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Downselection of Miniature X-Ray System for Spaceflight Applications

Ariel E. Tokarz and Jerry G. Myers
Glenn Research Center, Cleveland, Ohio

Chase A. Haddix
Universities Space Research Association, Washington, DC

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Hampton, VA 23681-2199

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Ariel E. Tokarz and Jerry G. Myers
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Chase A. Haddix
Universities Space Research Association
Washington, DC 20024

Executive Summary

The inclusion of a handheld, portable x-ray system is hypothesized to improve the management of crew health during long-duration spaceflight missions. A ground demonstration was performed with three such miniature x-ray systems to determine the full capabilities of the technology within the context of a spaceflight environment and to evaluate its suitability for flight certification. Criteria developed during this demonstration were used to select the most suitable system to recommend for flight. The scope of the demonstration was defined with input from NASA flight surgeons, engineers, and operations experts. This scope was intentionally broad to support the identification of both clinical and nonclinical applications of the system and also to establish evaluation criteria for recommending the most appropriate system for a future flight demonstration. Considerations within scope included x-ray hardware design, clinical diagnostic capability, engineering failure analysis, and in-space science applications. The ground demonstration identified many distinct selection criteria to quantify these applications. These selection criteria were then condensed to 20 key figures of merit, allowing for uniform comparison between criteria and strong comprehension of the study by stakeholders. System scores for each figure of merit were obtained from ground demonstration data. Project stakeholders used pairwise rating to weight figures of merit by relative importance for different mission profiles (a space-station demonstration mission and a long-duration mission to Mars). The top system was then determined by summing the weighted scores for each system under consideration. The resulting recommendation for a portable x-ray system to include in spaceflight missions is robust to variations in scoring and weighting of the figures of merit. Rather than recommending the system with the smallest mass and volume, this process recommends the x-ray system that provides the most clinical capability. This highlights the impact of using pairwise weighting to support decision making in a trade study with many complex criteria. Stakeholder weighting identifies the most important decision-making criteria for the system under evaluation, concluding the ground demonstration effort with a recommendation of the portable x-ray system hypothesized to best improve health management and to reduce the most risk during a long-duration spaceflight mission.

1.0 Introduction

As human spaceflight ventures further from Earth, mission success and crewmember health will depend on the inclusion of advanced, versatile, and usable medical equipment. Medical systems that address hazards anticipated during spaceflight, such as reduced real-time guidance from mission support on Earth or increased risk of bone fracture following gravity transitions, will be vital to mission success. Medical imaging, such as sonography, enables quick and accurate diagnosis in space. The incorporation of an x-ray system into spaceflight operations is hypothesized to further improve management of crew health. In addition, an x-ray system will provide a unique imaging tool for engineering and science applications.

The inclusion of an x-ray system in spaceflight medical operations has been under consideration since the design of the Freedom Space Station in the 1980s (Ref. 1). The Health Maintenance Facility for this station included a diagnostic radiographic imaging system for x-ray image acquisition and downlink (Ref. 2). However, the x-ray technology of the 1980s, much like standard hospital x-ray systems used today, exceed mass, volume, and power capabilities of spaceflight. Technological advancements since then have led to the production of miniature (i.e., handheld and portable) x-ray systems.

X-ray systems consist of an x-ray generator and a flat-panel detector operated by an associated imaging capture and processing software. The detector is independent of the x-ray generator; it is possible to use the hardware in any combination of generator + detector. Miniature x-ray systems currently employ panel detectors of the same size as traditional hospital systems. However, the generators are small and mobile (5 to 30 lb and 3 to 21 L, Ref. 3) with reduced radiation production capacity and increased internal shielding, allowing for the safe acquisition of x-ray images while held by the operator.

The Exploration Medical Integrated Product Team (XMIPT) at NASA Glenn Research Center (GRC) performed a comprehensive ground demonstration to determine the full capabilities of mini x-ray systems from three different vendors within the context of a spaceflight environment. The team also evaluated the suitability of the systems for flight certification. Criteria developed during the ground demonstration were used to select the most suitable system from nine combinations of generator + detector.

Relative significance of the figures of merit (FOMs) was defined by project stakeholders and engineers through pairwise weighting. For each combination of generator + detector, the weighted sum of scores was used to identify the mini x-ray systems best suited for spaceflight applications. This summary report describes the downselect process, including scoring rationale and a weighting method used to recommend a portable x-ray system for flight demonstration.

2.0 Process

2.1 Define Scope

The ground demonstration of the mini x-ray systems performed by GRC included imaging of many different subjects across clinical, engineering, and science applications. Clinical applications were informed by flight doctors at NASA, and nonclinical applications were identified by previous use cases in literature (e.g., extravehicular activity (EVA) spacesuits, Ref. 4 and geology, Ref. 5) or through an internal NASA crowd-sourced Spark campaign (e.g., 3D-printed plastic parts and welded joints). Various applications comprising the scope of the ground demonstration are provided in Table I. The scope was intentionally broad, as the stated goals of the demonstration were to (1) determine the full capabilities of the x-ray system within a spaceflight context, including nonclinical applications, and (2) establish evaluation criteria to recommend the most appropriate system among candidates. While exploring the potential clinical and nonclinical use cases, subject matter experts from across NASA and partner institutions were consulted.

