Medical Bay Design Considerations for the Moon and Mars Base Analog (MaMBA)

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NASA is currently placing a considerable effort in the Artemis Program together with international partners and commercial space entities to land the first woman and next man on the moon and develop infrastructure for sustainable lunar operations. Establishing lunar infrastructure will be a stepping stone on the journey to Mars and the first crewed mission on Mars. Habitats on the Moon and Mars must be well-functioning for maximizing crew safety, comfort, and operational efficiency. A habitat concept of the Moon and Mars Base Analog (MaMBA) is being developed at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany. MaMBA is intended to serve as a functional prototype of a habitat that is suitable for both the Moon and Mars. The preliminary interior design concept of MaMBA was presented at ICES 2019. In the paper presented here, we discuss baseline design considerations for the medical bay with reference to the MaMBA concept. A set of existing standards, guidelines, and recommendations (e.g., NASA-STD-3001) was reviewed to capture key design considerations for medical facilities. Additionally, we explored several terrestrial bases in extreme environments (e.g., Antarctic research stations) and space habitats (e.g., the ISS) focusing on architectural design features, operational procedures in emergency situations, and lessons learned. The case studies allowed us to identify some commonalities between the investigated medical facilities and to gain additional design considerations. We organized a set of baseline considerations for MaMBA medical bay architecture by categorizing them into six facets: (1) design and development process, (2) architectural features, (3) working environment influencing factors, (4) medical equipment and medication, (5) operation, and (6) sanitation. We use these insights to develop design recommendations for the medical bay architecture of MaMBA and other habitats.

Nomenclature

AMO	=	Autonomous Mission Operations
CHeCS	=	Crew Health Care System
CMRS	=	Crew Medical Restraint System
CMS	=	Countermeasures System
ConOps	=	Concept of Operations
EHS	=	Environmental Health System
EVA	=	Extravehicular Activity
HMS	=	Health Maintenance System
ISS	=	International Space Station
MaMBA	=	Moon and Mars Base Analog

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SMEs	=	Subject Matter Experts
TOCA	=	Total Organic Carbon Analyzer
ZARM	=	Center of Applied Space Technology and Microgravity

I. Introduction

THE International Space Station (ISS) as well as the previous space programs, including the Apollo missions and Skylab, have provided many fruitful insights into physiological and psychological responses to the austere environment, serving as a stepping stone to future human space explorations to the Moon and Mars. The Moon and Mars expeditions pose additional medical challenges and risks due to the harsh environment and limited support from Earth, including but not limited to partial gravity conditions, higher radiation exposure, lunar dust, surface EVA-induced injury, isolation, etc[1-4]. Patel et al. put an emphasis on top-priority health risks in long-term missions: (1) space radiation health risks, (2) spaceflight-associated neuro-ocular syndrome (formerly termed as vision impairment intracranial pressure), (3) behavioral health and performance, and (4) inadequate food and nutrition[5]. Robertson et al. identified five medical events that would have a critical impact on long-duration exploration missions and could be significantly improved by effective non-technical skills of crewmembers (e.g., leadership, teamwork, communication, situation awareness): sudden cardiac arrest, toxic exposure, smoke inhalation, seizure, and eye penetrating injury[6]. Alongside crewmembers' skillsets, it is imperative to provide them with a usable medical treatment area to improve casualty's survivability. A well-designed medical facility could allow them to perform medical treatments efficiently in nominal and off-nominal scenarios. Mancl and Andrews developed a medical bay design concept for a deep space habitat and conducted a human factor engineering analysis using a physical mockup and virtual reality[7]. The importance of designing a usable medical facility will be more pronounced in time-critical emergency medical operations. Yet, few studies seem to place an emphasis on designing such a medical facility for extraterrestrial habitats.

This study aims to identify baseline design considerations for medical bay architecture for extraterrestrial bases. First, this paper presents a summary of design considerations and recommendations that were extracted from existing standards, guidelines, and recommendations (e.g., NASA-STD-3001). Then, this paper discusses case studies of analog bases, including Antarctic research stations, Everest ER, the Apollo, Skylab, and the ISS. A rationale behind the case studies was to: (1) gain additional insights into medical facility design and (2) investigate emergency medical operations and lessons learned. Finally, this paper addresses the applicability of the gained insights to the Moon and Mars Base Analog (MaMBA) concept, which is being developed at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany.

II. Existing Standards, Guidelines, and Recommendations

We reviewed a set of available standards, guidelines, and recommendations for medical facility design to identify key design aspects. The review indicates five categories of key considerations for medical facility design: (1) architectural features (e.g., size, material), (2) work environment influencing factors (e.g., gravity level, temperature), (3) medical equipment and medication (e.g., types of equipment, storage), (4) operation (e.g., the transportation of a casualty), and (5) sanitation (e.g., waste management). The following subsections present information extracted from the reviewed documents with an emphasis on the five categories.

