Selecting Medical Conditions Relevant to Exploration Spaceflight to Create the IMPACT 1.0 Medical Condition List

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INTRODUCTION: Medical conditions occurring in spaceflight pose risks to the crew and the mission and these risks will be exacerbated during exploration-class missions. Probabilistic risk assessment is a method used at NASA to quantify this risk for low-Earth orbit operations. Informing Mission Planning via Analysis of Complex Tradespaces (IMPACT) is a next-generation tool suite that will perform these assessments for exploration-class missions. It will require a robust list of medical conditions of significant likelihood and/or consequence to exploration-class missions to accurately inform the tool suite.

METHODS: The IMPACT 1.0 Medical Condition List (ICL 1.0) contains 120 conditions selected in the context of a 210-d cis-lunar, Mars analog design reference mission. The conditions were selected via a systematic process that preserved institutional knowledge from nine prior condition lists. Conditions were prioritized for inclusion in the ICL 1.0 based on history of occurrence in spaceflight, concurrence among the nine source lists, and concurrence among subject matter experts.

DISCUSSION: The ICL 1.0 has notable advantages over its predecessor lists in that it is more specific to exploration-class missions, contains a greater number, breadth, and depth of conditions, and was derived via consensus across multiple medical specialties.

KEYWORDS: IMPACT 1.0 medical condition list, ICL 1.0, condition list, medical condition, exploration-class mission, long-duration spaceflight, integrated medical model, evidence library.

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Medical conditions occurring in spaceflight can pose risks to the crew and the mission. Constraints of exploration-class spaceflight missions will exacerbate these risks. These constraints include communication delays, lack of resupply, limited or no opportunity for evacuation, restricted mass and volume, and unprecedented mission lengths. To mitigate medical risk posed to the crew and mission, it is necessary for mission planners to first identify medical conditions of significance for exploration-class missions. A spectrum of conditions exists from low likelihood, low consequence, to high likelihood, high consequence. Those of high likelihood or high consequence must be considered for appropriate mission planning. The National Aeronautics and Space Administration (NASA) has produced several lists of spaceflight medical conditions in the past that have been leveraged to create the Informing Mission Planning via Analysis of Complex Tradespaces (IMPACT) 1.0 Medical Condition List.[5] The purpose of this paper is to describe the IMPACT 1.0 Medical Condition List (ICL 1.0), how it was derived, and its application to exploration-class spaceflight missions.

NASA's Integrated Medical Model (IMM) is currently used for medical trade space assessments for the International Space Station (ISS).[2–4] It was the first attempt to apply probabilistic risk assessment (PRA) to medical system design. PRA modeling runs hundreds of thousands of simulated missions to estimate

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risks of crewmembers being afflicted by medical conditions and models subsequent health outcomes. To do so, the model must have a pool of medical conditions from which to select. The IMM was based on a list of 100 medical conditions known as the "IMM Medical Condition List" (IMCL).[2] IMM's successor is IMPACT, a novel tool suite developed by NASA's Human Research Program, Exploration Medical Capability Element, to apply PRA to medical system design for exploration-class missions.[5] During PRA, conditions that affect crewmembers are based on a predetermined spaceflight incidence. The essential elements of the model for each medical condition consist of condition incidence, duration of illness or injury, capabilities and resources deemed necessary for treatment of that condition, probability of the need for escalation of care, probability of mortality resulting from the condition, and impaired ability to perform mission specific tasks due to the condition. These elements are collectively known as the "Evidence Library" (EL). Based on these inputs, the IMPACT model can provide various outputs beyond the scope of this paper which inform resource planning, design, and mission risk. The ICL 1.0 was created in the context of IMPACT and provides the pool of possible medical conditions that may affect crewmembers during the PRA modeling for exploration-class missions.

The ICL 1.0 contains 120 conditions (**Fig. 1**). This limit was established by project leadership as a schedule- and resource-feasible goal for IMPACT version 1.0. The ICL 1.0 development effort occurred under the context of a 210-d mission to cis-lunar space, a design reference mission (DRM) analog for future Mars missions. This mission includes 150–180 d in transit or halo orbit and 30–60 d on the lunar surface, with both transit/orbital and surface operations inclusive of extravehicular activity (EVA). Anticipated crew exposures were based on this DRM to inform included conditions.

METHODS

Evidence Library Team

The Exploration Medical Capability Element (ExMC) of the Human Research Program at NASA's Johnson Space Center in Houston, TX, created the ICL 1.0 for IMPACT. ExMC's EL condition list development team (the "EL Team") represented a collaborative effort inclusive of subject matter experts (SMEs) from the following backgrounds: Physician—Aerospace Medicine, Family Medicine, Internal Medicine, Emergency Medicine, Pain Medicine, Pathology, Physical Medicine and Rehabilitation, Sports Medicine, Wilderness Medicine, and Public Health; Nursing—Registered Nurse, Master of Science in Nursing (emergency nursing, critical