TABLE I.—INITIAL SCOPE OF MINI X-RAY SYSTEM GROUND DEMONSTRATION

System design	Medical diagnostics	Failure analysis	Science
Mass, volume, and power	Medical imaging	EVA suits	Geology
Image quality	Bone mineral density	Lunar rover	Botany
Training and operation	Dentistry	Electronics	
Radiation dose		Plastic parts	
		Welded joints	

Throughout the ground demonstration, 114 individual characteristics were generated. These characteristics comprehensively describe intrinsic properties of the x-ray system (mass, volume, power, manufacturing data), hardware and software features, system usability, durability and flight qualification potential, image quality, diagnostic capability, and use in engineering analysis, geology, and botany applications. Table II provides each characteristic, grouped into general categories. Data gathered during the ground demonstration were assigned to each characteristic for initial system evaluation.

2.2 Condense Scope

The 114 characteristics were condensed into 20 key FOMs, following the categories determined during the initial definition process. The key FOMs integrate these characteristics and the data associated with each with the intent that no information defined in the initial scope is excluded from the decision-making process. A definition for each used FOM is provided in Table II, which also lists the evidence from the ground study or manufacturer information used to inform the score.

Condensing the FOMs means there are less distinct items that must be evaluated, weighted, and compared. This allows for a strong comprehension of the study scope by stakeholders and supports uniform weighting across each FOM.

TABLE II.—MINI X-RAY TRADE STUDY FIGURE OF MERIT EXPLANATION AND ASSOCIATED EVIDENCE

FOM	Characteristics	Explanation
Mass of mini x-ray system is <10 kg	Mass of generator system Mass of generator battery charger Mass of detector, including battery Mass of detector battery charging station	10 kg was identified by a risk-assessment tool evaluation as the effective mass of medical capability that is displaced by the mini x-ray device at 1 in 20 loss of crew life odds per mission. Mass is determined as a sum of the generator, detector, and necessary battery charging equipment.
Volume of x-ray system is <14 L	Volume of generator system Volume of generator battery charging station Volume of detector Volume of detector battery charging station	Volume is determined as the sum of the generator, detector, and necessary battery-charging equipment volumes. Note that each system is <20 L.
Sufficient battery life for system components within mission vehicle	Generator number of means for powered operation Generator battery life Generator battery charge time Detector number of means for powered operation Detector battery life Detector battery charge time Removability of generator battery	Having sufficient battery life means that the system can take multiple images without needing to be plugged in during an imaging session (i.e., the battery life is sufficient for a full test session). This number of images is associated with the target medical conditions that the system should contribute to treating (maximum of 18 for dental full-mouth series x-ray-, minimum of 2 to 3 for clinical evaluation).
No issues requiring waiver or device modification to meet flight certification testing	Concerns with cleaning or disinfecting device Previous use in austere environments Fragile materials and containment Ability to operate in Exploration Atmosphere Electric shock risk Touch temperature Ambient noise	Concerns or high-risk items for flight certification and operation in the spaceflight environment are identified in this FOM. Driving evidence considered for this FOM includes manufacturer's cautions against shock (or intense vibration), the risk of electric shock from the system, and the system's ability to operate in a low-pressure high-O_2 environment.

TABLE II.—MINI X-RAY TRADE STUDY FIGURE OF MERIT EXPLANATION AND ASSOCIATED EVIDENCE

FOM	Characteristics	Explanation
	Hardware modifications SSP 30234 Noncritical designation Contains liquids Convection cooling needed Soft-stowage-capable for launch? Vibration and shock testing Electromagnetic interference testing	
System has Food and Drug Administration (FDA) regulatory approval for extremities		May be handheld or stand mounted.
System has FDA regulatory approval for head and abdomen locations		May be handheld or stand mounted.
System has FDA regulatory approval for dental applications		The FDA separately considers full-body and dental radiographic applications. The generators considered by the reported trade study are full-body devices; for this reason, no generator considered in this report has FDA approval for dental x-rays.
System Technology Readiness Level (TRL) ≥6		Each hardware component was assigned a TRL on the scale 0 to 9. This FOM is binary to match the binary nature of the trade study; TRL 6 was chosen as the cutoff because it is the inflection point for spaceflight heritage.
Diagnostically sufficient commercial off-the-shelf (COTS) software can be flight certified	Ability to install postprocessing software on any laptop Compatible with planned health data platforms Software operating system Experience working with manufacturer Export as export as standard file types Software ability to annotate images	This FOM is an indication of whether the COTS software associated with the system is expected to integrate into a flight computer or exploration mission medical system to allow for in-mission diagnostics to be performed.
System enables the capture of diagnostically sufficient images	Training and guidance in software General software navigability and user experience Software ability to load externally acquired image files Software can review multiple images at once X-ray image modifications (brightness, contrast, window leveling, and sharpness) Software usability score Ability to collimate Inclusion of exposure index or sensitivity number Radiography test tool quality indicators: line pair resolution consistent homogeneity, dynamic range, and background noise	This FOM is a measure of the system (hardware and software) usability as well as the inclusion of any interpretation aides or setup and procedure guidance that would enable clinical exposures and diagnostics during exploration missions. Driving evidence considered for this FOM include the inclusion of collimators on the generator, the inclusion of an exposure index or sensitivity number, and the quality of calibration images.
System likely to be diagnostically sufficient for hand and ankle conditions expected in mission		These FOM correspond to the proven capability of the system to provide quality images at positions associated with spaceflight-relevant injuries. Scores were determined from the ability of x-ray novices to obtain
System likely to be diagnostically sufficient for chest conditions expected in mission		

