18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID #92

Enabling Earth-Independent Medical Operations: the CSA Connected Care Medical Module Framework

Cyril Mani, B.Eng.[a]*, Charlotte Pearce, B.Eng.[a], Gurneet Jassal, MSc.[a], Anastasiia Prysyazhnyuk, MHSc.[a], Annie Martin, PhD.[a], Elias Gedamu, P. Eng. M. Eng. PMP[a], Tristan Richmond, B. Eng.[a], Jocelyn Coulombe[a] and Conrad Mielczarek, M. Eng.[a]

[a] *Canadian Space Agency, Canada, charlotte.pearce@asc-csa.gc.ca*
* *Corresponding Author*

Abstract

Current ISS medical operations in Low-Earth Orbit heavily depend on proximity to ground resources. Astronauts currently hold regular telemedicine sessions with flight surgeons and specialists on Earth, relying on live bandwidth to upload medical data and ensure continuity of care. They also depend on Earth for emergency resupplies or evacuation. For sustainable long-duration and deep-space missions, challenges such as communication delays and emergencies require a paradigm shift toward autonomous medical operations. Future capabilities must include interoperable biomonitoring devices in a loosely coupled architecture, featuring electronic medical records and expert AI modules - all accessible via an intuitive user interface. Modularity, health informatics, and on-board decision support are vital to the future of care in deep space.

The Canadian Space Agency's response to this shift is the Connected Care Medical Module (C2M2) framework, a central computer-based system enabling flexible point-of-care health informatics to stage AI-driven medical operations in resource-scarce settings. Each C2M2 implementation provides a modular platform for simulating medical operations on a planetary surface, isolated from Earth. Early prototypes demonstrated live EMR-based diagnostics and seamless integration of commercial off-the-shelf (COTS) medical devices into the interoperable C2M2 architecture. Testing and validation of these prototypes will guide future iterations of the C2M2 framework as humanity ventures beyond Low-Earth Orbit. Ultimately, C2M2 aims to evolve astronaut health and bridge gaps in remote healthcare delivery, addressing medical capabilities required for deep-space exploration.

The purpose of this work is to examine how the C2M2 framework transforms medical operations and mitigates risks by addressing critical gaps identified by NASA for future exploration-class missions. C2M2 impacts operations by demonstrating improved clinical decision autonomy, successful integration of commercial medical devices into a modular EMR-based system, and functional delivery of simulated care workflows in communication-limited, resource-constrained environments. It addresses at least 2 critical technological gaps identified by NASA, under the risk of adverse health outcomes and decrements in performance due to medical conditions that occur in mission.

Keywords: Autonomous Medical Operations, Deep-Space Exploration, Connected Care Medical Module (C2M2), Health Informatics, Remote Healthcare Delivery

Acronyms/Abbreviations

Abbreviation	Definition
AED	Automated External Defibrillator
AI	Artificial Intelligence
AI4H	Pan-Canadian Artificial Intelligence for Health
AR	Augmented Reality
CBC	Complete Blood Count
CDSS	Clinical Decision Support System
CG	Caregiver
CMO	Crew Medical Officer
COTS	Commercial Off-the-Shelf
C2M2	Connected Care Medical Module
DRM	Design Reference Mission
ECG	Electrocardiogram
EMR	Electronic Medical Record
EVA	Extravehicular Activity
ExMC	Exploration Medical Capability
FHIR	Fast Healthcare Interoperability Resources
FOIA	Freedom of Information Act
HL7	Health Level Seven International (standards organization)
HIPAA	Health Insurance Portability and Accountability Act
HUD	Heads-Up Display
ILMA	Intubating Laryngeal Mask Airway
IoT	Internet of Things
ISS	International Space Station
JIT	Just-in-Time
LoC	Levels of Care
LLM	Large Language Model
MRI	Magnetic Resonance Imaging
MS	Medical System
NASA	National Aeronautics and Space Administration
NLP	Natural Language Processing
PIPEDA	Personal Information Protection and Electronic Documents Act
PMC	Private Medical Conference
PoCUS	Point-of-Care Ultrasound
PRA	Probabilistic Risk Assessment
UI	User Interface
VR	Virtual Reality

1. Introduction

1.1 Current Medical Operations in Space

Current spaceflight medical protocols, as established aboard the International Space Station (ISS), are fundamentally dependent on Earth-based medical oversight. A terrestrial cadre of flight surgeons and clinical specialists is available in real time to support astronauts via scheduled telemedicine consultations and emergency conferencing [1,2]. The ISS's low Earth orbit permits near-instantaneous audio-visual communication, enabling real-time clinical decision-making, continuous medical telemetry, and rapid data transmission. Proximity to Earth additionally facilitates rapid emergency evacuation and resupply operations, forming the basis of the current "stabilize-and-return" model for serious medical events [2]. Consequently, astronauts exercise limited clinical autonomy, as most medical decisions are contingent on ground-based expert consultation. This architecture assumes reliable, low-latency contact with Earth, a condition that will not hold during deep-space missions.

1.2 Challenges in Deep-Space Missions

Exploration-class missions to cis-lunar space, Mars, and other deep-space destinations introduce medical constraints that fundamentally differ from current ISS paradigms. Most notably, interplanetary distances result in significant communication latency. For Mars missions, signal propagation delays can reach 20 minutes one way (up to 40 minutes round-trip) [3], rendering real-time telemedicine infeasible. This latency severely hampers synchronous clinical support, particularly for time-sensitive medical interventions such as trauma resuscitation, acute neurological events, or cardiovascular emergencies.

Moreover, medical evacuation from deep space is operationally impractical [1,2]. Beyond low Earth orbit, no infrastructure exists for rapid return to Earth, and abort trajectories often require months, if feasible at all. As such, astronauts must possess the means to provide definitive medical care autonomously, including diagnostic evaluation, treatment initiation, and long-term monitoring without external assistance. The absence of emergency evacuation capability necessitates a transition toward autonomous stabilization and management of critical conditions [2,4].

Resupply logistics further constrain deep-space medical operations. In contrast to the ISS, which receives regular cargo deliveries, interplanetary missions are burdened by extreme limitations on mass, volume, and power availability. Medical hardware must therefore be multi-functional, modular, and fault-tolerant, while pharmaceuticals must remain stable under prolonged exposure to spaceflight stressors including radiation and temperature fluctuations [2]. Additionally, consumables and diagnostic reagents must be conserved or regenerated in-situ, requiring sustainable inventory management [1].

Environmental and psychosocial stressors compound these clinical challenges. Astronauts in deep-space environments are exposed to chronic low-dose radiation beyond Earth's magnetosphere, increasing risks of oncogenesis, neurocognitive decline, and cardiovascular pathology. Microgravity induces fluid shifts, musculoskeletal atrophy, immune dysregulation, and neurovestibular disturbances, fundamentally altering human physiology and disease presentation [5,6,7]. Circadian misalignment, prolonged confinement, and isolation further contribute to psychiatric vulnerability and diminished cognitive performance [8,9]. Together, these factors necessitate advanced, integrated medical systems capable of adapting to dynamic health states in physiologically altered conditions.

1.3 The Paradigm Shift

In response to these operational realities, space medicine is undergoing a critical paradigm shift from Earth-dependent to Earth-independent healthcare delivery. This transition is driven by the imperative to ensure mission resilience and crew survivability in the face of delayed communication, logistical isolation, and environmental extremes. Central to this evolution is the integration of adaptable artificial intelligence (AI)-based diagnostic systems, onboard clinical decision support, and modular medical infrastructure designed for autonomous operation [10, 11].

Advanced autonomous systems leverage machine learning algorithms and rule-based engines to interpret biomonitoring data, identify pathological trends, and propose differential diagnoses independently [7]. Continuous physiologic surveillance through wearable and ambient biosensors feeds into adaptive models that calibrate against individual baselines, enabling early detection of preclinical conditions [11]. In parallel, onboard clinical decision-support tools are being developed to guide astronauts through therapeutic protocols and procedural workflows in a user-friendly, stepwise manner [12, 13].

Equally essential is the development of a modular, interoperable, and scalable medical architecture capable of supporting diverse mission profiles. Hardware miniaturization, functional integration, and software interoperability are key to ensuring that medical platforms can transition seamlessly between mission phases (e.g., lunar surface habitat, transit vehicle) while maintaining full functionality. Such systems must balance comprehensive care capabilities with mission-imposed constraints on mass, volume, and energy consumption [14].