A. NASA Standards (NASA-STD-3001 and NASA/SP-2010-3407)

We referred to NASA-STD-3001 and SP-2010-3407 to capture what must be considered for medical care facility design in extraterrestrial habitats[8,9]. Both documents highlight Levels of Care, and NASA-STD-3001 presents a list of medical capabilities according to destination and mission duration. Lunar missions (> 30 days) and Mars expedition missions are categorized as Level IV and V respectively, and medical care capabilities must be advanced from medical care systems used in the ISS. The additional medical capabilities include advanced life support (i.e., capability to stabilize and/or recover crew in critical condition), dental care, surgical care, etc. Key considerations are summarized and listed in relation to the five categories as shown in Table 1. Although the standards discuss a provision of restraints specifically in microgravity condition, this consideration is also critical in partial gravity environments to improve ergonomic comfort during medical treatment. Deceased crew treatment strategy seems to need further discussions since a not well-established plan could have an adverse influence on remaining crewmembers.

B. Recommendation for a Medical System Concept of Operations for Gateway Missions

Recommendations for a Medical System Concept of Operations for Gateway Missions describes critical design, operation, and management considerations for a medical system for the proposed Gateway[10]. The document first addresses stakeholder needs and system goals for the Gateway Habitat medical system. Then, a set of Concepts of Operations (ConOps) are presented with reference to some Gateway medical scenarios. Subsection 2.2 in the document discusses Gateway Habitat medical system goals with a focus on medical equipment and operation. The medical system goals are applicable to medical bay architecture in extraterrestrial habitats, and some of important considerations are summarized as shown in Table 2.

Table 1. Key Design and Operational Considerations for Medical Care Systems in Spacecraft /Habitat

Categories	Key Consideration
Architectural Features	- Size of medical care area depends on crew size, duration, etc. - Operational strategies in emergency also affect medical care area design (e.g., scenario where multiple crewmembers become incapacitated and need medical care simultaneously)
Work Environment Influencing Factors	- In microgravity, restraints must be provided for patient, care provider, and equipment during treatment
Medical Equipment and Medication	- Medical equipment must be simple and usable with minimal training - Decision aids enable crew to perform medical emergency operations efficiently - Some medical consumables require environmental control (e.g., temperature)
Operation	- Autonomous medical care capabilities are needed for exploration missions due to the limited real-time support from Earth - Facility and treatment strategy for loss of a crewmember must be developed
Sanitation	- It is critical to ensure appropriate waste management (e.g., blood, bodily fluid) and disposal method of medical equipment (e.g., syringe needle) in order to prevent crew injury, disease transmission, etc.

Table 2. Key Design and Operational Considerations for Medical Care Systems in Gateway Missions

Categories	Key Consideration
Medical Equipment and Medication	- Medical systems should be flexible and extensible, allowing for compensation for the inability to cover all possible medical conditions. - Human factors and usability need to be well considered to improve crew performance in medical treatment. - Medical systems should be able to be updated by integrating gained knowledge during missions. - Medical care system should have a capability of fitness assessments, including crew physical, cognitive, and behavioral states.
Operation	- Autonomous operation capabilities should be provided to support crewmembers. - Extra attention should be paid to sensitive health and medical data management. - Level and frequency of communications between in-flight crew and ground station have an impact on an operational strategy.

C. Studies of Medical Capabilities for Missions to Mars

Medical System Concept of Operations for Mars Exploration Mission-11 discusses medical care capabilities required for future Mars exploration missions[11]. This document initially covers a set of key medical system goals (e.g., comprehensive health management, crew autonomy, etc.). Whereas a higher degree of crew autonomy is required for Mars missions, it is still critical to maintain ground situation awareness; the mission control should be kept in the loop. This document places an additional emphasis on medical evacuation considerations and addresses medical evacuation availability through the entire mission phases (i.e., from pre-launch to post landing recovery). A medical evacuation option will not be available during the Mars transit phase, and therefore a comprehensive medical care capability is required (i.e., Level of Care: V). A set of ConOps are provided, including an unplanned dental care scenario; dental care is one of the key capabilities as seen in the Level of Care taxonomy. Stuster et al. established a preliminary list of tasks that the crew will perform during an expedition to Mars from a launch to the earth landing[12]. The preliminary list of tasks covers the Mars surface phase as well as transit phases, and dental emergencies can require crew to perform a series of tasks (e.g., conduct dental examination, apply temporary tooth filling and smooth excess, etc.).