TABLE II.—MINI X-RAY TRADE STUDY FIGURE OF MERIT EXPLANATION AND ASSOCIATED EVIDENCE

FOM	Characteristics	Explanation
System likely to be diagnostically sufficient for pelvic conditions expected in mission		quality images at these locations and from any hardware limitations (i.e., the lack of a collimator) that hinder the acquisition of diagnostic images at a given location. Separate scores for multiple views also allows for highlighting the importance of evidence of one imaging location over another.
System likely to be diagnostically sufficient for spine conditions expected in mission		
System likely to be diagnostically sufficient for arm, leg, and long bone conditions expected in mission		
System is capable of dual-energy x-ray absorptiometry (DXA) at locations that can characterize space flight bone loss		The manufacturers for all systems in this study are developing software which use postprocessing to obtain a measure similar to DXA. However, they are not available for purchase or clinically proven, and all use different locations in the upper body for diagnosis; software is not considered evidence that the system is DXA capable.
Dental x-ray capable	Ease of use (generator) Evidence of dental bone identification Evidence of dental pulp canal identification Evidence of dental dentin identification Evidence of dental enamel identification Evidence of imaging interproximal spaces	This FOM considers the ability to identify different elements a dental technologist (or dentist) looks for in a dental x-ray. In addition, any changes to the generator position required to obtain a diagnostic image at a given location (i.e., the usability of the system) is considered.
Sufficient to support general engineering inspection and failure analysis	Identification of broken pins Identification of frayed wires Ability to trace wire routing Characterize configuration of a connection Characterize system status Quality and usability	Evidence that a system is sufficient to support inspection and failure analysis includes the ability to identify the internal configuration of an object (e.g., to identify broken pins in an electrical connection or any blockage in tubing) and the ability to characterize the state of an object (e.g., to identify tears or cracks).
Sufficient to support triage of acquired geological samples	Contrast sensitivity and differentiation between minerals Detail and clarity for porosity Identification of embedded materials of different density Ability to meaningfully image internal features Ability to meaningfully image surface features Subject matter expert feedback	For this study, triage of geology samples includes consideration of contrast sensitivity between minerals, characterization of sample porosity, and the imaging of internal features.
Sufficient to support low-gravity plant growth activities	Rating for root structure Rating for contrast Rating for visibility Rating for clarity	Low-gravity plant growth encompasses both plant research and the imaging of plants used for mission support (e.g., food supply). Evidence contributing to this FOM includes the ability to image root structure and the clarity of internal plant structures.

2.3 Obtain Scores and Weights

After FOMs were defined, scores and weights were assigned to each. Scores are the technical evaluations of the ability of each generator + detector combination to meet a FOM. For each combination listed in Table I the FOMs were assigned a score of 2 (“Yes or highly likely”), 1 (“Possible or likely with additional information or effort”), or 0 (“No or unlikely”). The scores were informed by the data gathered during the ground demonstration.

Further details of the scores are provided in Section 3.0, “Scoring Description.”

Weights are the relative importance of each FOM for a mission application. A pairwise weighting process was used to define the weights for each FOM. Six unique weighting profiles were defined by project stakeholders from the XMIPT leadership (“XMIPT” profiles), engineers from Sierra Lobo Inc. (SLI) with flight project experience (“SLI” profiles), and XIMPT engineers involved with device testing (“GRC” profiles). The weights for an International Space Station (ISS) technology demonstration and operational use during Mars mission were assigned separately.

Further detail of the weighting process is provided in Section 4.0, “Weighting Process.”

2.4 Determine Top Systems

For each FOM, the scores were multiplied by the weight. The resulting weighted scores were then summed for each generator + detector combination. Each system can achieve a maximum weighted score of 2. The weighted scores determined for each system were averaged across the six weighting profiles. Finally, the systems were ranked according to the average score, with the highest score ranked first (1) and the lowest score ranked last (9).