1	Abdominal Wall Hernia	31	Dental Fracture/Exposed Pulp	61	Gravity Well - Entry Motion Sickness	91	Small Bowel Obstruction
2	Abnormal Uterine Bleeding	32	Dental Luxation/Avulsion (Tooth Loss)	62	Gravity Well - Neurovestibular Disturbance	92	Space Adaptation - Back Pain
3	Acute Coronary Syndrome	33	Dislocation - Finger	63	Gravity Well - Orthostatic Intolerance	93	Space Adaptation - Constipation
4	Acute Radiation Syndrome	34	Dislocation - Shoulder	64	Headache	94	Space Adaptation - Epistaxis
5	Allergic Reaction (Mild To Moderate)	35	Diverticulitis, Acute	65	Headache - CO2 Induced	95	Space Adaptation - Headache
6	Altitude Sickness	36	Dust Exposure - Lunar	66	Hearing Loss	96	Space Adaptation - Insomnia
7	Anaphylaxis	37	Ebullism	67	Hearing Loss - Noise-Related	97	Space Adaptation - Nasal Congestion
8	Appendicitis	38	Epistaxis	68	Hemorrhoids	98	Space Adaptation - Space Motion Sickness
9	Arthritis, Acute	39	EVA Related Decompression Sickness	69	Herpes Zoster Reactivation (Shingles)	99	Space Adaptation - Urinary Retention
10	Atrial Fibrillation/ Atrial Flutter	40	EVA Related Dehydration	70	Mouth Ulcer	100	Space Adaptation - Urinary Incontinence
11	Barotrauma (Ear/Sinus Block)	41	EVA Related Fingernail Delamination	71	Nephrolithiasis	101	Spaceflight Associated Neuro-Ocular Syndrome (SANS)
12	Benzodiazepine or Opioid Overdose	42	EVA Related Hand Injury	72	Neuropathy - Central, Impingement Related	102	Sprain/Strain - Back
13	BHP - Adjustment Disorder	43	EVA Related Heat Illness	73	Otitis Externa	103	Sprain/Strain - Lower Extremity
14	BHP - Anxiety	44	EVA Related Paresthesia	74	Otitis Media	104	Sprain/Strain - Neck
15	BHP - Depression	45	EVA Related Shoulder Injury	75	Pancreatitis, Acute	105	Sprain/Strain - Upper Extremity
16	BHP - Grief Reaction	46	EVA Related Suit Contact Injury	76	Pregnancy, First Trimester	106	Streptococcal Pharyngitis
17	BHP - Psychosis Secondary To Depression	47	Eye - Retinal Injury	77	Pregnancy, Risk For	107	Sudden Cardiac Arrest
18	BHP - Sleep Disturbance	48	Eye Foreign Body	78	Prostatitis, Acute	108	Tendinopathy/Enthesopathy/Bursitis/Over-Use Injuries - Lower Extremity
19	BHP - Spaceflight Related Relationship Problems	49	Eye Irritation/Corneal Abrasion/Ulceration	79	Rash, Spaceflight Associated	109	Tendinopathy/Enthesopathy/Bursitis/Over-Use Injuries - Upper Extremity
20	Burn - Chemical Eye	50	Eyelid And Anterior Eye Infection	80	Reactive Airway	110	Toxic Dermal Exposure
21	Burn - Chemical Skin	51	Fracture - Arm	81	Respiratory Failure	111	Toxic Inhalation Exposure
22	Burn - Mild, Thermal	52	Fracture - Cervical Spine	82	Respiratory Tract Infection - Lower	112	Toxic Inhalation Exposure - Combustion Products
23	Burn - Moderate To Severe, Thermal	53	Fracture - Distal Leg	83	Respiratory Tract Infection - Upper	113	Trauma - Abdominal Injury (Blunt)
24	Cerebrovascular Accident	54	Fracture - Femur	84	Seizures	114	Trauma - Chest Injury (Blunt)
25	Cerumen Impaction	55	Fracture - Hand	85	Sepsis	115	Trauma - Minor Head
26	Choking/Obstructed Airway	56	Fracture - Wrist	86	Shock - Cardiogenic	116	Trauma - Severe Head
27	Cholelithiasis/Biliary Colic, Acute	57	Fracture- Thoracic/Lumbar Spine	87	Skin Abrasion	117	Traumatic Hypovolemic Shock
28	Dental Abscess	58	Gastritis/Reflux/Esophagitis	88	Skin Infection - Bacterial	118	Urinary Tract Infection
29	Dental Crown Loss	59	Gastroenteritis/Acute Diarrhea	89	Skin Infection - Viral/Fungal	119	Vaginal Yeast Infection
30	Dental Filling Loss	60	Glaucoma, Acute Angle-Closure	90	Skin Laceration	120	Venous Thromboembolism

Fig. 1. IMPACT 1.0 Medical Condition List (ICL 1.0). BHP: Behavioral Health and Performance; EVA: extravehicular activity.

care, nursing informatics); Epidemiology; Pharmacy; and Clinical Science.