Several commercial and institutional initiatives have emerged in recent years aiming to bridge the autonomy gap in remote healthcare delivery. Wearable biosensors offer continuous physiologic monitoring with embedded analytics, yet most require connectivity to their separate proprietary cloud-based systems to extract analytics (instead of computing on the edge) and then combine data streams (data fusion), limiting their applicability in spaceflight scenarios characterized by high latency and bandwidth constraints [15, 16]. Commercial artificial intelligence platforms have demonstrated efficacy in clinical decision support, particularly in image interpretation and triage optimization, but are primarily designed for terrestrial, data-rich, high-power availability and high uptime environments [17, 18, 19] which are unapplicable to the spacecraft environment. Institutional programs like the European Space Agency's Telemedicine Toolbox I-DISCARE [20] and NASA's Exploration Medical Capability (ExMC) have advanced modular diagnostic kits and tele-mentoring protocols, integrating tools such as point-of-care ultrasound (PoCUS), blood analyser, and structured procedural checklists [21]. While these systems enhance in-situ care delivery, they remain largely Earth-reliant for clinical oversight and decision-making. Similarly, terrestrial analogues - including military medical field teams and international paramedic health teams - have informed the development of mobile, modular healthcare delivery platforms for austere environments but lack AI-driven autonomy and decision support integration [22. 23]. As such, existing technologies offer foundational capabilities in physiological sensing, portable diagnostics, and guided interventions, but no current platform comprehensively addresses the integration, modularity, autonomy, data processing and onboard analysis requirements necessary for deep-space operations.

Bridging these limitations, the Canadian Space Agency's Connected Care Medical Module (C2M2) framework exemplifies this paradigm shift. C2M2 is a scalable, AI-enhanced system-of-systems designed to deliver point-of-care medical operations in resource-constrained environments. The framework integrates interoperable commercial off-the-shelf (COTS) medical devices, electronic health records, and diagnostic support tools into a centralized informatics architecture. At its core is a computational engine capable of fusing multisource inputs to support real-time medical assessment, triage, and management. Rapid iterative prototyping has yielded multiple versions of C2M2, deployed in containerized configurations, with future versions targeting spaceflight integration. By abstracting clinical workflows into a modular, intuitive interface, the C2M2 enables crew members to deliver autonomous care while capturing operational data to inform future design iterations [24, 25].

The C2M2 framework represents a transformative step toward sustainable deep-space health systems, aligning technological innovation with the clinical exigencies of exploration missions.

2. Material and methods

2.1 C2M2 Framework Overview

The C2M2 is a system-of-systems design framework led by the Canadian Space Agency (CSA), aimed at enabling autonomous and semi-autonomous medical operations in remote and extreme environments. The first round of C2M2 prototypes was designed and produced in 2023, with four containerized configurations tested and deployed for validation. Building on lessons learned from this initial round, a second round concluded in March 2025, resulting in the production of three additional prototypes. The flexible C2M2 framework enabled the prototypes to be implemented in various physical forms by different industrial teams [24, 26] across iterations, ranging from deployable container modules to onboard kit-style integrations, yet with consistent underlying informatics and autonomy architecture. Despite differences in software, hardware configuration, and form factor, each prototype upholds the C2M2 framework's core design principles, including modularity, interoperability, real-time and delayed telemedicine, and AI-driven clinical decision support [24].

Common between the prototypes and central to the C2M2 architecture is a high-reliability computational platform that hosts a modular health informatics environment. This environment facilitates the integration and coordination of COTS medical devices through standardized interfaces. Core functional elements of a C2M2 implementation include:

- Adaptive data handling architectures supporting onboard analytics and remote data synchronization.
- Interoperability across multimodal data acquisition from biosensors, diagnostic imaging systems, and other diagnostics and therapeutic tools;
- A Clinical Decision Support System (CDSS), or a virtual medical assistant, capable of autonomous triage, anomaly detection, diagnostic reasoning, and procedural guidance;
- A local Electronic Medical Record (EMR) system that complies with HL7 FHIR and OpenEHR data exchange standards;
- Communication capabilities adaptable to communication latency;

- Just-in-time procedural training and context-aware user interfaces for crew with or without formal medical training.

2.2 Addressing Operational Challenges – Enabling Medical Autonomy

C2M2 prototypes incorporate stratified autonomy in their decision support infrastructure. As the design of the prototypes progresses, milestones represented by autonomy classes are reached. Across implementations, the decision support logic is distributed across three functional classes:

- **Class I**: Rule-based and deterministic logic for standard medical workflows. (e.g., computerized sequential procedure documentation made interactive and function based)
- **Class II**: Probabilistic inference engines (e.g., Bayesian Networks, knowledge graphs) and bounded LLMs that contextualize patient data for triage and diagnostic prioritization.
- **Class III**: Onboard adaptive machine learning and LLM modules, enabling long-term trend analysis, anomaly detection, and model retraining in situ (e.g. digital twins, continuous learning).

The current C2M2 prototypes reach an equivalent class 2, incorporating deterministic sequential logic suggestions, probabilistic inference engines and some elements of anomaly detection and long-term analysis.

Human-in-the-loop safeguards are integrated throughout these C2M2 decision support architectures via explainable AI outputs and a structured system of hierarchical override, directly addressing regulatory requirements and fostering user trust in autonomous healthcare systems. Interoperability is achieved through the adoption of HL7 FHIR, OpenEHR schemas, and other open-source, privacy standards such as PIPEDA, enabling secure, consistent communication between biosensors, imaging platforms, point-of-care diagnostics, and CDSS. These design choices ensure that medical data is exchanged and processed in accordance with national and international privacy regulations. Collectively, the incorporation of these technical and ethical safeguards aligns the C2M2 framework with the highest standards outlined in the Pan-Canadian AI for Health (AI4H) Guiding Principles [27].

Building on these principles, the operational context in which C2M2 functions further demands a resilient, self-sufficient architecture - one that can maintain clinical functionality despite conditions of high-latency, bandwidth limitation, and intermittent connectivity. Local-first architecture ensures that essential medical data (vital signs, imaging) logs are stored redundantly and analyzed onboard. Asynchronous communication protocols (“store-and-forward”) allow prioritized data synchronization with Earth-based medical support teams when possible.

A canonical data flow structure underpinning C2M2 platforms consists of five sequential layers, each responsible for a distinct aspect of medical data processing and delivery as shown in Figure 1. The Sensing Layer initiates the process with observed symptoms and/or chief complaints through wearable sensors, diagnostic imaging, and point-of-care laboratory devices. Data from this layer enters the Integration Layer, where gateway modules standardize and format the raw inputs for compatibility with downstream systems, particularly the Clinical Decision Support System (CDSS). Within the Analytics Layer, the CDSS applies diagnostic algorithms, triage scoring, and longitudinal health modelling to derive clinically relevant insights. These insights are then presented to crew members via the Interface Layer, using intuitive user interfaces, tablet-based dashboards, or augmented reality (AR) systems for ease of interaction. Finally, the Communication Layer manages the asynchronous transmission of prioritized, encrypted telemetry to Earth, ensuring secure and efficient data exchange with flight surgeons in mission control. Together, these layers form a resilient, modular architecture capable of supporting autonomous medical operations in resource-constrained environments.

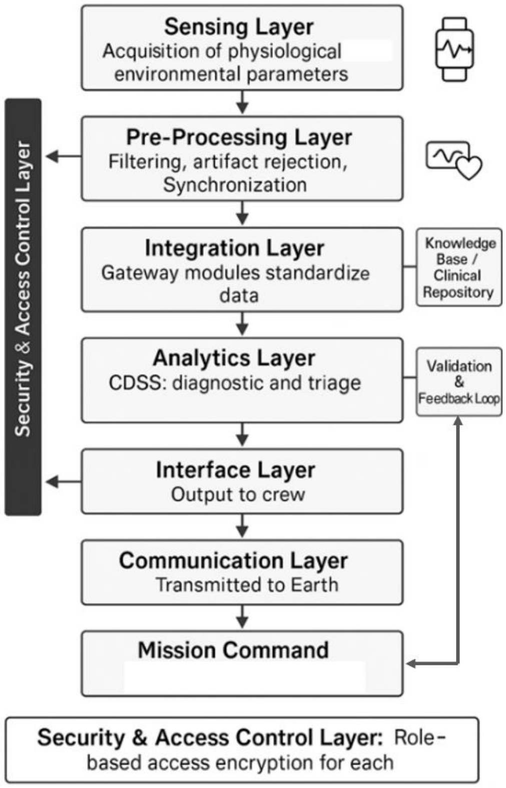

Figure 1: High level C2M2 data flow structure

Operational independence is further supported through embedded training platforms. These include just-in-time (JIT) procedural walkthroughs, AR overlays, and interactive multimedia modules. Training content is contextually delivered based on the user's role, task complexity, and system-recognized urgency, enabling informed intervention by non-clinician crew.

Currently, C2M2 modules are undergoing validation in analog settings, including remote Indigenous communities in Northern Canada. These field deployments inform system refinements regarding power availability, thermal regulation, ease of use, UI accessibility, cultural sensibility and quality of care. For example, some C2M2 implementations leverage reconfigurable interior spaces and solar-powered infrastructure, while others emphasize modular container linkage for scalable clinical capability Interfaces are designed to support high cognitive load scenarios, providing decision scaffolding and minimizing task complexity.