The rankings were determined for both an ISS and a Mars mission, using the unique weights provided for each mission by the evaluators. Table III shows the results with ISS weights, and Table IV shows the results with Mars weights. The top three ranking systems are shared between mission profile results.

TABLE III.—SYSTEM WEIGHTED SCORES AND RANKS, ISS RESULTS[a]

Weighting profile	Final weighted scores (max. possible = 2)											
XMIPT1	1.3876	1.0078	1.1705	1.1318	1.3333	1.3023	1.1318	1.3798	1.3488	1.0310	1.0543	0.8295
XMIPT2	1.5105	1.1579	1.2605	1.1632	1.3263	1.2658	1.1632	1.3711	1.3105	1.1816	1.1579	0.9368
SL1	1.3125	0.9167	1.0625	1.1250	1.3438	1.2917	1.1250	1.3542	1.3021	0.9896	1.0625	0.8229
SL2	1.6272	1.2130	1.2840	1.0473	1.2189	1.1302	1.0473	1.2781	1.1893	1.2485	1.2544	1.0059
GRC1	1.5974	1.2368	1.2868	1.1132	1.2895	1.2289	1.1132	1.3105	1.2500	1.1553	1.1553	0.9737
GRC2	1.3684	0.8737	1.0026	1.1079	1.3421	1.2553	1.1079	1.3763	1.2895	1.0895	1.1316	0.9079
Average	1.4673	1.0676	1.1778	1.1147	1.3090	1.2457	1.1147	1.3450	1.2817	1.1159	1.1360	0.9128
	Final ranking											
XMIPT1	1	11	6	7	4	5	7	2	3	10	9	12
XMIPT2	1	11	6	8	3	5	8	2	4	7	10	12
SL1	3	11	8	6	2	5	6	1	4	10	8	12
SL2	1	7	2	10	6	9	10	3	8	5	4	12
GRC1	1	6	4	10	3	7	10	2	5	8	8	12
GRC2	2	12	10	7	3	5	7	1	4	9	6	11
Average	1	11	6	9	3	5	9	2	4	8	7	12

[a]Final weighted scores and corresponding final ranking, determined from six weighting profiles, are presented for each generator + detector combination.

TABLE IV.—SYSTEM WEIGHTED SCORES AND RANKS, MARS RESULTS

Weighting profile	Final weighted scores (max. possible = 2)											
XMIPT1	1.4755	1.0385	1.1294	1.1503	1.2832	1.2517	1.1503	1.3287	1.2972	1.2168	1.2238	1.0315
XMIPT2	1.5053	1.1447	1.2289	1.1789	1.3474	1.2737	1.1789	1.3789	1.3053	1.1921	1.1763	0.9447
SL1	1.2917	0.8125	0.9792	1.1667	1.2917	1.2813	1.1667	1.3750	1.3646	1.1458	1.1146	0.9063
SL2	1.4734	1.0828	1.1538	1.1420	1.3077	1.2249	1.1420	1.3609	1.2781	1.1420	1.1598	0.9112
GRC1	1.5816	1.2237	1.2711	1.1000	1.2763	1.2158	1.1000	1.2947	1.2342	1.1500	1.1526	0.9711
GRC2	1.3947	0.9211	1.0395	1.1368	1.3289	1.2711	1.1368	1.3684	1.3105	1.1395	1.1579	0.9421
Average	1.4537	1.0372	1.1336	1.1458	1.3059	1.2531	1.1458	1.3511	1.2983	1.1644	1.1642	0.9511
	Final ranking											
XMIPT1	1	11	10	8	4	5	8	2	3	7	6	12
XMIPT2	1	11	6	8	3	5	8	2	4	7	10	12
SL1	3	12	10	6	4	5	6	1	2	8	9	11
SL2	1	11	7	8	3	5	8	2	4	8	6	12
GRC1	1	6	4	10	3	7	10	2	5	9	8	12
GRC2	1	12	10	8	3	5	8	2	4	7	6	11
Average	1	11	10	8	3	5	8	2	4	6	7	12

[a]Final weighted scores and corresponding final ranking, determined from six weighting profiles, are presented for each generator + detector combination.

3.0 Scoring Description

For each generator + detector combination, a score indicating the ability of the system and associated software to answer the FOM was assigned. These scores use the data gathered during the ground demonstration to evaluate the hardware, image quality, and usability of each system.

A score of 2, 1, or 0 was independently assigned to each FOM by two members of the XMIPT at GRC. The scores were then discussed by the entire engineering team and iterated until consensus was reached. Table V provides a description for the 0, 1, or 2 score as it relates to each FOM. These descriptions were determined using the evidence gathered during the ground study and from the manufacturers (see Table II).