In addition, the EL Team conferred with spaceflight and operational SMEs in the following fields regarding relevant conditions: Obstetrics and Gynecology, Dentistry, Behavioral Health and Performance, Undersea and Hyperbaric Medicine, Extravehicular Activity Physiology, Musculoskeletal Medicine and Rehabilitation, Optometry, Toxicology, and Life Sciences Research. Notably, the Behavioral Health and Performance Element (BHP) at NASA's Johnson Space Center was consulted regarding all behavioral health-related conditions. BHP prioritized eight conditions as candidates for inclusion in the ICL 1.0 and assisted in writing the definitions for these conditions.

Condition List Sources

Multiple groups within NASA are involved in developing systems to support human health in spaceflight. Thus, several spaceflight medical condition lists currently exist within the agency. These lists provide valuable perspective regarding conditions posing medical risk to crew and spaceflight missions. Legacy data from the nine source lists in **Table I** were combined to create a master list of over 400 conditions to leverage this institutional knowledge. A brief description of these lists follows.

The IMCL of 100 medical conditions was the foundation for the ICL 1.0.[2] Conditions from the IMCL that had occurred in spaceflight were considered the highest priority for inclusion. The EL Team supplemented these conditions by performing a pilot project that created four additional unique medical condition lists for exploration-class missions. These included a list of toxic exposures and injuries, common conditions that occurred terrestrially in a population restricted to mimic the demographics of the astronaut corps which was drawn from the Rochester Epidemiology Project database,[7] and two SME-created lists of conditions relevant to spaceflight and exploration-class mission environments. Additionally, the Exploration Medical Condition List was used as a source.[1] This is a condition list that was created to define the set of medical conditions most likely to occur during the following mission profiles: lunar sortie, lunar outpost, and near-Earth asteroid missions. The draft Artemis Phase I: Functional Medical Concept of Operations was also reviewed, and relevant medical conditions were identified. Finally, the Lunar EVA Incapacitation Condition List was drawn from an existing effort at NASA to identify potentially incapacitating events during lunar EVAs.

All unique conditions on the nine sources lists were combined and approximately 30 additional conditions relevant to exploration-class spaceflight were added by SMEs during EL Team meetings. Examples of added conditions include: "Behavioral Health and Performance (BHP)—Grief Reaction," "EVA Related Shoulder Injury," and "Gravity Well—Entry Motion Sickness/Neurovestibular Disturbance." These additions completed the creation of a working "master condition

Table I. Sources Contributing to the IMPACT 1.0 Medical Condition List (ICL 1.0).

CONDITION LIST TITLE	DESCRIPTION
IMM Medical Conditions List (IMCL)[2]	Condition list informing the Integrated Medical Model probabilistic risk assessment trade space assessments for the International Space Station.
IMCL Historical Spaceflight Condition List (Unpublished)	IMCL conditions known to have occurred in flight based on ISS and Shuttle data provided by the NASA Lifetime Surveillance of Astronaut Health[6] repository (this does not include terrestrial-based conditions thought to be related to spaceflight). This list is a subset of the conditions listed in the IMCL.
Evidence Library Pilot Project Toxic Exposures and Injuries Condition List (Unpublished)	Medical (Emergency Medicine, Internal Medicine, Aerospace Medicine) SME-derived list of plausible toxic exposures and injuries during exploration missions.
Evidence Library Pilot Rochester Epidemiology Project (REP) Study Condition List (Unpublished)	The REP is a large, well-known clinical database based in Olmsted County, MN.[7] The REP study performed by ExMC identified an astronaut analog population within the REP database and determined the incidence of conditions in a 3-yr period based on International Classification of Disease (ICD) codes. The resulting 1393 ICD codes corresponding to clinical diagnoses were reviewed to identify medical conditions that could occur in flight for inclusion in the master condition list.
Evidence Library Pilot Project Spaceflight Condition List (Unpublished)	Medical (Emergency Medicine, Internal Medicine, Aerospace Medicine) SME-derived list of conditions that result from human exposure to the spaceflight environment.
The Evidence Library Team Condition List (Unpublished)	SME-derived list of conditions anticipated to occur during an exploration mission. SMEs included members of the EL Team.
Exploration Medical Condition List (EMCL)[1]	Created in June 2013 to define the set of medical conditions most likely to occur during the following mission profiles: lunar sortie, lunar outpost, and near-Earth asteroid. The list was derived from the following sources: 1) ISS Integrated Medical Group Medical Checklist (JSC-48,522); 2) The Flight Data File Medical Checklist (JSC-48,031); 3) In-flight medical incidence data in the Lifetime Surveillance of Astronaut Health[6] repository; and 4) NASA flight surgeon subject matter expertise.
Artemis Phase I: Functional Medical Concept of Operations Condition List (Unpublished)	Relevant conditions drawn from the draft medical concept of operations document for the Artemis Phase I Mission.
Lunar Extravehicular Activity (EVA) Incapacitation Condition List (Unpublished)	A list of conditions that may lead to incapacitation during lunar surface EVAs. This list contained the original IMCL as well as new conditions of concern. Only the new conditions were abstracted for inclusion.

