew schedule; launch, re-entry, and recovery; and flight surgeon–crew interactions. Certain well-documented areas relating to crew health or performance, such as lunar dust, were identified but not covered in detail during this study. Likewise, areas that affected the Apollo crews but were not relevant to the new vehicle design, such as the Apollo water chlorination system, were identified in the data collection but were not addressed during the face-to-face meetings.

2.1. Data collection

The historical data collected were organized and compiled into an Access® database (Fig. 1). Data were organized by mission, source of information, topic (category), medical/hardware issue, crewmember involved (if applicable), description of the problem, general comments about the issue, and resolution/reoccurrence. In total, 655 data records were generated that reflected human integration and operational issues from the Apollo

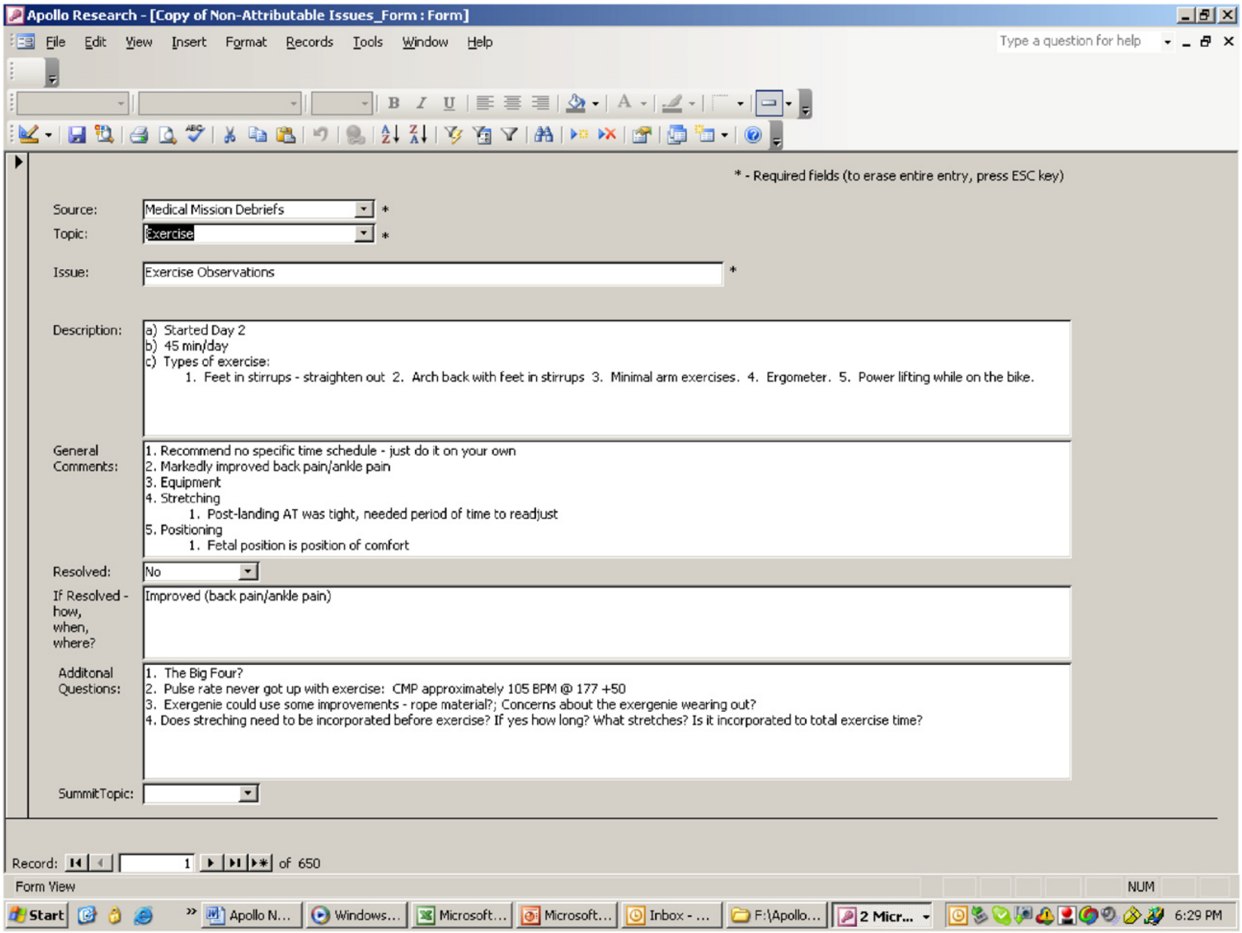

Fig. 1. Sample Access® data record from the Apollo Medical Operations Project.

mission. Each of the data records were then further categorized based on 10 operational areas, and used to develop the survey.