TABLE V.—SCORING DETAILS FOR EACH MINI X-RAY SYSTEM TRADE STUDY FIGURE OF MERIT

FOM	Scoring details
Mass of mini x-ray system is <10 kg	2: System mass is <10 kg 0: System mass is >10 kg
Volume of x-ray system is <14 L	2: The system volume is <14 L 0: The system volume is >14 L
Sufficient battery life for system components within mission vehicle	2: Battery life for generator or detector allows for completion of full imaging session. 1: Low battery life for generator or detector means system must be plugged in during an imaging session. 0: Battery life for generator or detector is insufficient for evaluation, and system can only be battery powered.
No issues requiring waiver or device modification to meet flight certification testing	2: No concerns with obtaining flight certification for hardware. 1: Hazardous battery; must evaluate system's ability to operate in low-pressure high-O_2 environment. 0: Concerns from score 1 as well as increased risk of detector electrical shock or failure when exposed to launch loads.
System has FDA regulatory approval for extremities	2: Has FDA approval for indicated use. 0: Does not have FDA approval for indicated use.
System has FDA regulatory approval for head and abdomen locations	2: Has FDA approval for indicated use. 0: Does not have FDA approval for indicated use.
System has FDA regulatory approval for dental applications	2: Has FDA approval for indicated use. 0: Does not have FDA approval for indicated use.
System TRL level ≥6	2: Hardware TRL is ≥6. 0: Hardware TRL is <6.
Diagnostically sufficient COTS Software can be flight certified	All systems are assigned score of 2, since it is anticipated that flight-certifying COTS software will not be issue, as long as software is contained on dedicated laptop.
System enables capture of diagnostically sufficient images	2: System is user friendly and enables acquisition of diagnostic images. 1: System captures high quality exposures, but software has low usability; or source does not have collimation and thus decreases quality of images (scatter is increased). 0: Software does not have EI or S number and thus is not diagnostically sufficient.
System likely to be diagnostically sufficient for hand and ankle conditions expected in mission	2: System is likely to be diagnostically sufficient for this view. 1: Generator lacks features (i.e., collimation), which results in system being less likely to be diagnostically sufficient for this view. 0: System cannot capture diagnostically sufficient exposures for this view.
System likely to be diagnostically sufficient for chest conditions expected in mission	2: System is likely to be diagnostically sufficient for this view. 1: Generator does not produce high technique required for this view. 0: System cannot capture diagnostically sufficient exposures for this view.
System likely to be diagnostically sufficient for pelvic conditions expected in mission	2: System is likely to be diagnostically sufficient for this view. 1: Generator does not produce high technique required for this view. 0: System cannot capture diagnostically sufficient exposures for this view.
System likely to be diagnostically sufficient for spine conditions expected in mission	2: System is likely to be diagnostically sufficient for this view. 1: Generator lacks features (i.e., collimation), which results in system being less likely to be diagnostically sufficient for this view; or software postprocessing for spine views produced poor images. 0: System cannot capture diagnostically sufficient exposures for this view.
System likely to be diagnostically sufficient for arm, leg, and long bone conditions expected in mission	2: System is likely to be diagnostically sufficient for this view. 0: System cannot capture diagnostically sufficient exposures for this view.

TABLE V.—SCORING DETAILS FOR EACH MINI X-RAY SYSTEM TRADE STUDY FIGURE OF MERIT

FOM	Scoring details
System is DXA capable at locations that can characterize space flight bone loss	2: System is DXA capable at spaceflight-relevant locations. 1: Detector has multiple scintillating layers of hardware that provide evidence for DXA capability. 0: System has no evidence of DXA capability at spaceflight relevant locations.
Dental FMX capable	2: Generator is easy to use and produces high-quality dental exposures. 1: Generator is not easy to use or produces only passable dental exposures. 0: System cannot capture dental images.
Sufficient to support general engineering inspection and failure analysis	2: System captures high-quality images (detail), detects multiple energy levels, or has high-energy-exposure capability (penetration). 1: System has evidence for engineering applications, but further investigation of usable space is required. 0: Poor image quality means system is unable to support engineering applications.
Sufficient to support triage of acquired geological samples	2: System captures high-quality images that characterize features of interest for geology. 1: System has evidence for geology applications, but further investigation of usable space is required. 0: Poor image quality means the system is unable to support geology triage.
Sufficient to support low-gravity plant growth activities	2: System captures high-quality images that characterize features of interest for botany. 1: System has evidence for botany applications, but further investigation of usable space is required. 0: Poor image quality means the system is unable to support botany applications.

4.0 Weighting Process

Multi-criteria decision making (MCDM) (Ref. 6) or analysis (MCDA) is a domain of practice aimed at determining the best alternative by considering more than one criterion in a selection process. The most well-known subjective weighting process is that of Analytical Hierarchical Process (AHP) decision making, introduced by Saaty in 1977, and subsequently improved through 1995. The AHP process utilizes a form of pairwise comparison that decomposes a decision into its constitutive parts (i.e., criteria), creates weightings and hierarchies from one-to-one comparisons and normalization of the criteria, and generates ranking of alternative choices by their evaluation with the weighted (or ranked) criteria.