IMPACT: Informing Mission Planning via Analysis of Complex Tradespaces; IMM: Integrated Medical Model; SME: subject matter expert; ExMC: Exploration Medical Capability Element; EL: Evidence Library.

list" (MCL) pool from which the ultimate 120 conditions on the ICL 1.0 were selected.

Concurrence Ranking Across the Source Lists

Every condition was assigned a concurrence ranking. Each source list on which a condition appeared was counted toward that condition's concurrence ranking (i.e., if a condition occurred on five of the nine lists, it received a concurrence ranking of 5). The maximum possible concurrence ranking was a score of 9 and scores spanned from 1–9. All conditions with a concurrence ranking of 3 or higher were discussed to consensus in EL Team meetings. Select conditions with a concurrence ranking of 1 or 2 were also discussed to consensus in EL Team meetings due to potential relevance for the cis-lunar DRM for IMPACT 1.0 (e.g., "EVA-Related Dehydration").

Consensus Evidence Library Team Meeting Approach

All conditions were initially reviewed individually by EL Team SMEs who provided annotations to the Condition List Lead. The Condition List Lead compiled these comments for discussion. The EL Team then met for approximately 25 h of consensus meetings comprised of a minimum of four SMEs. Notably, conditions were created by EL Team consensus during these meetings to fill gaps unaddressed by the original conditions in the MCL. In the event that consensus could not be reached among the EL Team, the ExMC Element Scientist and Deputy Element Scientist were consulted for resolution.

Stratification of Conditions from the Master Condition List

Fig. 2 provides a graphical overview of the process of selecting conditions for the ICL 1.0. The highest priority for inclusion of a condition was prior occurrence in spaceflight. All conditions from the IMCL that had occurred previously in spaceflight were included on the ICL 1.0. The next consideration was concurrence between the nine source lists (Table I). Review of the MCL occurred sequentially during EL Team meetings, starting with conditions with the highest concurrence ranking. If all EL Team SMEs supported inclusion of the condition in the ICL 1.0,