With the C2M2 framework and its core architecture now defined, the following results section explores the operational implications of its implementation and illustrates how it de-risks healthcare in future deep space mission. Specifically, it examines how medical workflows, roles, and system capabilities are expected to evolve from current ISS-era paradigms to future deep-space missions leveraging the C2M2 systems-of-systems approach. The analysis highlights key changes in clinical autonomy, data management, crew responsibilities, and emergency response, providing insight into the practical outcomes and anticipated performance of this paradigm-shifting framework.

3. Results

3.1 Progression in Levels of Care and Autonomy Enabled by C2M2 Implementation

The integration of the C2M2 framework across mission architectures results in a quantifiable progression in medical autonomy. This progression is evaluated using NASA's Levels of Care (LoC) model, which categorizes onboard clinical capabilities from Level I (basic first aid and life support) to Level V (comprehensive, autonomous medical and surgical care) [2], [28].

As previously mentioned, on the ISS, current medical support is classified within LoC I–II. Medical interventions are limited to non-invasive monitoring, minor procedures, and emergency stabilization, all of which are heavily reliant on real-time private telemedicine conferences with ground-based flight surgeons. Capabilities are constrained by limited diagnostic infrastructure (e.g., i-STAT handheld blood chemistry analyzer, ultrasound with real-time guidance) and absence of definitive care options. In this context, critical pathologies such as appendicitis, orbital trauma, or serious infection would necessitate urgent evacuation to Earth [1, 2].

In contrast, preliminary C2M2 deployments and simulations of Gateway and lunar surface missions have demonstrated an operational shift to LoC III–IV. These missions involve latency of approximately 1.3 seconds one-way, allowing intermittent communication but requiring onboard medical autonomy during communication outages or contingency events. The C2M2 system enables this through embedded AI-based triage systems, clinical decision support tools, and modular diagnostic platforms such as AI-guided point-of-care ultrasound and compact hematology analyzers. For instance, in simulated lunar scenarios, the system has demonstrated the ability to autonomously detect abnormal cardiovascular parameters, guide the crew through a differential diagnosis, and recommend an evidence-based treatment algorithm, including intravenous fluid resuscitation and continued monitoring - capacities required as part of the NASA’s 3001 Vol. 2 standards in missions beyond-LEO of >30 days [29].

For Mars-class missions, where communication delays reach up to 20 minutes one-way and emergency evacuation is infeasible, C2M2 systems are designed to eventually meet LoC V requirements. These include the capacity for autonomous, procedural and eventually minor surgical care under prolonged isolation. Architecturally, the C2M2 supports this level through the integration of context-aware procedural guidance systems, real-time health trajectory modeling, just-in-time AR-assisted training for non-expert crews and closed-loop therapeutic feedback based on onboard analytics. Specific operational outcomes include autonomous stabilization of simulated non-life-threatening traumatic injuries (e.g., compound limb fracture with hemorrhage), AI-supported wound debridement procedures, and autonomous decision-making for pharmacological interventions in pathologies such as venous thromboembolism, all executed without real-time Earth input.

This observed progression - from ISS LoC I–II to lunar LoC III–IV and planned Martian LoC V - is a direct result of the modular, interoperable, and AI-enhanced architecture of the C2M2 framework. It enables the transition from supervised care delivery to autonomous health management, ensuring that the medical system remains commensurate with mission risk profiles and communication constraints. The operational outcome is a scalable medical autonomy capability that reduces reliance on Earth-based infrastructure and provides crews with the tools required to manage complex clinical scenarios during long-duration, deep-space missions.

3.2 Crew Roles and Interaction with Medical Systems

With ISS operations, the crew medical officer (CMO) is typically a non-physician astronaut with moderate medical training, supported closely by a ground-based flight surgeon in any health event. Crew members routinely conduct health checks and treatments under direct teleconsultation - e.g. weekly private medical conferences via real-time video with flight surgeons [30]. In emergencies on ISS, the protocol is to stabilize the patient and, if needed, coordinate an evacuation to Earth or consult ground for immediate guidance. This drastically changes for deep-space missions using C2M2. NASA now anticipates crews will include at least one physician astronaut and one assistant medical officer (paramedic-level trained) among a four-person team for long term, deep-space missions [2, 12]. These medically trained crew take primary responsibility for care, using C2M2’s decision-support tools for guidance. Ground flight surgeons become advisors rather than directors for acute and emergent care scenarios, given two-way communication delays on the order of 40 minutes. Teleconsultations shift to a store-and-forward model: for example, a crew might send a recorded ultrasound scan or query to Earth, and if nothing is immediately flagged by the CDSS, awaits expert input hours or days later

During a communications blackout, care is entirely crew driven. To compensate, the C2M2 system provides on-demand resources such as AI-driven diagnostic algorithms and just-in-time training modules. For instance, the C2M2’s AI decision support can help the crew diagnose by suggesting likely conditions and treatment protocols based on sensor data and symptoms. The crew’s interaction with the medical module is therefore much more hands-on: they rely on smart checklists and autonomous protocols triggered by the system rather than waiting for ground instructions. Examples of medical scenarios will be provided in the discussion.

Overall, the crew on a C2M2-enabled mission must assume far greater medical responsibility. They practice emergency drills and medical simulations extensively pre-flight, and C2M2 provides ongoing training refreshers in-flight (e.g. modules for procedures or trauma care) to maintain proficiency. The Flight Surgeon’s role evolves into one of periodic health data review and consultation during scheduled comm windows, rather than active minute-to-minute involvement. These operational changes empower the crew to manage health events internally, a necessity for Mars-distance expeditions.

3.3 Emergency Response Protocols and Redundancy

Emergency response on the ISS is designed around the capability to abort the mission or return an astronaut to Earth within hours if needed. Critical medical events (e.g. serious injury or illness) are managed by stabilizing the patient with basic life support and consulting ground, with the implicit knowledge that definitive care can be reached via evacuation (the Soyuz or Dragon spacecraft) relatively quickly. In contrast, deep-space missions lack any near-term evacuation option - no emergency evacuation back to Earth - is possible during Mars transit or habitation [31]. Therefore, C2M2 protocols emphasize on-site definitive treatment. The results indicate a need for built-in operational redundancy to handle such emergencies. This includes redundancy in crew skills (at least two crew capable of performing medical procedures, so one can treat the other if the primary medical officer becomes incapacitated) and redundancy in critical medical equipment. For example, C2M2 would carry backup life-support medical hardware (spare defibrillator pads, extra oxygen concentrators, etc.), an inventory management system to track this hardware consumption over long periods of care and duplicate diagnostic tools, since resupply is infrequent, and failures could be catastrophic.

Protocols are also adapted for autonomy. Upon recognizing an emergency, the C2M2 immediately triggers an "Emergency Medical Event" protocol: alerting and dispatching all crew depending on the level of medical training, suggesting initial actions (such as administering emergency medication or placing the patient in a stabilized position), and continuously logging vitals and treatment steps. Without real-time ground voice loops, the crew relies on these standardized sequences and on-board checklists. Operational contingency plans are expanded: for instance, if a critical piece of medical equipment fails during an emergency, or the inventory management system detects consumables are missing for a specific procedure, the C2M2 database contains offline references for repurposing of unrelated equipment, potential off-label use of other medication - with secondary effects indicated - improvised for alternative medical approaches using available materials. Another layer of redundancy is in communication - the C2M2 system would queue distress signals or updates to send the instant a comm link is available, reorganising these messages as the situation evolves, ensuring the ground team is informed of the most up-to-date situation as soon as possible even after a blackout, instead of a backlog of rolling messages. In summary, future long-duration missions demand a robust, multi-redundant emergency operations framework, whereas ISS-era protocols could lean on evacuation and immediate ground help as the ultimate safety net.

3.4 Equipment and Diagnostic Capability Differences

There are notable differences in the medical hardware between ISS operations and C2M2-enabled missions. The ISS medical inventory [32] includes a range of medication packs, airway and intravenous support tools, basic diagnostic devices, and surgical kits. While extensive for its class, the system is inherently designed around Earth-based support. For instance, although ISS crews are equipped with endotracheal tubes, laryngoscopes, suction devices, and surgical instruments, their use is tightly coupled with live ground consultation, and definitive care is still intended to occur post-evacuation.

Diagnostic capacity is similarly constrained. Point-of-care tools include the i-STAT blood analyzer for basic electrolytes, digital glucometers for blood sugar levels, but the crew remains dependent on telemedical support for interpretation. Otoscopic and ophthalmic tools (e.g., tonometer, panoptic head, eye simulator) are present for basic sensory assessment but are not integrated into a broader diagnostic AI platform. Often biomonitoring equipment are used in the context of research protocols, but the live data generated by the equipment is not integrated into a CDSS or analyzed for long term changes, rather it is sent back to the ground [33]. ISS medical kits also include advanced airway management tools (e.g., ILMA hardware, AMBU bags), intraosseous access kits, and a variety of injectable and topical medications for acute stabilization. However, these are implemented within a "stabilize-then-evacuate" framework.