AHP can be somewhat difficult to apply, especially when decision makers have difficulty with weighting a large number of criteria (>10) on a wide scale of relative importance scale (typically in the comparison, the winner is scored on a scale of 1 to 9 for relative importance, while the loser is scored on the reciprocal; i.e., 1/winner score). To simplify the MCDM approach in this analysis, a common form of pairwise ranking analysis is modified to estimate the weights to apply to each of the criteria alternatives.

Pairwise comparison in this MCDM application is carried out using a pair comparison matrix (PCM), sometimes called a paired matrix. The weighting estimate adopts a modified win-rate approach, where each cell is evaluated as 0 if the row criterion is less important than the corresponding column criterion, 0.5 if the row and column criteria are considered equal, and 1 if the row criterion is considered to be of higher importance. The diagonal is not scored, although by convention it is often represented as a 1 to allow matrix operations. Note that the matrix is consistent across the diagonal, with both the corresponding row and column and the column and row locations having the sum of 1. Further, the matrix is assumed to follow the principle of transitivity, which indicates that if option A is relatively more important than B, and B is relatively more important than C, then it can be assumed A is relatively more important than C. An example PCM is shown in Table VI.

TABLE VI.—EXAMPLE PAIR COMPARISON MATRIX WITH RANKING AND WEIGHTS

	Criterion 1	Criterion 2	Criterion *N*	Sum score	Rank	Weight
Criterion 1	NA	0.5	1	1.5	1	1.5/3
Criterion 2	0.5	NA	0	0.5	3	0.5/3
Criterion 3	0	1	NA	1	2	1/3

Each of the 20 FOM's were evaluated in this manner by six individuals: two from the XMIPT leadership with medical or space medical device backgrounds, two from Sierra Lobo Inc. (SLI) with flight project experience with inbuilt and COTS flight equipment, and two from the XMIPT at GRC involved with the testing and evaluation of the mini x-ray devices. Everyone completed two evaluations: the first considered the importance of the criteria should the mini x-ray device be planned for an ISS-based technology demonstration mission, and the second focused on the use of the mini x-ray device as an operational tool for a potential Mars mission. Table VII illustrates a completed PCM in Microsoft® Excel® for an ISS Technology Demonstration Mission. Note only the lower diagonal needed to be populated by the evaluators, as the upper diagonal was automatically populated from the symmetry with lower diagonal evaluations.

Criteria for Table VII:

1. Mass of mini x-ray system less than 2× GE US System (~10 kg)
2. Volume of x-ray system less than ~2× GE US system (~14 L)
3. Sufficient battery life for system components within mission vehicle
4. No issues requiring waiver or device modification to meet flight certification testing
5. System has regulatory approval (FDA) for extremities
6. System has regulatory approval (FDA) for head and abdomen locations
7. System has regulatory approval (FDA) for dental applications
8. System TRL ≥ 6
9. Diagnostically sufficient COTS software can be flight certified
10. System enables the capture of diagnostically sufficient images
11. System likely to be diagnostically sufficient for hand and ankle conditions expected in mission
12. System likely to be diagnostically sufficient for chest conditions expected in mission
13. System likely to be diagnostically sufficient for pelvic conditions expected in mission
14. System likely to be diagnostically sufficient for spine conditions expected in mission
15. System likely to be diagnostically sufficient for arm, leg, and long-bone conditions expected in mission
16. System is DXA capable at locations that can characterize space flight bone loss
17. Dental FMX capable
18. Sufficient to support general engineering inspection and failure analysis
19. Sufficient to support triage of acquired geological samples
20. Sufficient to support scientific and maintenance evaluation of low-gravity plant growth

The final weighting from each evaluator's PCM is presented in Table VIII. The table illustrates a shift in priorities of the FOM between mission profiles as is expected.