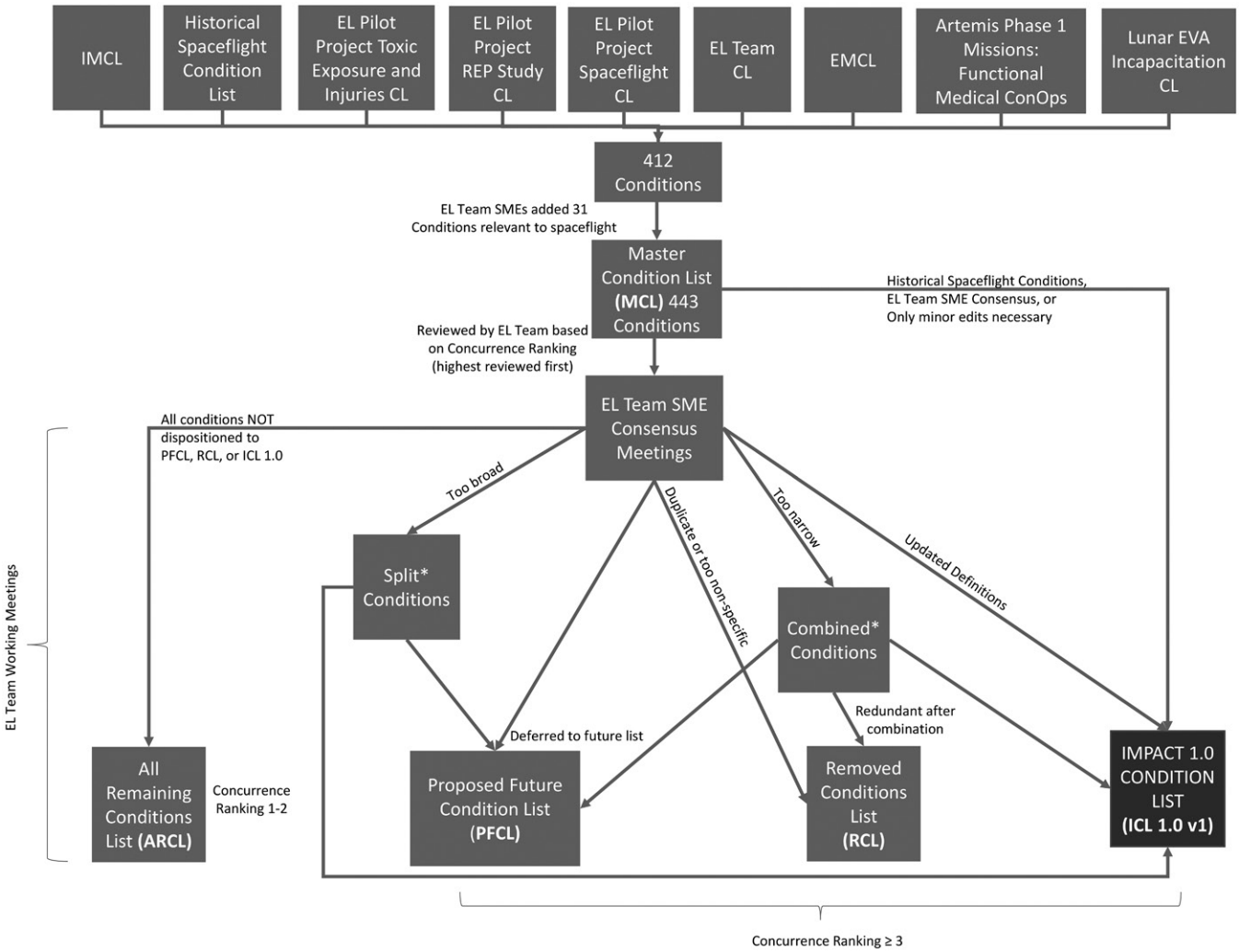

Fig. 2. IMPACT 1.0 Medical Condition List refinement methodology overview. All conditions included in ICL 1.0 had definitions updated. IMCL: IMM Medical Condition List; EL: Evidence Library; CL: condition list; EMCL: Exploration Medical Condition List; ConOps: concept of operations; EVA: extravehicular activity. *Additional conditions added during splitting/combining process.

then the condition was included. If a condition needed only minor edits (e.g., renaming of the condition "Visual Impairment/Intracranial Pressure Syndrome" to reflect the current nomenclature, "Spaceflight-Associated Neuro-ocular Syndrome") and the EL Team otherwise unanimously supported inclusion, then the change was made and the condition was included in the ICL 1.0.

Most conditions required further discussion in EL Team meetings. SME comments primarily encompassed conditions being too broad and requiring further stratification, conditions being too narrow and allowing combination with other relevant conditions, or conditions in need of revised definitions. Conditions accordingly underwent the following changes during EL Team meetings:

1) Definitions of the condition were updated to better match current literature.
2) Broad conditions were split into more granular conditions (e.g., "Abdominal Injury" was divided into two separate conditions, blunt and penetrating abdominal trauma).
3) Similar and/or overlapping conditions were combined into more broad conditions when the EL Team felt it was appropriate based on similarity in medical management or perceived lack of granularity in supporting literature. For example, shoulder, elbow, and wrist sprain/strain were combined into the condition "Upper Extremity Sprains/Strains." (After combination, shoulder, elbow, and wrist sprain/strain were each moved to the "Removed Conditions List").

When the ICL 1.0 reached 117 conditions, the EL Team again reviewed the full list to assess whether any existing conditions should be deferred or any conditions were missing. Two conditions were deferred to the Proposed Future Conditions List, described below, as a result. The condition "Dental Caries" was deferred based on spaceflight operational dentist SME opinion that caries would be unlikely to develop in astronauts during the defined DRM due to their excellent dental hygiene, preflight screening, the 210-d length of the DRM, and the carefully controlled dietary intake during spaceflight missions. The condition "Ovarian Cyst" was deferred based on EL Team SME consensus. After these changes the ICL 1.0 consisted of 115 conditions, leaving room for 5 additional conditions to reach the project goal of 120 conditions. Thus 12 candidate conditions were selected. The final five conditions were identified via majority vote by the EL Team.

Product Condition Lists

During EL Team meetings, three product condition lists were created in addition to the ICL 1.0. Conditions on all product lists were labeled with unique identifiers to allow traceability.

1) Proposed Future Conditions List (PFCL): The PFCL contains conditions that the EL team felt were relevant, but excluded from the ICL 1.0 due to the aforementioned project time and resource constraints. These conditions were felt to be less likely to occur and/or less severe. Many of these conditions have direct relevance for exploration missions, particularly to Mars DRMs. Inclusion of these additional conditions is recommended for future iterations of the ICL.
2) Removed Conditions List: This list contains conditions that were identified as potential candidates during initial list development, but were subsequently removed from consideration because they were addressed by existing ICL 1.0 condition definitions, or they were nonspecific, limiting ability to identify supporting medical literature, obtain incidence data, and assign medical resources (e.g., "Non-specific musculoskeletal pain"). Note that for most of these conditions, similar but more specific conditions were included in the ICL 1.0.
3) All Remaining Conditions List (ARCL): The ARCL contains all conditions that were considered for ICL 1.0, but were not included on any of the aforementioned lists. These conditions should also be considered for inclusion in subsequent iterations of the ICL, but are a lower priority than the PFCL conditions. The ARCL contains only conditions with a concurrence ranking of 1–2.

Conditions Not Explicitly Stated

The ICL 1.0 consists of 120 named conditions, but it should be noted that some condition definitions encompass a spectrum of disease that includes another condition (e.g., "transient ischemic attack" is included in the definition spectrum for "cerebral vascular accident"). These conditions were tracked and are included in the evidence for each condition under the heading "Conditions Included, But Not Explicitly Stated (CNES)." The ICL 1.0 contains 123 CNES (**Fig. 3**).

Internal Review and Versioning

After the completion of ICL 1.0 version 1, three SMEs reviewed the list and provided comments regarding condition definitions. Changes were made to incorporate their comments in version 1. These SMEs were an astronaut physician and two operational flight surgeons from the NASA Johnson Space Center.