2.2. *Panel questions*

Questions were generated within the 10 categories from the historical data search effort. Additional input was provided by operational and research disciplines associated with each category. The categorized questions were reviewed by flight surgeons and current astronaut physicians at JSC for relevance and operational applicability to the exploration effort. This resulted in a final list of 285 questions used during the face-to-face meeting with the Apollo astronauts.

2.3. *Face-to-face summit*

The face-to-face summit with the Apollo astronauts was held June 2006 in Houston, TX. As per the crewmembers' request, days 1 and 2 were limited to Apollo crew, the current flight surgeon cadre, and astronaut physicians. Day 3 was limited to invited guests and the Apollo flight surgeons. The purpose of the meetings was to capture the experiences of the Apollo astronauts, to validate findings from the historical data search and to apply aspects of the Apollo operational experience to the exploration initiative.

A professional transcriptionist recorded all comments from the astronauts and later organized the responses with the corresponding questions. This document was then reviewed by the project team for accuracy and clarification. Notes taken by the panel team during the question sessions were added to the document as appropriate.

2.4. *Post-summit review and validation*

The purpose of the post-summit phase was to compile the accumulated responses to the panel questions and organize the information into a comprehensive report. Apollo astronauts who participated in the face-to-face summit reviewed and validated the report. They also submitted additional input and points of clarification. After review by the project team, the updated version including recommendations was submitted to all the Apollo astronauts, including the eight crewmembers who attended the face-to-face meetings. These crewmembers provided input to the panel question and answers via written report, e-mail, phone conversation, or personal interviews.

3. Results

3.1. Data

Sixty-four percent of the surviving Apollo astronauts participated in the project (14 of 22). The combined responses (astronauts attending the summit and those commenting via survey only) to the 285 questions yielded 107 recommendations for exploration medical operations. Table 1 summarizes each of the 10 categories with the corresponding number of questions and post-summit responses. The number of recommendations generated within each category is listed in the last column.

3.1.1. EMU/EVA suit

The EVA suit will be critical to carrying out lunar missions. The Apollo astronauts are the only human beings who have had the experience of operating under $1/6$th g lunar environment, making their observations and recommendations very timely and relevant to current exploration efforts.

Recommendations centered first and foremost on improving the functionality of the suit then improving both the human factors integration as well as specific safety features. The most adamant of the suit recommendations and a consensus statement among the crewmembers was to improve the dexterity of the glove. This recommendation had mission accomplishment and safety as the driving concerns. Similarly, the astronauts recommended increasing ambulatory and functional capability through increased suit flexibility and decreased mass and internal pressure. This would have the projected added benefit of decreasing fatigue as well. The astronauts' human factors recommendations revolved around consumables and excretion. They recommended in-suit access to large amounts of high energy liquids and plain water, a heads-up display (HUD) with consumable, biomedical, navigation information on demand, and an improved urinary collection system. Safety concerns revolved around redundancy being built into the suit. In particular, they suggested a system to prevent helmet fogging under all circumstances, a self-sealing pressure garment in case of puncture, and a system to protect the zipper from abrasive lunar dust. Improving field of vision within the helmet would greatly reduce concern over upper extremity injuries related to falling on an outstretched arm.