TABLE VII.—REPRESENTATIVE COMPLETED PCM FOR ISS TECHNOLOGY DEMONSTRATION MISSION[a]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Sum (row)	Rank	Weight
1		0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0	6.00	15.00	0.0316
2	1.0		1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0	7.00	13.00	0.0368
3	0.0	0.0		0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0	5.00	16.00	0.0263
4	1.0	1.0	1.0		1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	1.0	1.0	13.00	7.00	0.0684
5	1.0	1.0	1.0	0.0		1.0	1.0	0.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	9.50	9.00	0.0500
6	1.0	1.0	1.0	0.0	0.0		1.0	0.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	8.50	10.00	0.0447
7	1.0	1.0	1.0	0.0	0.0	0.0		0.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	6.50	14.00	0.0342
8	1.0	1.0	1.0	0.0	0.5	0.5	0.5		1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.5	8.50	10.00	0.0447
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.5	0.0	0.0	0.0	0.0	0.0	1.0	0.5	1.0	0.5	3.50	18.00	0.0184
10	1.0	1.0	1.0	0.0	1.0	1.0	1.0	0.0	1.0		0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	14.00	6.00	0.0737
11	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5		0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0	16.00	5.00	0.0842
12	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5		0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0	16.50	1.00	0.0868
13	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5		0.5	0.5	1.0	1.0	1.0	1.0	1.0	16.50	1.00	0.0868
14	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5		0.5	1.0	1.0	1.0	1.0	1.0	16.50	1.00	0.0868
15	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5		1.0	1.0	1.0	1.0	1.0	16.50	1.00	0.0868
16	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0		0.0	1.0	1.0	1.0	8.50	10.00	0.0447
17	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0		1.0	1.0	1.0	12.00	8.00	0.0632
18	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1.0	1.0	4.00	17.00	0.0211
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.00	20.00	0.0000
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0		2.00	19.00	0.0105

[a]0.0 = Row criterion is less important than column criterion.
0.5 = Row and column criteria are equal.
1.0 = Row criterion is more important than column criterion.

TABLE VIII.—FINAL WEIGHTS ESTIMATED FROM PCM MCDM FROM ALL EVALUATORS[a] AND TWO MISSION PROFILES
[Weights are presented in percentages, and each column sums to 100%.]

	ISS							Mars						
	XMIPT1	XMIPT2	SL1	SL2	GRC1	GRC2	Average	XMIPT1	XMIPT2	SL1	SL2	GRC1	GRC2	Average
1	8.91%	6.05%	8.33%	0.00%	3.16%	8.42%	5.81%	6.64%	6.32%	10.94%	0.00%	3.16%	8.42%	5.91%
2	8.91%	6.05%	9.38%	0.59%	3.68%	10.00%	6.44%	6.64%	6.32%	10.94%	10.65%	3.68%	10.00%	8.04%
3	0.78%	1.32%	6.25%	6.51%	2.63%	3.16%	3.44%	0.70%	1.58%	5.21%	5.92%	2.63%	2.11%	3.02%
4	7.75%	2.89%	10.42%	3.55%	6.84%	9.47%	6.82%	2.45%	2.37%	4.17%	2.96%	6.84%	6.58%	4.23%
5	6.98%	6.32%	4.17%	1.78%	5.00%	0.00%	4.04%	2.80%	5.79%	1.04%	1.18%	4.47%	0.53%	2.64%
6	6.20%	5.00%	4.17%	1.78%	4.47%	2.11%	3.95%	2.10%	4.21%	1.04%	1.18%	4.47%	2.63%	2.61%
7	0.00%	5.00%	4.17%	1.78%	3.42%	0.53%	2.48%	0.00%	3.95%	1.04%	1.18%	4.21%	0.53%	1.82%
8	1.55%	2.89%	2.08%	3.55%	4.47%	7.11%	3.61%	8.74%	3.68%	7.29%	2.96%	4.47%	7.63%	5.80%
9	2.33%	1.05%	11.46%	3.55%	1.84%	8.16%	4.73%	8.74%	1.05%	8.33%	2.96%	1.84%	8.16%	5.18%
10	10.08%	8.68%	2.50%	11.24%	7.37%	8.42%	9.72%	8.39%	8.68%	12.50%	11.24%	7.37%	8.95%	9.52%
11	5.43%	9.21%	3.13%	7.10%	8.42%	3.95%	6.21%	5.59%	9.21%	3.13%	6.51%	8.42%	4.47%	6.22%
12	5.43%	9.21%	3.13%	7.10%	8.68%	6.05%	6.60%	5.59%	9.47%	3.13%	6.51%	8.68%	6.58%	6.66%
13	5.43%	6.58%	3.13%	7.10%	8.68%	5.53%	6.07%	5.59%	7.63%	3.13%	6.51%	8.68%	5.79%	6.22%
14	5.43%	4.47%	3.13%	7.10%	8.68%	5.26%	5.68%	5.59%	4.21%	3.13%	6.51%	8.68%	5.53%	5.61%
15	5.43%	9.21%	3.13%	7.10%	8.68%	3.68%	6.21%	5.59%	8.95%	3.13%	6.51%	8.68%	3.68%	6.09%
16	5.43%	5.00%	3.13%	7.10%	4.47%	6.58%	5.28%	5.59%	6.32%	3.13%	6.51%	4.47%	5.26%	5.21%
17	2.33%	5.53%	3.13%	7.10%	6.32%	5.53%	4.99%	7.69%	6.05%	3.13%	6.51%	6.32%	6.05%	5.96%
18	4.65%	4.47%	1.04%	5.92%	2.11%	3.42%	3.60%	4.55%	3.16%	8.33%	5.33%	1.84%	3.95%	4.53%
19	3.88%	0.79%	0.00%	5.33%	0.00%	1.58%	1.93%	3.85%	0.53%	0.00%	4.73%	0.00%	1.58%	1.78%
20	3.10%	0.26%	4.17%	4.73%	1.05%	1.05%	2.39%	3.15%	0.53%	7.29%	4.14%	1.05%	1.58%	2.96%

[a]XMIPT = XMIPT evaluators, SL = Sierra Lobo, Inc., evaluators, GRC = GRC XMIPT evaluators, and Average = average of all six evaluators for each mission profile.