During the process of data collection for the Evidence Library (condition incidence, duration, treatment capabilities and resources, probability of need for escalation of care, probability of mortality resulting from the condition, and impaired ability to perform mission specific tasks due to the condition), several changes were made to the ICL 1.0. Three conditions were removed. The conditions "Cold Injury—Chilblains/Frostbite" and "Hypothermia" were removed because of the paucity of data related to spaceflight incidence, dependence of cold injury on mission phase, and significant operational and engineering mitigations resulting in any cold injury being expected to result in the loss of the crew. The condition "Vertebral Disc Disorder" was also removed because all published cases of in-flight back pain during U.S. spaceflight were captured by other conditions ("Sprain/Strain—Back" and "Space Adaptation—Back Pain"). Therefore, there was no added value of including "Vertebral Disc Disorder" in the ICL 1.0.

Three conditions were added to again bring the total number of conditions on the current ICL 1.0 final version to 120.

1	Acute Hypovolemia	32	Eye - Retinal Burn	63	Gastrointestinal bleed (upper)	94	LRI - Pneumonia, Bacterial
2	Angina, Unstable	33	Eye - Retinal Tear	64	Gastrointestinal Ulcer - Duodenal	95	URI- Pharyngitis, Non-strep
3	Arthropathy, acute - crystalline	34	Eye - Ruptured Globe	65	Gastrointestinal Ulcer - Gastric	96	URI- Rhinitis, Acute
4	Back Pain, Acute Low	35	Eye - Scleral Laceration	66	Hearing Loss - Conductive	97	URI- Sinusitis, Acute
5	Back Pain, Chronic Low	36	Eye -Retinal Detachment	67	Hearing loss - Sensorineural	98	Shock - Anaphylactic
6	BHP - Adjustment Reaction	37	Fecal Impaction	68	High Altitude Cerebral Edema	99	Shock - Sepsis
7	BHP - Apathy	38	Finger tendon injury	69	High Altitude Headache	100	Shoulder - Labral Tear
8	BHP - Circadian Rhythm-Sleep Wake Disorders	39	Folliculitis	70	High Altitude Pulmonary Edema	101	Sprain - Finger
9	BHP - Grief, Complicated	40	Fracture - Capitate	71	Impetigo	102	Sprain/Strain – Achille's tendon injury
10	BHP - Insomnia	41	Fracture - Finger	72	Intracranial Bleed (Non-surgical)	103	Sprain/Strain - Ankle
11	BHP - Irritability	42	Fracture - Hamate	73	Intracranial Hematoma, Epidural	104	Sprain/Strain - Elbow
12	BHP - Low Motivation	43	Fracture - Humerus	74	Intracranial Hematoma, Subdural	105	Sprain/Strain - Foot
13	BHP - Mood Disturbance	44	Fracture - Knee	75	Menorrhagia	106	Sprain/Strain - Hip
14	BHP - Panic Symptoms	45	Fracture - LE Stress	76	Menses, Irregular	107	Sprain/Strain - Knee
15	Cellulitis	46	Fracture - Lunate	77	Myocardial Infarction	108	Sprain/Strain - Medial gastrocnemius muscle strain
16	Cholecystitis	47	Fracture - Metacarpal	78	Neuropathy - Brachial plexus injury	109	Sprain/Strain - Shoulder
17	Concussion	48	Fracture - Pilon	79	Neuropathy - Lateral femoral cutaneous nerve entrapment	110	Sprain/Strain - Wrist
18	Deep Vein Thrombosis	49	Fracture - Pisiform	80	Neuropathy - Pain related to nerve root impingement/disc herniation	111	Status Epilepticus
19	Diffuse Axonal Injury	50	Fracture - Proximal Fibular	81	Neuropathy - Sciatica/piriformis syndrome	112	Toxic Inhalation Exposure - Carbon Monoxide poisoning
20	Dust Exposure (Lunar) - Pneumonitis	51	Fracture - Radius (excluding radial head)	82	Onycholysis	113	Toxic Inhalation Exposure - Cyanide Poisoning
21	Erysipelas	52	Fracture - Scaphoid	83	Osteoarthritis, acute	114	Toxic Inhalation Exposure - Hydrocarbons
22	Erythrasma	53	Fracture - Thumb	84	Oval Window Rupture	115	Toxic Inhalation Exposure - Sulfur Dioxide
23	EVA related - Contusions	54	Fracture - Tibial Shaft	85	Peritonsillar Abscess	116	Toxic Inhalation Exposure -Nitrogen Dioxide
24	EVA Related - Heat cramps	55	Fracture - Trapezium	86	Post-Concussive Syndrome	117	Transient Ischemic Attack
25	EVA Related - Heat Exhaustion	56	Fracture - Trapezoid	87	Prostatic Abscess	118	Trauma (Blunt) - Hemomediastinum
26	EVA Related - Heat Stroke	57	Fracture - Triquetrum	88	Pulmonary Embolism	119	Trauma (Blunt) - Hemopericardium
27	EVA related - Skin blister	58	Fracture - Ulna (non-olecranon)	89	Pyelonephritis	120	Trauma (Blunt) - Hemothorax
28	EVA related - Skin Chaffing	59	Fracture- Elbow (radial head/ supracondylar / olecranon)	90	Respiratory Distress Syndrome, Acute	121	Trauma (Blunt) - Mesenteric Injury
29	Eye - Corneal Laceration	60	Furuncles	91	LRI - Bronchitis, Viral	122	Trauma (Blunt) - Peritonitis
30	Eye - Dry Eyes	61	Gastroesophageal Reflux Disease	92	LRI - Coronavirus	123	Traumatic Brain Injury
31	Eye - Hyphema	62	Gastrointestinal - Indigestion	93	LRI - Influenza		