3.1.2. Lunar surface operations

Among the lunar surface operations recommendations, crew scheduling, feasibility of surface activity commencement, and airlock and hatch designs were given particular importance with regard to exploration architecture. The Apollo astronauts' recommendations address human factors, safety, and operational efficiency. A recurrent theme on the lunar surface was an overwhelmingly packed schedule. For extended operations, the astronauts were adamant about decreasing the workload in the schedule. They suggested a maximum of two lunar extravehicular activities (LEVAs) within a 3 day period and a schedule with flexibility and 'breathing room' built into it. They also stated that surface operations should begin once operationally feasible, and each LEVAs should be one continuous event with ample food and liquids available before and during the event, and that the schedule should be front-loaded early on to minimize error and injury. Risk factors for injuries on the lunar surface included falling onto an outstretched arm or from a height, rover operations, and navigating slopes in excess of 20–26°. Improvements in suit functionality will contribute to reduction in some of the risks identified.

To increase operational efficiency the astronauts recommended using HUD technology, robots for repetitive tasks, and the rover to recharge suits. They also stated that for extended operations, LSAM ingress and egress portals must be closely scrutinized. They emphasized with a consensus statement that the hatch size must comfortably accommodate pressurized suits and that engineers consider an airlock. In general, they felt that the familiarization training with $1/6g$ and analog training was sufficient.

3.1.3. In-flight illness

This category reflected human factors issues of pain, gastro-intestinal dysfunction, and preventative screening. In particular, treatments or preventative measures were sought for lower back and forearm pain and soreness, constipation and diarrhea, and heart disease. The recommendations for in-flight illness demonstrated the inter-disciplinary nature of space operations. For

Table 1
Apollo Medical Operations Project summary of categories, corresponding questions, post-summit responses and number of recommendations generated for the exploration effort

Input from 14 of 22 astronauts (summit and post-summit)	64		
Apollo 7–17 categories	# of questions	Post-summit # of responses	Recommendations
EMU/EVA suit	63	30	13
Lunar surface ops	36	20	16
In-flight illnesses/medications	16	24	9
Medical kit	3	4	4
Bioinstrumentation	3	5	0
Environmental impacts	35	75	16
Radiation	5	4	5
Exercise	20	33	8
Food nutrition	28	76	8
Performance/human factors	16	48	11
Crew work–rest Schedules	10	30	5
Launch recovery	34	121	10
Flight surgeon–crew interaction	2	7	2
General questions	14	31	0
Totals	285	508	107

example, it was discovered that crewmembers intentionally constipated themselves with medications to reduce or completely prevent bowel movements. On further examination, it was found that a reason for this was a poor waste management collection system.

Nearly all of the lunar crewmembers complained of forearm soreness occurring during each of the lunar EVAs which was attributed to issues with the EVA glove. This category, although significant, has less relevance due to Skylab, Shuttle, and ISS operations in microgravity where improvements in glove fit and function have reduced upper extremity complaints. Environmental factors, such as exposure to lunar dust, caused mucous membrane irritation to some degree in most crewmembers. Of note was the report from one Apollo flight surgeon who had progressively worsening upper respiratory symptoms with exposure to the lunar space suits upon unpacking from stowage. He reported marked eosinophilia with each of his three missions. Headaches were a common finding requiring the use of analgesia. Two injuries occurred on the lunar surface, a shoulder strain related to a malfunctioning drilling tool and a wrist laceration attributed to the EVA suit wrist ring.

3.1.4. Medication and medical kits

Recommendations from this category focused on medications that would have improved operational efficiency and comfort. Kit contents requested included allergy medications, saline eye drops, standard toiletries (nail clippers, lotions, etc.), headache analgesia, efficacious sleep medications, and an efficient decongestant delivery system. All of these are currently accounted for or improved upon (i.e. including eyewash in addition to saline drops) in the constellation requirements.

3.1.5. Environmental impacts

Human factors and operational design were the two foci of the environmental impacts recommendations. Within human factors, recommendations dealt with waste management, sleep, and consumables. The astronauts unanimously recommended the adaptation of the Skylab waste management system. They also recommended a device that allows squatting for bowel movements, stated that the Apollo bag aperture and capacity both needed to be larger, and would prefer that the galley and waste areas be separated. To foster restful sleep, the astronauts recommended minimizing environmental noise, having water available during sleep, increasing the sleeping bag size to allow for the "fetal position", and the incorporation of the command module sleep restraint system. Hot water capability was deemed essential and non-negotiable via a consensus statement. A food warmer was considered desirable.