In contrast to legacy architectures that depend on distributed tools and ground-based interpretation, C2M2-equipped platforms integrate sensing, analysis, and decision support into a cohesive, semi-autonomous diagnostic ecosystem. Physiological data from FDA/ Health Canada-approved wearable devices, environmental telemetry, and longitudinal EMRs are aggregated and processed by the CDSS. This system continuously evaluates data streams to identify aberrant trends, generate preliminary differentials, and suggest follow-up diagnostics. Instead of requiring continuous manual surveillance, the onboard medical officer is notified only when actionable anomalies are detected, accompanied by a synthesized summary of findings and direct access to the corresponding EMR entries. This approach not only enhances situational awareness but also optimizes crew workload allocation by triaging attention toward clinically significant events.

Advanced diagnostic capabilities are extended through AI-enhanced imaging modules capable of autonomous lesion characterization, vascular mapping, and fluid analysis in real-time - eliminating the dependence on Earth-based sonography interpretation. Similarly, laboratory capabilities are expanded through self-contained "lab-in-a-box" modules capable of executing multiplexed infection panels, complete blood counts, and biochemical assays-far beyond what is currently achievable with the i-STAT alone.

Furthermore, the pharmaceutical management subsystem within the C2M2 framework leverages EMR integration to deliver automated guidance on drug selection, dosing, and contraindications, tailored to crew-specific physiological profiles and current clinical status. This capability is particularly critical for long-duration missions that necessitate autonomous administration of complex pharmacological agents, including second-line antimicrobials, psychoactive medications, and procedural sedatives. In addition, where ISS dental kits are limited to temporary fillings and manual extraction tools, the C2M2 framework supports AI-guided dental triage and procedural support for more definitive interventions. Table 1 outlines the comparative equipment and functional enhancements across diagnostic, therapeutic, and procedural systems introduced by the C2M2 framework, some already present in current prototypes.

Table 1. Summary of Key Medical Equipment and Capabilities: ISS vs. C2M2

Capability	ISS	C2M2
Diagnostic Imaging	Ultrasound with remote guidance	AI-guided ultrasound, compact digital X-ray.
Laboratory	*i*-STAT for blood chemistry; advanced tests Earth-based	Offline-capable CBC, biochemical panels, infection biomarkers.
Biomonitoring	Wearables used during specific activities (e.g., EVAs), standard vital signs monitoring devices.	Continuous multi-parametric monitoring (e.g., ECG, SpO_2, core temp) for all crew, with subsequent data fusion to enable analytics.
Therapeutic Tools	Basic medications, AED; improvised tools for trauma	Expanded formulary; procedural kits, medical oxygen concentration.
Computing & AI	Medical software on laptops; limited automation	Integrated CDSS with real time AI differential diagnosis, AR-guided procedures.
Pharmaceutical Management	Manual inventory and administration; ground-guided dosing	EMR-integrated decision engine for personalized dosing, contraindication alerts
Dental Capability	Temporary filling kit; manual extraction tools	AI-guided procedural support for more definitive interventions.
Training & Guidance	Crew trained pre-flight; emergency reference books	Just-in-time procedural training modules, multimedia guides, and adaptive cognitive support
Data Handling & Privacy	Real-time downlink; private medical comms via video	Encrypted, store-and-forward telemetry; role-based access control; compliance with PIPEDA/HIPAA
Redundancy & Resilience	Crew fallback on ground; minimal onboard redundancy	Redundant crew training, software and database backup, diagnostic hardware duplication.

These equipment and capabilities upgrade collectively enable a higher level of care (approaching on-board hospital functionality) within the mass and volume constraints of spaceflight. The C2M2's emphasis on portable, multi-function devices and AI interpretation is specifically to reduce reliance on Earth-based expertise, in line with the needs of a 2.5-year Mars mission

.

3.5 Alignment with NASA-STD-3001 Health and Human-Factors Requirements

To evaluate regulatory and operational adequacy, the C2M2 system was analysed against the functional domains defined in NASA-STD-3001, Volume 1 ("Crew Health") and Volume 2 ("Human System Integration Requirements") [29, 30] -which collectively establish the biomedical and operational standards for all human-rated spaceflight systems. The results of the C2M2 implementation demonstrate compliance with and operationalization of key standards in a deep-space context.

3.5.1 Circadian Rhythm and Fatigue Risk Management

NASA-STD-3001, Volume 1, Requirement V16001 states: "*Crew schedule planning and operations shall be provided to include circadian entrainment, work/rest schedule assessment, task loading assessment, countermeasures, and special activities.*" While ISS crews benefit from dynamic lighting systems and Earth-directed schedule adjustments, deep-space missions must implement these countermeasures autonomously. Future implementations of C2M2 platforms could incorporate an ambient light modulation and crew-specific sleep analytics module to maintain circadian alignment in variable solar day environments such as the 24.6-hour Martian sol. Sleep/wake cycles could be managed locally using wearable-derived sleep metrics and embedded fatigue risk prediction models. When abnormal patterns are detected, the system would recommend adjustments (e.g., light therapy, melatonin administration) and flags mission control asynchronously.

3.5.2 Private Medical Communications

NASA-STD-3001, Volume 1, Requirement V16002 & V16003 respectively require: *"A PMC shall be scheduled on a routine basis, as determined by the Flight Surgeon, at a frequency dictated for short- or long-duration missions." and "Medical information that is sent to/from the ground via spacecraft telemetry shall be considered private communication."* On ISS, this is achieved via encrypted private audio/video conferences with flight surgeons. In deep space, the C2M2 ensures privacy through secure data handling of stored messages and medical records. For example, the EMR data is stored in an open-source HIPAA compliant commercial Clinical Data Repository which can be retrieved and combined with the audiovisual recording and packaged in the custom aggregator in an encrypted format to be sent to ground. Even when using store-and-forward communication due to delays, all personal health data transmissions are encrypted and marked private. The frequency of private medical consults may decrease (perhaps monthly or on an as-needed basis instead of weekly) because real-time exchange is not possible, but the standard's intent - giving crew a confidential outlet to discuss health - is maintained by C2M2 through asynchronous channels. The system might, for example, enable a crew member to record a private message to the flight surgeon detailing a sensitive issue, encrypt it, and transmit when link is available, satisfying the Privacy Act, PIPEDA and NASA-STD-3001 rules even without live contact.

3.5.3 Behavioural Health and Performance

NASA-STD-3001, Volume 1, Requirements V16004 and V14011 respectively mandate: *"Provisions shall be made to implement appropriate psychological support programs for the crew, key ground personnel, and crew families throughout the mission." and "Pre-mission, in-mission, and post-mission crew behavioural health and crewmember cognitive state shall be within clinically accepted values as judged by behavioural health evaluation."*

Here both ISS and deep-space missions require strong behavioral health support, but execution differs with autonomy. ISS crews have real-time psychological support (private weekly conferences with psychologists, ability to call family on Earth weekly, etc.), and ground teams monitor crew mood and cohesion. For a mission with a 2-week blackout potential, C2M2 will provide onboard behavioral health tools. This can include digital mental health modules (mood-tracking apps, relaxing VR environments, NLP chatbots, cognitive behavioral therapy exercises) available to crew at any time. The crew will also conduct scheduled Private Psychological Conferences in a delayed format– e.g. recording a session to send to a psychologist for feedback. The C2M2's data system can support the tracking of behavioral markers (sleep, activity levels, group interaction metrics) to alert the crew commander of potential stress or conflict and longitudinally analyse this data to track changes in habits, recommending different interventions, therapies and schedule changes as required. Autonomy means the crew themselves take a larger role in supporting each other, following guidelines from the Behavioral Health and Performance program but with minimal Earth intervention.

3.5.4 In-Mission Preventive Health Care

NASA-STD-3001, Volume 1, Requirement V13003 mandates: *"All programs shall provide training, in-mission capabilities, and resources to monitor physiological and psychosocial well-being and enable delivery of in-mission preventive health care, based on epidemiological evidence-based probabilistic risk assessment (PRA) that takes into account the needs and limitations of each specific design reference mission (DRM), and parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more."* ISS missions meet V1 3003 preventive care requirements through ground-directed scheduling and intervention. For instance, sleep hygiene is monitored remotely via actigraphy [34], and diet logs are reviewed by flight surgeons on Earth. In contrast, C2M2 implementations automate and localize these functions. Continuous biosensor telemetry supports real-time monitoring of general health status (V1 3003a).