D. International Health Facility Guidelines (iHFG) Part B

The iHFG Part B was reviewed to extract general design considerations for terrestrial medical facilities[13]. The guidelines provide a set of design and operational considerations for an extensive range of medical units, including day surgery/procedure unit, birthing unit, mental health unit, catering unit, etc. Table 3 summarizes some frequently observed key words and aspects throughout the guidelines, which should be critical for medical facilities in extraterrestrial habitats as well. We also explored several medical units in more detail, including Day Surgery/Procedure Unit, Dental Surgery Unit, Mortuary, and Waste Management Unit (Table 4). As mentioned in Subsection A, the Moon and Mars expeditions require advanced medical care capabilities (i.e., Levels of Care IV and V respectively), including dental and surgical care capabilities. A mortuary was referred to in order to gain a general insight into how a deceased body should be handled. A Waste Management Unit was also investigated to better understand types of medical waste and corresponding disposal methods.

Table 3. Common Key Design and Operational Considerations across Medical Units

Item	Key Consideration
Functional Relationships	- External and internal functional allocation - Location, accessibility (i.e., ease of access and transport)
Environmental Considerations	- Acoustics, natural light / lighting, privacy, climate control, etc.
Space Standards and Components	- Accessibility, corridors, doors, size, layout, ergonomics, etc.
Safety and Security	- Fire protection - Access and egress - Rooms used for storing equipment, files, records, etc. should be lockable
Finishes	- Acoustic properties, durability, ease of cleaning, infection control, fire safety, movement of equipment, non-slip surface, shock absorption, etc.
Fixtures, Fittings, and Equipment	- Furniture, fittings, and equipment should be made with consideration to ergonomics and Occupational Health and Safety aspects
Building Service	- Communications, patient information systems, telemedicine, heating, ventilation, air-conditioning, medical gases, etc.
Infection Control	- Handbasins, hands-free activation, negative pressure isolation room

Table 4. Additional Considerations for Specific Medical Treatments

Medical Unit	Key Consideration
Day Surgery/Procedure Unit	- Information Technology & Communications (e.g., clinical records) - Radiation shielding for medical imaging - Emergency call to request urgent assistance
Dental Surgery Unit	- Dental plant accommodates equipment, including water filtration equipment, silver water treatment system, dental suction plant, and air compressors
Mortuary	- Body holding area and chamber temperature control - Infection control - Heating, Ventilation, & Air-Conditioning
Waste Management Unit	- Hospital waste: infectious and pathological waste, sharp waste, pharmaceutical waste, radioactive waste, and general waste - Easy-to-access from all functional areas - Located away from food and clean storage areas - Clinical waste storage: enclosed and secured - Washing facilities adjacent to clinical waste storage

E. Recommendations for Ship Medical Facilities

Ships and space habitats face some common design constraints, including limited volume, supply of logistics, on-board medical equipment, etc. Due to the working environment, onboard crew can have physiological and psychological health issues during a mission, and therefore a provision of appropriate medical care is imperative. Design recommendations offered by the Norwegian Maritime Medical Centre addresses architectural considerations for sickbay design[14]. Section 1 in the document provided an insight for medical bay design process; it is encouraged to explore a number of different "what if" scenarios. This recommendation seems to accord with NASA's design strategy; that is, development of ConOps as demonstrated in Ref. [10]. Section 2 (i.e., physical design) and 3 (i.e., medical equipment and medicines) in the document align well with the scope of this study. Table 5 summarizes some key considerations extracted from the set of recommendations according to the five major categories.

The Ship's Medicine Chest and Medical Aid at Sea summarizes several key recommendations for sickbay design in Chapter 1[15]. The design recommendations are related to a functional allocation (e.g., away from noisy areas), environmental conditions (e.g., temperature), medical equipment, etc. The International Medical Guide for Ships provided by the World Health Organization (WHO) also discusses considerations for ship's medication storage and inventory management while putting a main focus on first-aid procedures[16]. Medicine cabinets should be designed to accommodate the same type or category of medicines in a group. This easy-to-identify feature should be more critical in a life-threatening and time-critical situation.

Table 5. Key Design and Operational Considerations for Ship Medical Facilities

Categories	Key Consideration
Architectural Features	- Accessibility, corridors, doors, size, layout, ergonomics, etc. - Water closet accessibility - Adequate working space
Work Environment Influencing Factors	- Temperature control, lighting, etc.
Medical Equipment and Medication	- Equipment maintenance system - Environmental control for medicine (e.g., a refrigerator for eye drops)
Operation	- Secondary medical facility in a case where the usual medical facility is damaged or inaccessible due to fire or other reasons - Ability to evacuate patients by helicopter
Sanitation	- Isolation strategy (i.e., infection control) - Floor covering to withstand water and a drain in the floor (e.g., burns, chemical spills)

F. Industry Guidelines for First-Aid Medical Equipment on Offshore Installation

An offshore platform is a unique work environment and poses some design and operational challenges for medical facility design. Work related diseases and injuries include, for instance, gastrointestinal problems, dental problems, mental disorders, and fractures; severe cases require evacuations via helicopter[17]. We referred to industrial guidelines for medical facilities on offshore installations[18]. Table 6 presents a brief summary of key insights gained from the industry guidelines.