Fig. 3. Conditions included, but not explicitly stated (CNES) in the condition title on the ICL 1.0. LE: lower extremity; LRI: lower respiratory infection; URI: upper respiratory infection.

"BHP—Spaceflight Related Relationship Problems" narrowly missed being included in the first version of the ICL 1.0. When "Vertebral Disc Disorder" was removed, this condition was added. "Gravity-Well—Entry Motion Sickness" was initially included in the condition definition spectrum with another condition, "Gravity Well—Neurovestibular Disturbance." While gathering the evidence for the condition, it was determined that it was not possible to combine entry motion sickness and neurovestibular disturbance into one condition. Thus, the conditions were split. Finally, "Pregnancy, First Trimester" was added to the ICL 1.0 to augment the existing condition, "Pregnancy, Risk For." The current version of the ICL 1.0 is listed in Fig. 1.

DISCUSSION

The Exploration Medical Capability Element of NASA's Human Research Program is designing IMPACT, a next-generation tool suite that will be used to apply probabilistic risk assessment to medical system design for exploration-class spaceflight missions. The model relies on a list of medical conditions of significant likelihood and/or consequence to these missions. The IMPACT 1.0 Medical Condition List (ICL 1.0) provides these conditions.

The ICL 1.0, designed specifically for exploration-class missions, has notable enhancements as compared to the predecessor list used for probabilistic risk assessment related to low-Earth orbit missions on the International Space Station. First, it was created for a 210-d cis-lunar Mars analog DRM, which is more applicable to exploration-class missions. Second, the ICL 1.0 contains 120 conditions, a 20% increase from its predecessor. In addition to these named conditions, within the condition definitions it includes an additional 123 "Conditions Not Explicitly Stated," expanding the breadth of the list. Third, the ICL 1.0 includes more EVA-related and Behavioral Health and Performance related conditions than its predecessor. It also includes dust exposure and gravity-well conditions that will be specific to exploration-class missions. These additions further enhance the depth and relevance of this list for exploration spaceflight. Fourth, the process used nine existing source condition lists drawing on existing institutional knowledge. History of condition occurrence in spaceflight and concurrence among these source lists carried the highest weighting for condition inclusion. Fifth, condition definitions were updated to make a more discrete connection with necessary in-flight diagnostic and treatment capabilities, as well as making the definitions more closely aligned with reported evidence used for risk

estimation. Sixth, the conditions included on the ICL 1.0 were selected via consensus from ExMC's Evidence Library Team. The EL Team is comprised of a diverse background of medical specialties and additional expertise was sought in many spaceflight specific areas such as Behavioral Health and Performance and EVA-related concerns. Lastly, the final list was independently reviewed by operational flight surgeons and a physician astronaut not involved in the original selection process. This interdisciplinary expertise enhanced the quality of conditions and the breadth of their associated definitions.

Limitations

The ICL 1.0 is limited to 120 conditions. This number was selected to keep the initial data collection within budget and schedule constraints. While it does not capture all medical conditions anticipated in future exploration missions, it is comprised of conditions with a suspected significant likelihood of occurrence or mission consequence. Future iterations should expand the conditions and associated evidence to further define medical risk in the exploration spaceflight environment.

The ICL 1.0 is limited to medical conditions known to researchers, but there are "unknown unknowns," including the risk of conditions that have yet to occur during spaceflight. Increasing mission durations beyond 1 yr—the current maximum experience for human spaceflight—will result in diminished ability to conduct routine medical surveillance and risk mitigation. This may result in novel incidence or increased incidence of conditions that would otherwise be identified and mitigated preflight. Insight into novel spaceflight medical conditions is provided by continued spaceflight experience and vigilance in the aerospace medicine community. Recognition of such "new" conditions or disease processes should drive future iterations of the ICL 1.0.

Condition definitions are assumed to be mutually exclusive but pose the possibility of overlap. This is particularly true with Behavioral Health and Performance conditions. This may affect the incidence and outcomes related to overlapping conditions during PRA.

Common side effects of frequently used pharmaceuticals have not been considered in the ICL 1.0. A more extensive formulary is anticipated to be carried onboard during exploration missions. It is likely that more undesirable medication side effects will be encountered. Serious side effects from medications are recommended to be considered for inclusion in future versions of the ICL 1.0, along with appropriate treatment resourcing. This is also true for complications of diagnostic or therapeutic procedures.