On the ISS, fitness is maintained through scheduled treadmill and resistance exercises with oversight from ground-based physiologists. C2M2 augments this with future capability to dynamically assess aerobic and strength conditioning (V1 3003d), agility and sensorimotor function (V1 3003e), and offering feedback through wearable-linked coaching. Sleep and circadian rhythm control (V1 3003f) - managed on ISS by schedule optimization and lighting cues - is made autonomous in C2M2 via embedded fatigue models and ambient lighting modulation. Environmental health (e.g., CO_2 levels) monitored on the ISS by ground controllers is instead locally managed in C2M2 through AI-driven regulation of life support interfaces (V1 3003g).

For emerging mission-specific risks-such as venous stasis, SANS, and neurovestibular dysfunction - the ISS relies on periodic ultrasound with Earth guidance. In contrast, C2M2 systems perform real-time neck and orbital ultrasound analysis onboard (V1 3003lm), logging trends for longitudinal evaluation. Behavioral cohesion on the ISS is supported through live psychological consults and family calls. Under C2M2, this is replaced by digital cognitive behavioral therapy tools and mood tracking analytics with local alerting features (V1 3003j). These autonomous capabilities allow the C2M2 to meet and, in many areas, exceed the preventive health functions currently implemented on the ISS, despite full Earth-independence.

3.5.4 In-Mission Medical Care

NASA-STD-3001, Volume 1, Requirement V13004 mandates: "*All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, clinical practice guidelines and expertise, historical review, mission parameters, and vehicle-derived limitations*." ISS currently satisfies V1 3004 through real-time voice/video consultation with flight surgeons, enabling diagnosis, medication decisions, and basic procedural guidance. Onboard capabilities are limited to first-aid, ultrasound with remote guidance, and use of reference manuals such as the ISS Medical Checklist. Complex diagnostics, surgical procedures, and definitive care are deferred to rapid return-to-Earth capability.

In contrast, C2M2 fulfills V1 3004 across all subdomains through systematized autonomy. The onboard EMR supports clinical documentation (V1 3004d–j), automatic diagnostic prompts, and treatment logging. Medical imaging and lab diagnostics (subsection g) are enabled via AI-guided ultrasound, compact digital X-ray, and biochemical/molecular lab-in-a-box systems.

C2M2 also supports medication administration and management (V1 3004k) through EMR-integrated dose calculators, personalized pharmacogenomics modules, and onboard pharmacy storage with environmental conditioning (e.g., refrigeration for biologics, satisfying subsection a). Crew members use AR-guided procedural overlays for IV access, wound care, and airway management (V1 3004h). Secure, role-restricted access and encrypted communication protocols address privacy (V1 3004p–q), even under store-and-forward communication models.

Whereas the ISS relies on evacuation (V1 3004s) for high-risk conditions, C2M2 provides autonomous advanced life support capabilities (V1 3004r), including triage engines, closed-loop physiological stabilization workflows, and palliative care modules (V1 3004t) for end-of-life events. These results demonstrate that C2M2 not only meets the functional expectations of V1 3004 but does so in a fully Earth-independent manner - making it viable for long-duration lunar and Martian operations.

3.6 Gaps Identification

The C2M2 framework was assessed to determine its potential in addressing critical technological gaps identified by NASA regarding health outcomes for future deep space missions [35]. Preliminary findings indicate that it may effectively bridge two open gaps - targeting health risk mitigation during missions - as summarized in Table 2 below.

Table 2. Mapping of NASA-Identified Medical Gaps to CSA C2M2 Capabilities

NASA-Identified GAPS	Status	CSA C2M2 Capability
Medical-501: We need to develop integrated exploration medical system models for the Moon and Mars. **Target for Closure:** Concept of Operations and exploration medical system models for future exploration missions including: a) Long-duration lunar orbital and surface missions (Closed) b) Future Mars missions (Open)	Open	Comprehensive, modular medical system model offering different care levels, adaptable to diverse mission requirements.
Medical-701: We need to increase inflight medical capabilities and identify new capabilities that (a) maximize benefit and/or (b) reduce "costs" on human system/mission/vehicle resources.	Open	Deployable system with onboard edge processing that leverages pre-trained adaptive algorithms, continuously refined through incremental learning and ground-based

Target for Closure: NASA acceptance of the Medical Risk as determined by high confidence in the ability of an exploration medical system to maintain astronaut health necessary for a successful human Mars mission		retraining, ensuring optimal real-time decision support.

The CSA's C2M2 framework directly addresses the current Medical-501 gap by translating medical capabilities into engineering language early in the systems engineering lifecycle - ensuring that these vital functions are integrated into mission plans and spacecraft designs from the onset. Traditionally, medical system requirements have been defined in later stages of development, limiting the scope and integration of medical capabilities within mission designs. The C2M2 mitigates this risk by embedding exploration medical system requirements early in the concept and design phases, allowing for seamless integration.

It also offers a tiered system model that can be adjusted based on mission-specific requirements. The modularity enables the system to scale from basic to advanced medical functions, ensuring it remains effective across a wide range of mission profiles - from long-duration lunar operations to Mars exploration. The C2M2 breaks down capabilities into detailed medical system functional requirements, while also deriving additional requirements necessary for system utility - such as integrated medical data architecture. This ensures that every aspect of medical care, from data collection to human-machine interaction, is systematically addressed. The framework also incorporates rigorous testing and evaluation processes that demonstrate the system's effectiveness and interoperability. This approach supports the standardized codification of all relevant information into robust system models that can be continuously refined and validated.

Ultimately, by aligning with the best available industry practice and incorporating a detailed, systems-engineering approach to medical requirements, the C2M2 meets NASA's Medical-501 gap. It supports the development of adapted Concept of Operations and integrated exploration medical system models that are crucial for reducing medical risks on long-duration lunar and future Mars missions.

The C2M2 framework's approach to NASA Medical-701 gap uses the development of technology prototypes and operational protocols that enable astronauts to provide medical care in a progressively Earth independent fashion (e.g. medical decision-making support tools). The dual-update CDSS mechanism enables real-time, optimized decision support despite the resource constraints - such as limited mass, volume, and communication delays. In doing so, it supports autonomous medical care by adapting to dynamic physiological challenges and ensuring that astronauts have reliable, Earth-independent medical solutions during prolonged missions beyond Low Earth Orbit.

Together, these features make the deployable system a robust solution, effectively meeting NASA's gap by providing a high-functioning, easy-to-use medical decision support tool designed for the autonomous provision of medical care in a deep space environment.

4. Discussion

4.1 Scenario & Case Studies

The implementation of the C2M2 framework redefines how clinical care is conceptualized and delivered in human spaceflight, transitioning from Earth-reliant paradigms to autonomous, crew-centric healthcare. This section illustrates the operational significance of these changes through plausible mission scenarios, reflecting current NASA mission architectures and biomedical risk profiles established in HRP-47065 and NASA-STD-3001 requirements.

4.1.1 Scenario 1: Routine Medical Care, Planned

This scenario evaluates how the C2M2 system can be used to manage routine medical assessments during deep-space missions, where regular health monitoring is essential to ensure the well-being of astronauts in an environment with no immediate Earth-based medical support.

At Sol 55 of a Mars transit mission, the C2M2 alerts the CMO that it is time for the crew's routine health check-up. The scheduled check-up is part of a bi-weekly health monitoring cycle, which includes an assessment of key physiological parameters, such as cardiovascular function, hydration status, and sleep patterns. The CMO, a trained physician astronaut, proceeds to initiate the routine medical care protocol in the C2M2 system.

Upon activation, the C2M2 system prompts the CMO to conduct a full crew health survey. The system automatically checks the crew member's EMR for prior health data, ongoing medications, and any potential contraindications. The medical system then guides the CMO through the routine physical exam steps, displaying pre-programmed, stepwise instructions for each procedure (e.g., auscultation, palpation, reflex testing, etc.).

For this session, the crew member, who has no current health complaints, undergoes a thorough assessment. The C2M2 system collects and records vital signs using the integrated wearables sensors. Data, such as blood pressure, heart rate, respiratory rate, SpO2, and body temperature, is automatically acquired and logged into the medical system in real time.

The C2M2 integrates wearables (e.g., ECG sensor) and environmental data (e.g., CO2, temperature) into a comprehensive analysis of the astronaut's health status. It uses predictive algorithms to analyze long-term trends, such as a slow decline in cardiovascular health or potential dehydration, which is especially important during the long duration of the Mars mission. The CMO is alerted if any abnormal readings are detected. For instance, if the blood pressure shows a sustained elevation, the C2M2 system will recommend additional diagnostic testing. If necessary, the CMO can initiate further tests, such as a blood panel or advanced imaging (e.g., ultrasound), which the C2M2 will guide. While the CMO is conducting the check-up, the system continuously provides suggestions based on real-time data, including potential dietary recommendations, reminders for physical fitness, and supplements (e.g., Vitamin D, calcium). The system will also suggest updates to exercise schedules or changes in work-rest cycles if needed based on the health data trends observed. Once the routine check-up is completed, the C2M2 system generates a comprehensive health summary, including the current status, detected anomalies, and recommended actions. It then securely uploads the updated data to the central mission health system for the crew's ongoing health monitoring. If the communication link is unavailable, the data is stored in the onboard medical archive until the next scheduled contact window, when the information can be securely transmitted to Earth.