Table 6. Key Design and Operational Considerations for Offshore Platform

Categories	Key Consideration
Architectural Features	- Clearly identified as a sickbay - Size of the sickbay should consider the numbers of people - Non-slip surface material - Surface should be impervious and easy to clean - Access to lifts and a helicopter pad
Work Environment Influencing Factors	- Heating and ventilation system - Fixed and mobile lighting (e.g., angle-poise lamp)
Medical Equipment and Medication	- First-aid boxes should be of a suitable material (i.e., waterproof and impervious to dust) - Clearly identified as first-aid containers - Kits should be located at each offshore first-aider's place of work or at convenient locations - List of medications should be readily available
Operation	- Communication link to onshore; otherwise, at least communication with an adjacent installation or vessel - At least two offshore first-aiders in the installation with less than 25 people for a redundancy purpose (e.g., in the event of an offshore first-aider being injured)
Sanitation	- Washbasin and water closet - Sink with a supply of hot and cold water and adequate drainage arrangements - Floor drain should be provided

III. Case Studies of Analog Bases

We also investigated several medical facilities in extreme environments. The case studies aimed to extract additional information focusing on two facets: (1) architectural design features and (2) actual emergency operations (e.g., fatality, close-call medical events, etc.) and lessons learned. Together with the reviewed standards, guidelines, and recommendations, the case studies allowed for gaining additional insights into medical bay architecture for extraterrestrial bases.

A. Research Stations in Antarctica

Many nations are currently operating research stations in Antarctica, and crewmembers are working on scientific research, observations, etc. In this study, we explored three research stations in Antarctica; Syowa Station, Neumayer-Station III, and Concordia Station (Table 7). A study reported by Hasegawa et al. revealed that Syowa Station and Neumayer-Station II (currently Neumayer-Station III) offered extensive medical care capabilities and had a wide range of medical equipment from electrocardiogram (ECG), X-ray examination, ultrasound equipment, and endoscopy[19]. Since the survey was conducted in 2005, advancement of medical care capabilities is expected across the investigated research stations. Concordia Station, a French-Italian research base, allows scientists to conduct research and observations; the station also serves as a testbed to gain insights into future Mars missions[20].

The number of occupants and age demographic vary depending on each research station as well as the season. We observed that a medical facility seems easy-to-access from other areas via a corridor or stairs across the three research stations. In the case of Neumayer Station III and Concordia Station, adjacent rooms on the same floor are mission-oriented (e.g., station services). In contrast, a recreation area is located on the same floor as the medical facility at the Syowa Station.

Another different strategy was observed in terms of the number of medical officers; two medical doctors stay at the Syowa Station throughout the year whereas one physician stays at Neumayer-Staton III, and Concordia Station accommodates different numbers of medics depending on the seasons. All of the three research stations offer dental, surgical medical care, and telemedicine capabilities. Telemedicine plays a critical role in handling medical treatments at Antarctic stations[24]. There are some cases where intensive medical treatments were required (e.g., surgery under lumbar anaesthesia at Syowa Station[25]). Emergency evacuation options are available across the three research stations during a summer period. Ohno et al. reported that Syowa Station has experienced four medical evacuations due to severe cases, including pelvic and femoral fractures, acute renal failure, and arrhythmia[24]. The very first evacuation during winter was carried out at Syowa Station in 2020. The result of a regular health diagnosis indicated that one of crewmembers was suffering from a disease, requiring a higher level of medical care treatment. A telemedicine between Syowa Station and Japan concluded that an evacuation was needed even though the crewmember was not in a life-threatening condition. Fortunately, a Russian icebreaker ship, Akademik Fedorov, stopped at Molodyozhnaya Station approximately 300 km away from Syowa Station at that time. With the help of the Russian Antarctic expedition team, the crewmember returned to Japan with a medical doctor. The evacuation was carried out by helicopter, ship, and commercial airplane, and it took approximately one and half months[‡]. Whereas this emergency medical response was achieved with the telemedicine and evacuation capabilities, Mars missions where no evacuation options are available necessitates a higher degree of crew autonomy, requiring crewmembers to handle such an emergency medical scenario with limited support from the mission control.

We also referred to a tragedy that occurred at India's Maitri Station. In 2009 during a winter expedition, a 57-year-old scientist passed away due to a massive acute myocardial infarction[26,27]. Due to the nature of the winter expedition, it was impossible to transport his body to his home by air. There were two options: (1) preserve his body until air transportation became available or (2) perform a cremation on site. His body was cremated on site eight days after he passed away, and his remains were returned to his family in India at the beginning of the next summer. The cremation was conducted at a place two kilometers away from the station under harsh weather conditions. The expedition team could not record the cremation due to technical constraints; yet, his family were in connection with the expedition team by phone[§].