Weighted scoring for each of the nine mini x-ray configurations was obtained using the estimated weights from each evaluator's completed PCM in the equation

$$Weighted\ score_{evaluator} = \sum_{FOM=1}^{20} Weight_{FOM} * Unweighted\ score_{FOM}$$

with a possible maximum weight score of 2 based on the criteria scoring scale. In addition to each individual evaluator's weights, a combined weight vector was created by averaging the FOM weight of all evaluators for each of the mission profiles.

5.0 Discussion

Using data from the ground demonstration performed at GRC, 20 FOMs were defined to characterize the suitability of mini x-ray systems (generator + detector combinations) for spaceflight applications. These FOMs integrate 114 detailed characteristics, which informed a score of 2 (“Yes or highly likely”), 1 (“Possible or likely with additional information or effort”), or 0 (“No or unlikely”) for each FOM for each combination. Two pairwise weighting profiles, considering use in an ISS technology demonstration mission and operational use in a Mars mission, were generated for each FOM by six evaluators, including project stakeholders and engineers. For each generator + detector combination, these weights were multiplied with the final scores for each FOM, and the results were summed. The system combinations were then ranked from 1 (highest sum of weighted scores) to 9 (lowest sum of weighted scores) for an ISS mission and a Mars mission.

The same top three systems were identified for each mission profile, and the result is robust to variations in weighting and in scoring. The first and second ranked systems are identified in these positions by all evaluators for both ISS and Mars missions. Twelve of the fourteen weighting profiles (including averages) identify the top three unweighted scorers as the top three weighted scores. Of the fourteen evaluations (including the averages): ten choose the top three in order of the unweighted score, two choose them with a slightly shifted order (usually switching 1 and 2), one drops the lowest top three, and one chooses the top unweighted scorer as the top weighted scorer while the remaining two top unweighted sums drop to third and seventh place, respectively. Altogether, this indicates that small changes to weights are unlikely to change the recommendation of this study.

At odds with the expected result, the top-ranking systems (Table IX) do not have the smallest mass and volume. The first ranked system, in fact, combines the heaviest generator with one of the heavier detectors. This result highlights the impact of using PCM MCDM to support decision making in a trade study with many complex criteria. Using pairwise comparison weighting, the FOM “System enables the capture of diagnostically sufficient images” was identified as the most important decision-making criterion for an x-ray system in either an ISS or a Mars mission. Although volume was the second most important criterion, the mass of the system was ranked 7th.

TABLE IX.—TOP-WEIGHTED FOMS ESTIMATED FROM PCM MCDM
FROM ALL EVALUATORS AND TWO MISSION PROFILES

Rank	FOM
1	System enables the capture of diagnostically sufficient images.
2	Volume of x-ray system is less than 14 L.
3	System is likely to be diagnostically sufficient for chest conditions expected in mission.
4–6	*… three other clinical diagnostic FOMs …*
7	Mass of x-ray system is less than 10 kg.

6.0 Conclusions

Through the development of detailed system characteristics, figures of merit of importance to the mission, and a pairwise evaluation from project stakeholders, the Exploration Medical Integrated Product Team (XMIPT) at NASA Glenn Research Center identified a strong candidate portable x-ray system to recommend for inclusion in future spaceflight missions. The scoring process produces a trade study result which is robust to small changes in individual scores or weights, increasing confidence in the recommended result.

The definition and weighting of figures of merit (FOMs) relevant to the mission and system under consideration also allow for clarity on the most important criteria for hardware suitability. This clarity helps to define a well-scoped, feasible, and relevant spaceflight demonstration.

The process is easy to apply to new hardware, which is important when evaluating hardware in such a dynamic industry as medical equipment. Any new mini x-ray system may be evaluated using the criteria defined by the ground demonstration, weighted using the pairwise weights defined by project stakeholders, and compared with previously evaluated systems to identify whether the new hardware is more or less suited for spaceflight applications.

Other systems may be evaluated by following the defined process. The identification of hardware characteristics and FOMs pertinent to the use case allow the viable solutions to be scoped. Utilizing pairwise evaluation of these FOMs incorporates engineering knowledge and stakeholder priorities in the decision-making process, ensuring the result meets success criteria for both the project and scientific objectives. New hardware may be evaluated against the same criteria, directly comparing potential new solutions with current systems. Finally, as the criteria for evaluation are defined for the desired solution, the process may be utilized across use cases from hospitals on Earth to future missions to Mars.

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