This scenario, summarized by a flowchart in Figure 2, highlights the semi-autonomous nature of routine medical care provided by C2M2, where the CMO takes an active role in conducting assessments with minimal guidance but receives assistance from AI-driven recommendations, decision support, and operational reminders for maintenance of crew health.

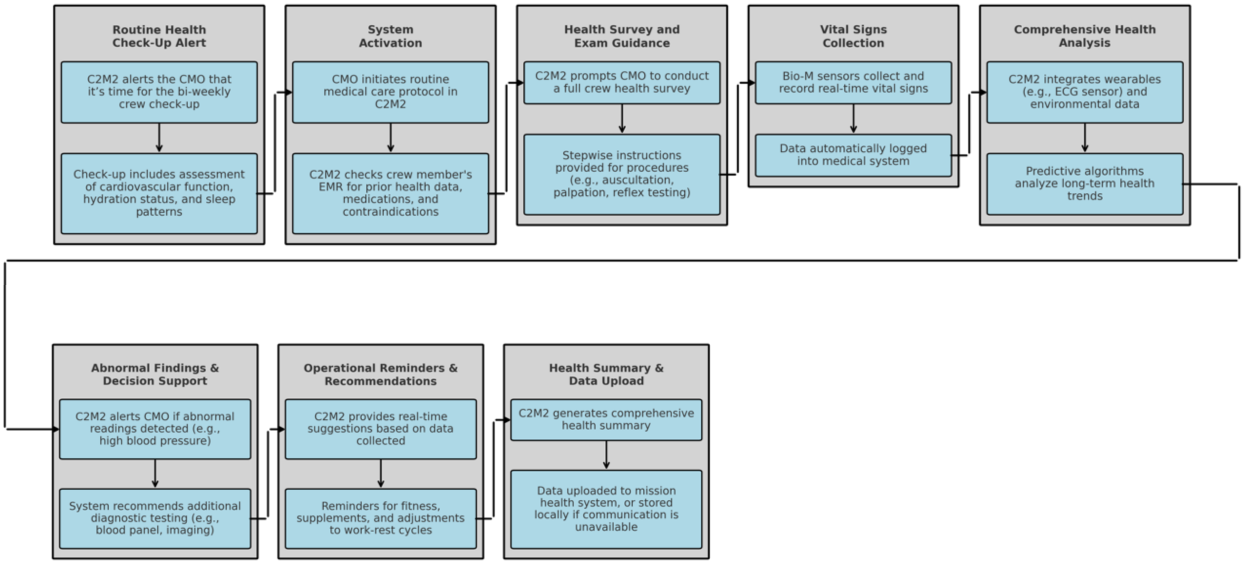

Figure 2: An example routine medical care workflow for a deep-space mission where the C2M2 medical system (MS) supports the medical operations of the crew medical offcier (CMO).

4.1.2 Scenario 2: CMO incapacitation, Unplanned, Directed Care, Autonomous

This scenario evaluates how the C2M2 system can be used to manage a CMO being incapacitated and unable to assist to their own medical assessment during deep-space missions. This is an essential scenario to assess if the system is resilient and adaptive to interaction with a non-medically trained crew member acting without ground support.

During a surface operations phase of a Mars mission (Sol 217), the crew is engaged in equipment maintenance inside the habitat. Suddenly, a crew member notices the CMO seated on the floor, visibly pale and disoriented. When approached, the CMO fails to respond appropriately and loses consciousness. The backup caregiver (CG), a geologist with basic pre-mission medical training, initiates the emergency care protocol through the C2M2 interface mounted on a tablet secured to the wall of the habitat's medbay.

Using biometric authentication, the C2M2 identifies the CG and activates a directed care workflow titled "Altered Mental Status - Unresponsive Patient." The system prompts the CG to place the wearable vital signs monitoring devices on the CMO, and within seconds receives vital signs: hypotension, bradycardia, and oxygen saturation trending downward. The CDSS flags an urgent alert and provides a just-in-time training module guiding the CG to secure the airway, position the patient for optimal perfusion, and begin supplemental oxygen therapy.

As the CG follows audio-visual instructions for airway positioning and IV fluid administration, the C2M2 records each intervention and simultaneously analyzes the CMO's baseline EMR for contraindications or recent health flags. The system recommends an isotonic fluid bolus, calculates the dose, and validates the CG's selection. Meanwhile, the onboard ultrasound unit is pre-calibrated to assess for potential internal bleeding, and the CG is prompted to conduct a focused abdominal sonography guided by AI-assisted imaging overlays.

Within 15 minutes, the CMO regains consciousness. The C2M2 confirms improved vitals and transitions into the post-event stabilization mode, recommending continuous monitoring and guiding the CG through documentation. The full encounter log, ultrasound data, and EMR updates are packaged and queued for transmission to the ground team once communication becomes available. In the meantime, the CDSS provides predictive analytics based on the event trajectory to support follow-up diagnostic plans.

This scenario, illustrated by the flowchart in Figure 3, demonstrates the C2M2's autonomous capacity to manage time-critical care, fulfilling NASA-STD-3001 V13004 (r), (f), and (h) while maintaining compliance with documentation, privacy, and triage standards.

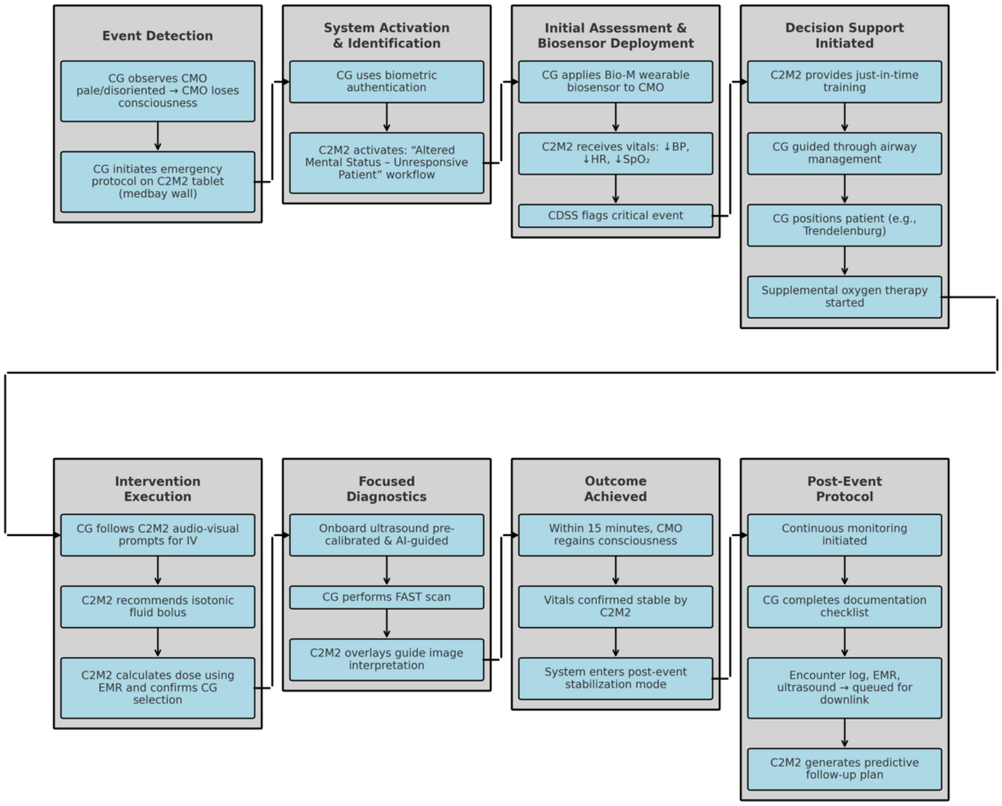

Figure 3: An example emergency medical care workflow for a deep-space mission where the C2M2 medical system (MS) supports the medical operations of the crew (Caregiver, CG) while the crew medical officer (CMO) is incapacitated and cannot conduct the operations themselves.

4.1.3 Scenario 3: Traumatic Injury During Mars EVA, Unplanned, Directed Care, Semi-Autonomous

This scenario evaluates how the C2M2 system can be used to manage trauma scenarios during deep-space missions, where CDSS systems are essential to the trauma workflow of the attending crew operating in an environment with no immediate Earth-based medical support and limited resources.

Sol 126, 1430 local Martian time. A crewmember engaged in geological sampling near the base of a rocky outcrop loses footing and sustains a high-impact fall, resulting in severe lower limb pain and visible suit deformation. The crewmate immediately notifies mission control and the C2M2 via voice command through the EVA suit's communication system.