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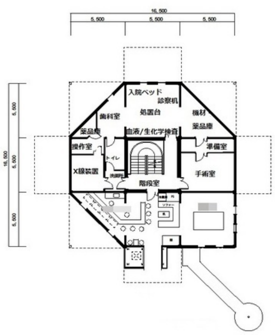
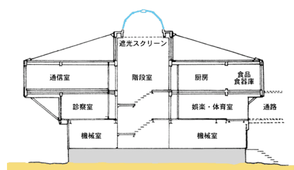
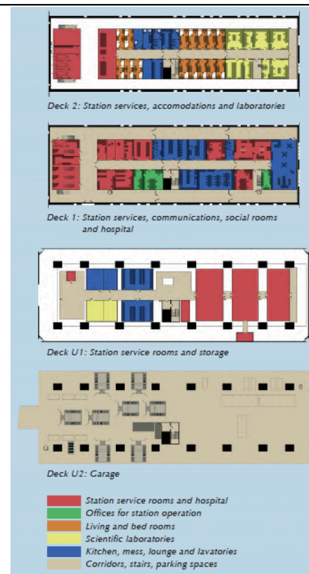
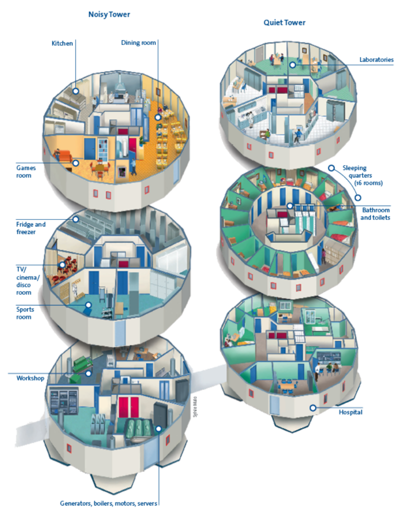
‡ National Institute of Polar Research, Topics, 05/25/2020 (in Japanese): https://www.nipr.ac.jp/antarctic/info/20200525.html (accessed 05/03/2021)

§ News articles: https://www.hindustantimes.com/delhi/a-quiet-farewell-in-a-far-off-land/story-eogHDQzGSWAWYXBEW5bg6J.html and http://archive.indianexpress.com/news/scientist-dies-in-antarctica-kin--agree-to-last-rites-in-icy-station/471574/ (accessed 05/03/2021)

Table 7. Overview of Medical Facilities in Three Antarctic Research Stations

	Syowa Station	Neumayer-Station III	Concordia Station
Occupants[21]	Max: 130 Winter: 40	Max: 60 Winter: 9	Max: 80 Winter: 13
Station Size[21]	Under Roof: 7,480 m^2 Scientific Labs: 1,330 m^2	Under Roof: 4,890 m^2 Scientific Labs: 410 m^2	Under Roof: 3,605 m^2 Scientific Labs: 748 m^2
Area of Medical Facility[21]	100 m^2 (Second Floor)	56 m^2 (Deck 1)	120 m^2 (First Floor / Quiet Tower)
Interior	 Floor Plan: 2nd Floor[**]  Section Plan[††]	 Image Captured from Ref. 22	 Image Credit: ESA
Adjacent Functional Areas	• Same Floor Recreation area, stairs, corridor to another building • Upper Level Communication • Lower Level Machine Room	• Same Floor Station services, communications, social rooms • Upper Level Scientific laboratories, living areas, etc. • Lower Level Station service rooms, storage	• Same Floor Offices, stairs, corridor to noisy tower • Upper Level Crew Quarters / Bathroom & Toilet
Number of Medics[23]	2 medical doctors	1 physician	2 physicians and 1 nurse (summer) / 1 physician (winter)
Medical Equipment[19]	Anaesthesia, Biochemistry, Diagnostic ultrasound, Diagnostic X-ray, Laboratory diagnostics, Telemedicine	Anaesthesia, Diagnostic X-ray, Laboratory diagnostics, Telemedicine	Altitude medicine, Anaesthesia, Biochemistry, Diagnostic ultrasound, Diagnostic X-ray, Haematology, Laboratory diagnostics, Telemedicine, Echography

** Image Credit: Hiromichi Machida / Nikkei Medical Online (in Japanese): https://medical.nikkeibp.co.jp/leaf/mem/pub/series/antarctica/201410/538382.html (accessed 05/03/2021)