Hematologic and metabolic analysis diagnostic tools are being actively investigated for use in exploration missions. While these are excellent for nonspecific complaints (e.g., fatigue), they pose a dilemma when abnormal values are encountered. Incidental findings such as thrombocytopenia, anemia, hyperkalemia, hyponatremia, and others may occur during routine testing. It is recommended that consideration be given to adding some of the more common and consequential of these incidental diagnostic findings to the ICL 1.0 in the future.

Conclusions

The IMPACT 1.0 Medical Condition List (ICL 1.0), developed by the Exploration Medical Capability Element of NASA's Human Research Program, will serve as the foundation for applying probabilistic risk assessment to medical system design for exploration-class missions. This list of 120 named medical conditions, encompassing an additional 123 medical conditions within the condition definitions (CNES), was developed systematically using nine condition source lists. It represents the most comprehensive condition list developed for exploration-class missions.

Future efforts should expand upon this list. Given the ever-increasing body of knowledge of Aerospace Medicine, the "Proposed Future Conditions List" and the "All Remaining Conditions List" will need to be periodically reviewed and updated. Input from operational SMEs should drive consideration for inclusion of additional conditions or updates to existing conditions. Refinement of future condition lists should consider the relative priority of condition types (e.g., adequately balancing musculoskeletal conditions vs. EVA-related conditions vs. Behavioral Health and Performance conditions). Definitions should be created and modified as necessary so that conditions are mutually exclusive, thereby reducing "double counting" of medical events and allowing for accurate representation of their incidence. As humans gain more experience with exploration-class missions, novel conditions in spaceflight should be added to this list. Associated evidence, such as condition incidence, duration, treatment capabilities and resources, probability of need for escalation of care, probability of mortality resulting from the condition, and impaired ability to perform mission specific tasks due to the condition, should be modified accordingly. Models that have been developed to predict the incidence of medical conditions can be validated or refined using flight experience. Finally, future iterations of this list should consider including more chronic conditions as these conditions are anticipated to be more common with longer, exploration-class missions.

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REFERENCES

1. Canga MA, Shah RV, Mindock JA, Antonsen EL. A strategic approach to medical care for exploration missions [Conference Paper]. In: 67th International Astronautical Congress (IAC 2016). Making space accessible and affordable to all countries; 2016 Sept. 26–30; Guadalajara, Mexico. [Accessed 9 February 2023]. Available from https://ntrs.nasa.gov/citations/20160011168.
2. Keenan A, Young M, Saile L, Walton M, Kerstman E, et al. The Integrated Medical Model: a probabilistic simulation model predicting in-flight medical risks [Conference Paper]. In: 45th International Conference on Environmental Systems (ICES); 2015 July 12–15; Bellevue, WA, USA. [Accessed 9 February 2023]. Available from https://ntrs.nasa.gov/citations/20150018879.
3. Kerstman E. Qualitative validation of the IMM model for ISS and STS Programs [Presentation]. In: NASA Human Research Program Investigators' Workshop (HRP IWS); 2016 Feb. 8; Galveston, TX, USA. [Accessed 9 Feb. 2023]. Available from https://ntrs.nasa.gov/citations/20170007276.
4. Kerstman E. The Integrated Medical Model: a risk assessment and decision support tool for space flight medical systems [Presentation]. In: 81st Annual Scientific Meeting of the Aerospace Medicine Association; 2010 May 12; Phoenix, AZ, USA. [Accessed 9 Feb. 2023]. Available from https://ntrs.nasa.gov/citations/20100023129.
5. Lumpkins S, Amador J, McGuire K, Urbina M, Thompson W, et al. Human Research Program: IMPACT concept of operations. Houston (TX): Johnson Space Center, National Aeronautics and Space Administration; 2019. Report No.: HRP-48020. [Accessed 9 Feb. 2023]. Available from https://ntrs.nasa.gov/api/citations/20200001712/downloads/20200001712.pdf?attachment=true.
6. NASA. Lifetime surveillance of astronaut health. [Accessed 20 June 2023]. Available from https://nlsp.nasa.gov/explore/lsdahome/lsahhome.
7. Rochester Epidemiology Project. [Accessed 19 May 2022]. Available from https://rochesterproject.org/.

Erratum

Strand T-E, Lystrup N, Martinussen M. *Under-reporting of self-reported medical conditions in aviation: a cross-sectional survey*. Aerosp Med Hum Perform. 2022; 93(4):376–383.

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In the above article, the authors made an error in the Results section, p. 380, right-hand column, last paragraph (incorrect words are struck through; correct words are bolded). The sentence should read: "Among the 1436 respondents with complete data for all variables, we found it ~~more~~ **less** likely that private pilots (MC 2) and ATCOs (MC 3) under-reported medical conditions compared to commercial pilots based on the logistic regression analysis (Table I)."

Further, in the next sentence on p. 381, it should read: "The results also indicated that individuals scoring high on the two scales assessing the AME as supportive (Scale 1) ~~rather than~~ **or** authoritative (Scale 2) were less likely to underreport (Table I)."

The authors apologize for these mistakes.