While the EVA buddy initiates field stabilization, the C2M2, interfaced with wearable biomonitoring sensor's telemetry routed through the suit, detects tachycardia, localized external pressure anomalies, and stress markers. It begins pre-loading trauma checklists and triggers the onboard triage protocol. Upon return to the habitat, the injured crewmember is transferred to the medical bay.

The C2M2 interface prompts the CMO through a focused trauma assessment. Guided by the system, the CMO performs a limb examination and deploys the portable X-ray system. The system assists in localizing the injury and overlays a fracture identification model, confirming a displaced tibial fracture.

Simultaneously, the CDSS recommends ketamine-based sedation and calculates an appropriate dose based on the crewmember's physiological profile. The CMO confirms this on the touchscreen interface. The system then provides step-by-step instructions for splinting, using augmented reality overlays in the HUD. Because the trauma kit inventory is synced with the C2M2, the system cross-checks the availability of all required consumables and warns of low stock of analgesic patches post-application.

Due to the nature of the injury, the CMO requests a delayed ground consultation, which is queued with high-priority transmission flags and pre-populated with the CDSS interpretation, imaging, and intervention logs.

This semi-autonomous scenario, illustrated by the flowchart in Figure 4, fulfills V13004 (e, g, h, i, j, k) and demonstrates real-time clinical triage and stabilization capacity, operationalizing NASA-STD-3001 trauma management requirements in the absence of near-Earth support.

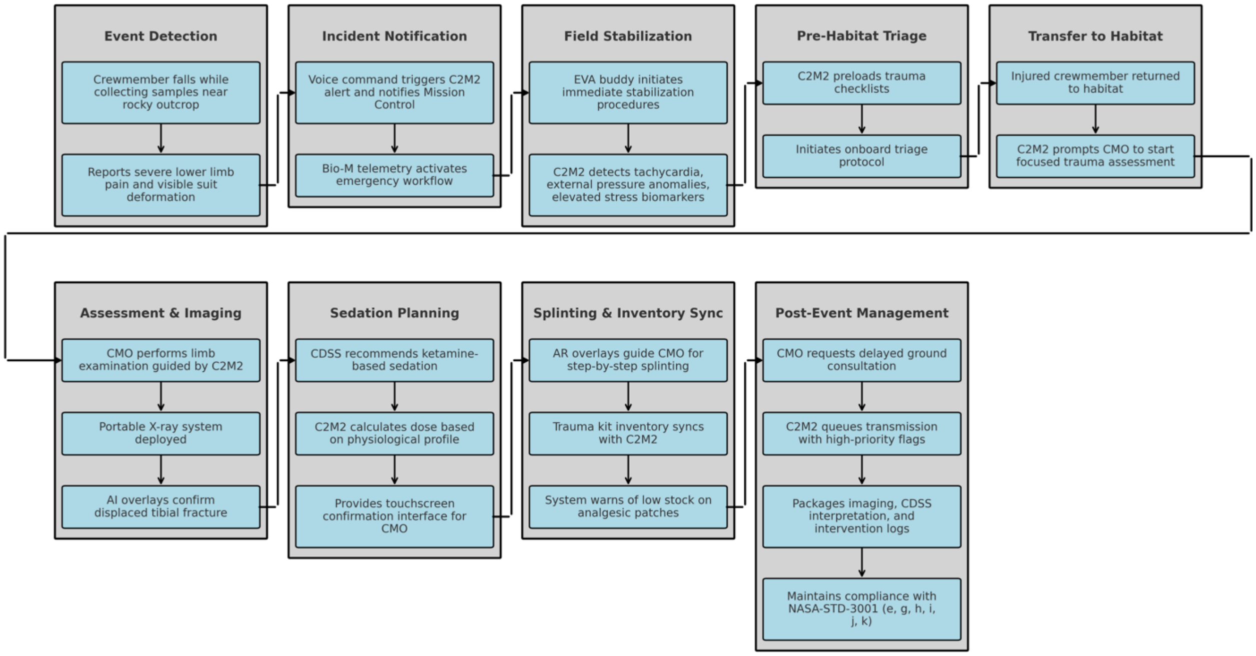

Figure 4: An example emergency medical care workflow for a deep-space mission where the C2M2 medical system (MS) supports the medical operations of the crew medical officer (CMO).

4.2. Long-Term Implications for Space Medical Autonomy

The successful integration of C2M2 in space operations marks a significant leap towards achieving medical autonomy for long-duration missions, particularly for Mars exploration. As mission duration and isolation increase, C2M2's scalability will become essential for both Mars missions and surface operations. The modularity of C2M2 enables it to evolve with the unique needs of Mars habitats, ensuring that astronaut health is maintained without relying on Earth-based intervention. With communication delays of up to 20 minutes one-way, C2M2's autonomous diagnostic and treatment capabilities are critical for ensuring mission success in environments where real-time support is impossible.

Beyond space applications, the expansion of C2M2 for terrestrial remote medical care offers a promising solution for underserved regions on Earth. The system's capacity to function in isolated environments, such as Arctic outposts or remote research stations, makes it a strong candidate for global health challenges, improving access to healthcare where traditional infrastructure is lacking.

However, the widespread implementation of AI-driven healthcare systems, particularly in space, faces challenges in astronaut trust and AI acceptance. Space crew members must place their faith in C2M2's recommendations and decision-making capabilities, particularly in high-stress emergency scenarios. To overcome this, continuous training, transparency in AI decision-making processes, and human oversight will be vital. Ensuring human-AI integration through intuitive interfaces and explainable decision support will be paramount for building trust and ensuring safe, reliable medical care during long-duration missions.

Ultimately, the evolution of C2M2 from a medical tool to a cornerstone of autonomous space medicine highlights its potential to revolutionize both human spaceflight and remote healthcare practices.

6. Conclusion

The C2M2 framework marks a significant advancement in space medical operations, addressing the critical need for autonomous healthcare in deep-space missions. As demonstrated through its integration of artificial intelligence, advanced diagnostic tools, and real-time health monitoring, C2M2 is designed to support astronauts' health management without the reliance on Earth-based oversight, a key challenge for long-duration missions such as those to Mars. This system allows for proactive medical care, with autonomous diagnostic and treatment capabilities, which are essential for managing health events in environments where communication delays are long, and emergency evacuation is not feasible.

The operational success of C2M2 not only prepares space missions for the challenges of deep-space exploration but also sets a precedent for future autonomous medical operations in space. By moving beyond Earth-dependent models of care, C2M2 redefines the concept of space health systems, enabling sustainable human presence on distant planets. As the system is further refined and scaled, it will play an integral role in ensuring the safety and well-being of astronauts during long-duration missions.

The implementation of C2M2 offers significant implications not only for space exploration but also for terrestrial applications in medically isolated healthcare settings. As we continue to refine the system through prototypes and field deployments, the C2M2 framework holds promise for advancing the delivery of medical care in underserved regions on Earth. The combination of autonomous diagnostics, therapeutic decision support, and remote training modules positions C2M2 as a cornerstone for future healthcare solutions, both in space and on Earth.

Moving forward, the continued development and testing of C2M2 will address operational challenges related to AI acceptance and astronaut trust, ensuring the reliability and safety of space medicine in extreme conditions. As humanity embarks on its next great frontier of deep-space exploration, C2M2's role in enabling Earth-independent medical operations will be instrumental in securing astronaut health, reducing mission risk, and advancing healthcare delivery for all.

Acknowledgements

We would like to thank the entire Health Beyond team at the CSA for their invaluable contributions to the development of the C2M2 initiative. Their expertise and collaboration have been essential in advancing space medicine and ensuring the success of this project. Special thanks to all the engineers, researchers, and clinicians in the various contractor's teams whose dedication has made this work possible.

References

[1] L. Gaetan, S. Jérémie, The development and evaluation of an innovative teleoperated medical platform for space applications, *Front. Space Technol.* 1 (2024) 1384457.

[2] D. Hamilton, K. Smart, S. Melton, J.D. Polk, K. Johnson-Throop, Autonomous medical care for exploration class space missions, J. Trauma 64 (2008) S354–S363.

[3] M. Parisi, T. Panontin, S.-c. Wu, K. Mctigue, A. Vera, Effects of communication delay on human spaceflight missions, 14th International Conference on Applied Human Factors and Ergonomics (AHFE), San Francisco, CA, United States, July 20–24, 2023.

[4] L.S. Johnston III, K.T. Smart, J.M. Pattarini, Medical evacuation risk and crew transport, in: Principles of Clinical Medicine for Space Flight, Springer, 2020, pp. 327–353.

[5] H. Kim, Y. Shin, D.-H. Kim, Mechanobiological implications of cancer progression in space, *Front. Cell Dev. Biol.* 9 (2021) 740009.

[6] L.H. Winkler, Human physiological limitations to long-term spaceflight and living in space, *Aerosp. Med. Hum. Perform.* 94 (2023) 444–456.