†† Image Credit: National Institute of Polar Research / Back Number (in Japanese): https://www.nipr.ac.jp/jare-backnumber/topics/backnumber/syowa2001/index.html (accessed 05/03/2021)

B. Everest ER

Mt. Everest Base Camp is located at an altitude of approximately 5,300 meters in the Himalayas. The harsh environment poses unique medical risks, including high-altitude sickness, cold exposure, trauma, etc. The Everest Base Camp Medical Clinic (Everest ER) provides expeditors and support staff with first-aid medical care treatment. The Everest ER is staffed by a minimum of two physicians, and the double-walled tent offers a medical treatment area with a set of medical equipment (Figure 1[‡‡])[28]. Solar energy serves as a main power source whereas a backup generator is available as needed[28]; an operational robustness was confirmed. The color coding (i.e., red and white) and Everest ER logo on the tent seem to allow for easy identification as a medical clinic, which is in agreement with one of the architectural design considerations for offshore platforms (i.e., clearly identified as a sickbay). An evacuation via helicopter has become available due to technological advancement of helicopters, and the Everest ER has access to a helipad for an emergency evacuation. It takes 20-30 minutes to ferry a casualty to a near hospital via helicopter for more medical treatment[§§].

Figure 1. Everest ER Clinic Tent

C. The Apollo, Skylab and the ISS

The Apollo; The Apollo crewmembers' consensus encourages astronaut participation in the design and development phase[29], which should become a top-level design recommendation. Involvement of actual end-users during design, development, and testing phases would offer a tremendous advantage. In the Apollo program, there were two injuries incurred on the lunar surface; a shoulder strain due to a surface drilling tool and a wrist laceration due to the EVA suit wrist ring[29]. Even though an improvement of EVA suit functionality and mobility is expected, these precedents serve as a reference for design and development of medical care systems and operations for future surface exploration missions.

Skylab; Figure 2 shows an interior of the Skylab where the medical care area was located[30]. There was a trash disposal airlock at the center of the "floor." A waste management system (toilet) was located between the wardroom and the sleep compartment. It was recommended that the galley in the wardroom and the waste area should be separated. Skylab 2 Science Pilot Dr. Joseph Kerwin provided a comment, *"I'm trying to think of criticisms; and a minor one was that if someone used the urine system in the middle of the night, you'd probably wake up your crewmates because the compartments were adjacent."* (Ref. 30, p. 80) This comment indicates the importance of well-functional allocation in a habitat.

Figure 2. Skylab Orbital Workshop (1-G Trainer Crew Quarter); medical activities were conducted in the experiments operation area. (Image Credit: NASA)

One of important lessons from Skylab includes maintainability and accessibility. Skylab 3 Pilot Col. Jack Lousma mentioned, *"One thing that caused a real problem on Skylab was that equipment failed that was behind compartment walls"* (Ref. 30, p. 81); the compartment walls were fixed with permanent-type screws, and he pointed out the importance of accessibility to equipment. Additionally, Skylab 4 Pilot Col. William Pogue suggested that for *"time-critical treatment (e.g., cardiac arrest), the CPR equipment should be stowed where it is readily available, identifiable with dedicated power supplies, etc."* (CPR: cardiopulmonary resuscitation) (Ref. 30, p. 17); this comment supports the importance of a consideration of medical equipment accessibility.

Col. Jack Lousma pointed out a consideration of lunar dust for future surface missions by referring to his experience with the Skylab shower; *"One more thing about the shower. On the moon, lunar dust is going to get into*

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‡‡ Photo Credit: Lhakpa Rhangdu Sherpa; available: https://www.theadventuremedic.com/adventures/everest-er-tent-citys-medical-marvel/ (accessed 05/03/2021)

§§https://news.yahoo.com/worlds-highest-er-battles-save-lives-everest-041204069.html (accessed 05/03/2021) *everything. It gets into all of the equipment; it's going to get into the habitat, and it is going to get on you. Just dealing with your suits, you're going to want a way to get that dirt off; and I think that [a] shower is going to be a good idea."* (Ref. 30, p. 83)

The ISS; The Crew Health Care System (CHeCS), a suite of medical care systems on board the ISS, provides medical care capabilities to ensure crew safety and health during long-duration missions[31]. The CHeCS includes three subsystems: (1) Countermeasures System (CMS), (2) Environmental Health System (EHS), and (3) Health Maintenance System (HMS). The CMS consists of exercise hardware and monitoring devices to mitigate the deconditioning effects posed by a long stay in microgravity, which plays a significant part in keeping crew healthy. The EHS is in charge of monitoring environmental conditions inside the ISS, including microbiology and water quality, radiation levels, toxicology, acoustics, and so forth. The HMS offers in-flight life support and resuscitation, medical care, and health monitoring capabilities (e.g., periodic health screening exams).