Operational concerns centered on engineering redesign, a contingency input, and increasing efficiency. First and foremost, the crewmembers' consensus was that astronaut participation in design and development is essential. Another consensus statement was to incorporate more reliable CO_2 monitors. They also said that the LSAM windows should be as small as possible and that there should be a system for clearing lunar dust from the cabin. A consensus statement born of

Apollo 13 was to include thermal protective gear in the event of a contingency. The last recommendation was to utilize RFID tags for stowage items.

The recommendations brought to light some points that would have been missed just as they were during Apollo. For example, as a result of the recommendations thermal protection is being added to the crew equipment.

3.1.6. Radiation

Apollo astronauts were concerned about radiation detection and contingency plans. They stated that all vehicles, habitats, and suits should have active or real-time radiation detection capabilities and built-in dosimeters. They also said that the rover should contain a radiation shield, there should be the ability to create trenches for solar particle events, and pharmacological radioprotectants should be made available.

Thanks to Skylab, the shuttle, and the ISS, there is a large body of operational knowledge regarding radiation in LEO; however, radiation on the surface of the moon is a different entity. The astronauts were clearly concerned about radiation, and emphasized that more research needs to be done.

3.1.7. Performance, human factors, and crew schedule

This category generated many recommendations which can be broken down into mental (and physical) health concerns and operational concerns. Mental health recommendations dealt with rest and relaxation (R&R) time, sleep, and psychological preparation. R&R consensus statements called for 1 day per week for astronaut discretionary use and the implementation of mental and physical rest plans. Some astronauts also requested recreational activities to be available during down time. Interestingly, the astronauts also displayed empathy and concern for the workload of the mission control teams. A recommendation addressing psychological support for flight controllers was developed to ensure the support teams would be taken care of during all mission phases. Regarding sleep, the astronauts stated that crew sleep periods should be concurrent, that adequate capability for sleep on the lunar surface should be provided, and that sleep medication use should not be stigmatized. Specific recommendations regarding the sleep accommodations onboard the LSAM and habitat focused on shielding penetrating sunlight, providing ear plugs, and developing a better "hammock" or make shift bed to protect the crews from the cool, dirty vehicle floor. They also unanimously agreed that a minimum of 8 h per day of sleep and rest must be protected. Regarding psychological preparation and well-being, the astronauts unanimously agreed that educational and psychological services must be available to their families and that if a crewmember dies during the mission, all involved must be prepared to "cut them loose".

Operational concerns overwhelmingly focused on scheduling issues. Crews stated that the preflight quarantine was very valuable and that the preflight training schedule must allow the crew time to focus on the mission. They also said countermeasures for mental fatigue are necessary and that adequate time for activities must always be provided throughout the mission including preflight. They also recommended that the mission focus be project-oriented and not time-lined. The final recommendation emphasized the importance of the crew authority structure over all other concerns of crew resource management or crew composition and strongly urged this consideration as a guide in choosing future exploration crews.

3.1.8. Exercise

Recommendations regarding exercise centered on scheduling concerns and the exercise equipment. While the astronauts felt that exercise is not necessary on trips less than 14 days from a strength and endurance perspective and that exercise prescriptions for short trips were likewise not necessary, they unanimously felt that the availability must exist to exercise for R&R during all phases of the mission. They felt exercise is required for longer duration lunar missions. Specific areas to be developed include forearm and upper extremity strength and stamina, core stability, and aerobic fitness. They also stated that scheduling needs to allocate time for preflight conditioning program in these same areas be included. The exercise device available on Apollo missions, the Exer-Genie, was considered sub-par and the astronauts unanimously said that new exercise devices should be reliable, simple, and safe. They also encouraged as much exercise variety be built into the vehicle and equipment as possible. They agreed that research will have to be done with extended duration lunar missions to determine whether the partial gravity environment will have a maintenance effect on muscle and bone strength.