[7] C. Mani, T.S. Paul, P.M. Archambault, et al., Machine learning workflow for edge computed arrhythmia detection in exploration class missions, *NPJ Microgravity* 10 (2024) 71.

[8] A.C. Stahn, S. Kühn, Brains in space: the importance of understanding the impact of long-duration spaceflight on spatial cognition and its neural circuitry, *Cogn. Process.* 22 (2021) 105–114.

[9] J.I. Pagel, A. Choukèr, Effects of isolation and confinement on humans—implications for manned space explorations, *J. Appl. Physiol.* 120 (2016) 1449–1457.

[10] R.A. Lacinski, J.G. Steller, A. Anderson, A.M. Nelson, Harnessing artificial intelligence for medical diagnosis and treatment during space exploration missions, NASA Technical Reports Server (2023). https://ntrs.nasa.gov/citations/20230009367

[11] R.T. Scott, L.M. Sanders, E.L. Antonsen, J.J.A. Hastings, S.-m. Park, G. Mackintosh, R.J. Reynolds, A.L. Hoarfrost, A. Sawyer, C.S. Greene, B.S. Glicksberg, C.A. Theriot, D.C. Berrios, J. Miller, J. Babdor, R. Barker, S.E. Baranzini, A. Beheshti, S. Chalk, G.M. Delgado-Aparicio, M. Haendel, A.A. Hamid, P. Heller, D. Jamieson, … S.V. Costes, Biomonitoring and precision health in deep space supported by artificial intelligence, *Nat. Mach. Intell.* 5 (2023) 196–207.

[12] B.K. Russell, B.K. Burian, D.C. Hilmers, B.L. Beard, K. Martin, D.L. Pletcher, B. Easter, K. Lehnhardt, D. Levin, The value of a spaceflight clinical decision support system for Earth-independent medical operations, *NPJ Microgravity* 9 (2023) 46.

[13] T. Lindsey, S. Shetye, T. Shaw, Exploration Clinical Decision Support System: Medical Data Architecture, 2016 Human Research Program Investigators' Workshop, Galveston, TX, United States, February 8–11, 2016. NASA Technical Report ARC-E-DAA-TN27913.

[14] B.E. Lewandowski, C.M. Schkurko, R.S. Miller, R.W. Valentine, K.M. Calaway, J.D. Yang, D.J. Ebert, A. Sargsyan, V. Byrne, M. Walton, J. Lemery, R. Suresh, M.S. Thompson, B.D. Easter, K.R. Lehnhardt, Technology modification, development, and demonstrations for future spaceflight medical systems at NASA, *Front. Space Technol.* 5 (2024) 1384457.

[15] R. Uddin, I. Koo, Real-time remote patient monitoring: a review of biosensors integrated with multi-hop IoT systems via cloud connectivity, *Appl. Sci.* 14 (2024) 1876.

[16] C.V. Anikwe, H.F. Nweke, A.C. Ikegwu, C.A. Egwuonwu, F.U. Onu, U.R. Alo, Y.W. Teh, Mobile and wearable sensors for data-driven health monitoring system: state-of-the-art and future prospect, *Expert Syst. Appl.* 202 (2022) 117362.

[17] F.A. Silva, C. Brito, G. Araújo, I. Fé, M. Tyan, J.-W. Lee, T.A. Nguyen, P.R.M. Maciel, Model-driven impact quantification of energy resource redundancy and server rejuvenation on the dependability of medical sensor networks in smart hospitals, *Sensors* 22 (2022) 1595.

[18] K. Khalil, U. Asgher, Y. Ayaz, R. Ahmad, J. Arzola Ruiz, N. Oka, S. Ali, M. Sajid, Cognitive computing for human-machine interaction: an IBM Watson implementation, in: Advances in Neuroergonomics and Cognitive Engineering, AHFE 2020, San Diego, CA, USA, July 16–20, 2020, pp. 400–406.

[19] L.N. Lima, A. Sabino, V. Barbosa, L. Feitosa, C. Brito, J. Araujo, F.A. Silva, Dependability analysis and disaster recovery measures in smart hospital systems, *J. Reliab. Intell. Environ.* 10 (2024) 377–393.

[20] E. Sutjiredjeki, S. Soegijoko, T.L.R. Mengko, S. Tjondronegoro, K. Astami, H.U. Muhammad, S. Suherman, Application of a mobile telemedicine system with multi communication links for disaster reliefs in Indonesia, in: *World Congress on Medical Physics and Biomedical Engineering*, Munich, Germany, September 7–12, 2009, IFMBE Proc. 25/5 (2009) 344–347.

[21] S.E. Phelps, Developing autonomous medical capabilities for exploration spaceflight, NASA Human Research Program, Johnson Space Center, Houston, TX, 26 May 2021. NASA Technical Report 20210015412.

[22] D.A. Vicente, O. Ugochukwu, M.G. Johnston, C. Craft, V. Damin, M.D. Tadlock, Preparing austere maritime surgical teams for deployment during the COVID-19 global pandemic: is it time to change the training pipeline?, *Mil. Med.* 186 (2021) e873–e878.

[23] World Health Organization, *Classification and minimum standards for emergency medical teams*, Technical Document, 18 June 2021, 147 pp. ISBN: 9789240029330. https://www.who.int/publications/i/item/9789240029330

[24] Canadian Space Agency, *Connected Care Medical Module (C2M2)*, Government of Canada, https://www.asc-csa.gc.ca/eng/funding-programs/health-beyond-canadian-flagship-c2m2.asp (accessed 12.03.25).

[25] Canadian Space Agency, *Space investment spin-off to help keep patients healthy on Earth*, News release, Government of Canada, 25 November 2024. https://www.canada.ca/en/space-agency/news/2024/11/space-investment-spin-off-to-help-keep-patients-healthy-on-earth.html (accessed 12.03.25)

[26] Canadian Space Agency, *$600,000 awarded to Canadian companies to advance remote healthcare technologies*, Government of Canada, 11 October 2024. https://www.asc-csa.gc.ca/eng/news/articles/2024/2024-10-11-six-hundred-thousand-dollars-awarded-to-canadian-companies-advance-remote-healthcare-technologies.asp (accessed 28.03.25)

[27] Health Canada, *Pan-Canadian AI for Health (AI4H) Guiding Principles*, Government of Canada, 30 January 2025. https://www.canada.ca/en/health-canada/corporate/transparency/health-agreements/pan-canadian-ai-guiding-principles.html (accessed 28.03.25)

[28] M. Hailey, M. Urbina, D. Reyes, E. Antonsen, *Interpretation of NASA-STD-3001 Levels of Care for Exploration Medical System Development*, NASA/TM-2017-219290, NASA Technical Memorandum, 2017. https://ntrs.nasa.gov/api/citations/20170004345/downloads/20170004345.pdf

[29] National Aeronautics and Space Administration, *NASA Spaceflight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health*, NASA-STD-3001, Volume 2, Revision D, Office of the Chief Health and Medical Officer, 15 September 2023. https://www.nasa.gov/wp-content/uploads/2023/11/nasa-std-3001-vol-2-rev-d-with-signature.pdf

[30] National Aeronautics and Space Administration, *NASA Space Flight Human-System Standard, Volume 1: Crew Health*, NASA-STD-3001, Volume 1, Revision B, 5 January 2022. https://www.nasa.gov/wp-content/uploads/2020/10/2022-01-05_nasa-std-3001_vol.1_rev._b_final_draft_with_signature_010522.pdf

[31] NASA Exploration Medical Capability (ExMC) Element, *Medical System Concept of Operations for Mars Exploration Mission-11*, Human Research Program, HRP 48021, Baseline, April 2019. https://ntrs.nasa.gov/api/citations/20200001715/downloads/20200001715.pdf

[32] National Aeronautics and Space Administration, *Emergency Medical Procedures Manual for the International Space Station (partial)*, released under FOIA, 14 March 2016. https://www.governmentattic.org/19docs/NASA-ISSmedicalEmergManual_2016.pdf

[33] Canadian Space Agency, *Bio-Monitor: Keeping an eye on astronauts' vital signs*, Government of Canada, 20 March 2025. https://www.asc-csa.gc.ca/eng/sciences/bio-monitor.asp (accessed 28.03.25)

[34] National Aeronautics and Space Administration, *Spaceflight Standard Measures: Actigraphy*, Life Sciences Data Archive (LSDA), Johnson Space Center. https://nlsp.nasa.gov/view/lsdapub/lsda_experiment/3a65fc6b-71da-5ce1-b9ef-0d208fbef40e (accessed 28.03.25)

[35] National Aeronautics and Space Administration, *Risk of Adverse Health Outcomes and Decrements in Performance Due to Medical Conditions that occur in Mission, as well as Long Term Health Outcomes Due to Mission Exposures*, Human Research Roadmap, Exploration Medical Capability (ExMC), last updated 31 October 2024. https://humanresearchroadmap.nasa.gov/Risks/risk.aspx?i=95 (accessed 28.03.25)