Figure 3. Crew Medical Restraint System (CMRS) in the U.S. Laboratory (Image Credit: NASA)

The Crew Medical Restraint System (CMRS), one part of the HMS equipment, provides an insight into medical care area design and operation for future human expeditions (Figure 3). Whereas a habitat and/or spacecraft for future missions would not be able to accommodate large and stationary medical equipment due to a constrained mass and volume manifesto, in particular in the early stage of missions, it is imperative to restrain a patient securely in order for a caregiver to perform a medical care treatment safely and efficiently. The CMRS consists of a rapidly deployable rigid platform and allows a caregiver to restrain himself/herself and a patient quickly[32]; this feature is crucial in a time-critical, life-threatening scenario. Accessibility and deployability of a restraint system would also be one of key design considerations for extraterrestrial bases' medical bays, which could affect a working envelope design (e.g., associated medical equipment layout).

Even though crewmembers onboard the ISS are currently working closely with the mission Control personnel, future human spaceflight operations require a higher degree of crew autonomy; this would be more pronounced for missions to Mars where a one-way communication delay can reach approximately 20 minutes between the earth and Mars. NASA's Autonomous Mission Operations (AMO) project aimed to demonstrate how an autonomous system could help a crew activity and improve its efficiency. Frank et al. reported how an AMO software helped crew tasks associated with the Total Organic Carbon Analyzer (TOCA), one part of the EHS equipment on board the ISS[33]. The usable AMO software allowed crew to monitor TOCA performance, diagnose TOCA faults, and isolate problems successfully with significantly less communications between the mission Control and the ISS. It should be promising to integrate these operational capabilities demonstrated by the AMO project into medical bay architecture from the early design and development stage.

A discussion of the appointing of a crew medical officer was included in the ISS lessons learned[34]. Deep space explorations require a higher degree of autonomy, and therefore it is advisable that all crewmembers can handle any medical procedures to a certain degree. For this operational strategy, in addition to a provision of an adequate medical training, it would also be promising to design and develop usable medical equipment.

Figure 4. NASA astronaut Reid Wiseman works with the TOCA using the AMO software (Image Credit: NASA)

IV. Application of Baseline Design Considerations to MaMBA Medical Bay Architecture

The literature review and case studies allowed for a better understanding of baseline design considerations for extraterrestrial habitats. This section demonstrates the applicability of the gained insights to the MaMBA medical bay design and development. The habitat concept of the MaMBA (Figure 5) is being developed at the ZARM in Bremen, Germany. The MaMBA project aims to provide a functional habitat prototype for the Moon and Mars missions. The preliminary interior design concept was presented at ICES 2019[35], and a mockup of a laboratory module was constructed. The mockup is being progressively developed and advanced to expand its functionality[36], and the MaMBA habitat will be designed to accommodate the medical care facility. The following subsections suggest baseline considerations for the MaMBA medical bay design and development. It should be noted that the following considerations should be further refined throughout iterations, including discussions with SMEs (e.g., medical experts, engineers, architects, ethical experts, etc.) and human-in-the-loop testing.

1) General Recommendations for Design and Development Process

- The MaMBA medical bay should be designed with developing ConOps and "What if" scenarios.
- End users' participation during design, development, and testing phases should be highly encouraged to improve overall usability of the medical facility.

2) Architectural Features

- The MaMBA medical bay should be easy-to-access and easy-to-identify from other modules.
- The location of the MaMBA medical bay should be decided considering functionalities of adjacent facilities (e.g., private/social, quiet/noisy, clean/dirty, etc.).
- The finishes of the MaMBA medical bay should be selected considering maintainability and protection against environmental factors, including sound, vibration, radiation, etc.
- The mockup of the MaMBA medical bay should have a plug-and-play capability, allowing for running usability testing and identifying a usable working space layout.

3) Work Environment Influencing Factors

- The mockup of the MaMBA medical bay should allow for conducting testing of medical activities in order to (1) collect time-series data of interior environmental conditions (e.g., temperature, humidity, sound levels, etc.) and (2) evaluate human factors of the working space (e.g., ergonomics, lighting intensity, etc.).

4) Medical Equipment and Medication

- Medical equipment for the MaMBA should be designed and developed with a focus on usability (e.g., Nielsen's usability heuristics[37]).
- Equipment of the MaMBA medical bay should be selected considering usability, maintainability, accessibility, and repairability; the mockup of the MaMBA medical bay should allow for conducting a series of usability testing of medical equipment.
- Equipment and medication selection for the MaMBA medical bay should be carried out with SMEs; some medications require an environmental control (e.g., temperature), which may influence a habitat power budget.