3.1.9. Food and nutrition

This category resulted in a surprising number of recommendations. The astronauts commented on nutritional requirements, taste preferences, logistics, and operations. The astronauts unanimously agreed that mission activity dictates the type and amount of food that will need to be consumed. They were also unanimous in recommending ample water availability for LEVAs and said that an in-suit source of carbohydrates would be helpful. They stated that for long duration missions, diet and food intake would need to be carefully optimized. Regarding food flavor they preferred spicy and salty foods and suggested research into how different environmental factors affect food flavor. They unanimously agreed that operations needs to schedule adequate time for food and the new vehicle should allocate space and areas to store food packs during meals.

3.1.10. Launch, landing, and recovery operations

This category was broken down into discussions regarding sea recovery, operations, and engineering ergonomic concerns. Many of the astronauts discouraged ground landings and stated that cooling capability upon landing was required to mitigate sea sickness. They also said food and water must be within reach of buckled crewmembers in case of delayed recovery. Additionally, they stated that the Apollo seats were adequate for water landings and the medications for motion sickness and fatigue should be available prior to re-entry. Operationally, they suggested a flight rule to limit sea state landings to less than 6–8 foot seas if recovery is to be delayed. They also said the crew surgeon best fulfills his or her duty from the recovery vessel not the helicopter. Training for pad aborts were thought to be adequate. Regarding engineering ergonomics, the astronauts said that the CM hatch location and size were adequate and that all switches and panels should be reachable during launch and landing. They unanimously agreed that the CEV hatch should open outward and seal with pressure.

3.1.11. Flight surgeon–crew interaction

The Apollo astronauts acknowledged that in most instances their flight surgeons worked to keep them on flying status, but they often felt as if they were part of an “experiment.” Particular frustration was expressed over delays in communicating medical information. The crews felt that the flight surgeon must act as an advocate for the crew and that the collaboration born of this study between the flight surgeons and the Apollo astronauts should continue and be an example to future generations.

4. Conclusions

The Apollo Medical Operations Project was undertaken to identify Apollo mission issues relevant to medical operations that had an impact on crew health and/or performance. The goals of this project were to develop or modify medical requirements for new vehicles and habitats, create a centralized database for future access, and share relevant Apollo information with various entities participating in the exploration effort at NASA and abroad. Secondary objectives included using this information to validate current requirements and refresh knowledge regarding lunar operations.

The theme of the Apollo astronauts’ 107 recommendations is *res ipsa loquitur* or “the thing speaks for itself”. As one of the astronauts said, “start with what worked on Apollo, and then prove to me why something should be different.” The authors likewise feel that the information gleaned from Apollo’s operational experiences are relevant even though the exploration missions have different objectives than the Apollo missions. These recommendations have broad implications for mission directors, engineers, astronauts, physicians, administrators, and anyone involved in exploration missions. To date organizations within the Life Sciences Directorate such as the Human Research Program (HRP) recognizes that input from the Apollo astronauts will provide operationally relevant evidence-based research for the exploration effort and has taken action on many of the recommendations to develop operational solutions to impacts these astronauts identified during their missions. The HRP has funded specific programs, such as the EVA Physiology and Performance Project (EPSP), exploration medical capabilities (ExMC), and Exercise Countermeasures Program (ECP) to develop hardware or systems based on the Apollo Medical Operations Project results. It is important to point out that the EPSP members are currently contributing to the Lunar Architecture Team (LAT) phase 2 study: surface and habitat focus elements which is addressing the issues related to crew habitat concerns, airlocks/suitlocks, radiation protection, EVA navigation and guidance, suit design and operations, etc.

It is the authors’ vision that the recommendations be evaluated by all relevant parties. Also, it is hoped that appropriate recommendations become requirements and go on to improve mission operations. Currently, 23% of the recommendations have created, modified, or validated requirements or are in practice; 77% are being considered or evaluated; and 0% have been rejected. It is incumbent on all who read the paper to keep the 77% from falling by the wayside.

Further work in this area may include additional follow-up or perhaps an ongoing dialogue with the Apollo astronauts to capture their opinions regarding mission operations and document implementation of their recommendations. Looking toward the future, with operationally driven outcomes derived from studies such as the Apollo Medical Operations Project, the hope is that humankind will be one step closer to the vision for space exploration goal of exploring the moon, Mars, and beyond.

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