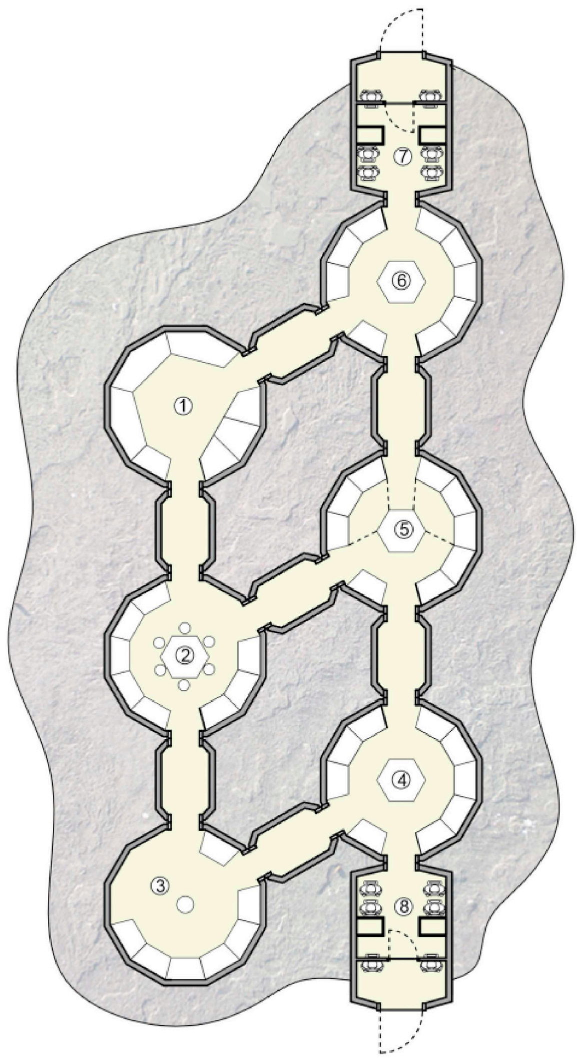

Figure 5. MaMBA consists of six modules, and each module has a primary function: (1) sleeping, (2) eating and socializing, (3) relaxing, (4) greenhouse, (5) laboratory, and (6) workshop. Also, there are two airlocks (7,8). The MaMBA medical bay is planned to be located in the second story of the laboratory module considering crew privacy concerns. Future works should explore alternative locations and evaluate different options based upon the baseline design considerations presented here.

5) Operation

- The mockup of the MaMBA medical bay should allow for running simulations of emergency scenarios (e.g., measurement of time required for the transportation of a casualty, equipment malfunction and its repair activity using 3D printing, etc.)
- The MaMBA medical bay should have a certain degree of automated systems to achieve crew autonomy; yet, additional aspects such as levels of automation and crew privacy must be considered. Yashar et al. developed a concept of an autonomous medical response agent for long duration missions by conducting a series of usability testing[38], which should also serve as a case study alongside the AMO demonstrations.
- Handling of deceased crew should be discussed further; the handling and treatment must be ethically, biologically, and physically acceptable. Preservation of a deceased body even for a couple of days may influence a habitat manifest, including volume and power requirements.
- An alternative operational plan should be developed for the worst-case scenario where the MaMBA medical bay becomes non-operational.

6) Sanitation

- The MaMBA medical bay should be easy-to-clean (e.g., ease of handling of chemical spills).
- Infection control measures (e.g., an isolation strategy) should be established considering the MaMBA habitat operation holistically.
- Location of medical waste storage and disposal methods should be selected considering both external and internal functional allocations (e.g., a waste management area should not be adjacent to a galley area).
- The MaMBA medical bay should provide washing facilities for handling lunar dust (e.g., waterbasin for eye wash).

V. Conclusion

This study aimed to identify baseline design considerations for medical facilities in extraterrestrial habitats. First, the existing standards, guidelines, and recommendations were reviewed to capture key design considerations for medical bay architecture. The review revealed the five major groups of the design considerations: (1) architectural features, (2) work environment influencing factors, (3) medical equipment and medication, (4) operation, and (5) sanitation. Furthermore, the case studies of the analog bases provided additional insights into architectural design and emergency procedures. We observed commonalities (e.g., accessibility) between the investigated sites and identified additional key considerations (e.g., maintainability, repairability) based upon lessons learned. Finally, the gained insights were applied to the MaMBA medical bay architecture design and development plan. The medical bay development requires a broad spectrum of knowledge, and multidisciplinary collaborations from an early stage would be highly encouraged. For instance, a selection process of medical equipment and medication should be carried out with the participation of SMEs in associated domains as well as medical personnel; types of equipment and storage may impact on habitat mass and power budget. Also, it is advisable to run a series of usability testing of working space as well as individual equipment with end users to identify operational issues and improve the overall usability. We will refine the initial baseline design considerations by delving into available resources. The baseline design considerations presented here should serve as a starting point for medical facility design and development of the MaMBA and other habitats.

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