X-Ray Imaging in the Simulated Microgravity Environment of Parabolic Flight

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INTRODUCTION: The advancement of human spaceflight has made urgent the need to develop medical imaging technology to ensure a high level of in-flight care. To date, only ultrasound has been used in spaceflight. Radiography has multiple advantages over ultrasound, including lower operator dependence, more rapid acquisition, typically higher spatial resolution, and characterization of tissue with acoustic impedance precluding ultrasound. This proof-of-concept work demonstrates for the first time the feasibility of performing human radiographs in microgravity.

METHODS: Radiographs of a phantom and human subject's hand, knee, chest, cervical spine, and pelvis were obtained aboard a parabolic flight in microgravity and simulated lunar gravity with various subject and operator positions. Control radiographs were acquired with the same system on the ground. These radiographs were performed with a Food and Drug Administration-approved ultra-portable, wireless, battery-powered, digital x-ray system.

RESULTS: The radiographs of the phantom acquired in reduced gravity were qualitatively and quantitatively compared to the ground controls and found to exhibit similar diagnostic adequacy. There was no statistically significant difference in contrast resolution or spatial resolution with a spatial resolution across all imaging environments up to the Nyquist frequency of 3.6 line-pairs/mm and an average contrast-to-noise ratio of 2.44.

DISCUSSION: As mass, power, and volume limitations lessen over the coming decades and the miniaturization of imaging equipment continues, in-flight implementation of nonsonographic modalities will become practical. Given the demonstrated ease of use and satisfactory image quality, portable radiography is ready to be the new frontier of space medical imaging.

KEYWORDS: radiography, space radiology, x-ray, diagnostic imaging.

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Human spaceflight has advanced rapidly in scope and frequency, with the successful completion of the first Artemis mission, the continued success of the Commercial Crew Program, and the advent of private spaceflights from multiple providers. Both national and commercial spaceflight programs promise additional milestones over the next two decades, including the development of space stations in both Earth and lunar orbits, a permanent return to the Moon, and eventual landings on Mars. As humankind begins to venture further into space and the population living in microgravity or on extraterrestrial surfaces increases, the risk of medical and surgical emergencies also increases. Because crew injury and illness can threaten the success of the mission and the life of the individual, accurate and timely diagnosis and treatment of medical events is an area of significant concern for NASA and its government and private partners. However, there are significant limitations to the equipment and skill set available in spaceflight for the performance of these tasks due to constraints in space, power, mass, and training time, among others, necessitating optimization of the available crew healthcare delivery system.[16]

As in the terrestrial environment, imaging is central to medical diagnostics in spaceflight. Diagnostic ultrasound was first

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used 40 yr ago aboard Soviet spacecraft and has continued to act as the workhorse for in-flight medical imaging, with two iterations of multiprobe ultrasound systems flown aboard the International Space Station (ISS) and, more recently, a hand-held single-probe whole-body unit aboard both the ISS and a commercial flight.[2,16] These units have been used both autonomously and with remote guidance and have been used in the evaluation of nearly every major organ system, including lung, cardiac, vascular, bowel, renal, bladder, spinal, and ocular ultrasound, among others.[4,5,13] Ultrasound has been used for research and diagnostic purposes but has also been proposed for future use in interventional guidance.[8–10] However, other than optical coherence tomography, no additional medical imaging modalities have been used for research or clinical purposes in spaceflight.

While ultrasound is versatile, portable, and free of ionizing radiation, it is not without limitations, including its operator dependence and limited acoustic windows. As a result, other advanced imaging modalities have been proposed for future use in spaceflight.[3,7] Foremost among these modalities is radiography, which possesses numerous advantages, including relatively low radiation dose, numerous potential applications, low power consumption, small size, and increasing portability.[11] There are multiple medical conditions of concern in spaceflight for which diagnostic radiography would prove superior or complementary to ultrasound, including but not limited to dental disease, spine/musculoskeletal trauma, inhalational injury, pneumothorax, and arthritis. However, no urgent use case for radiography in low Earth orbit has yet necessitated a technical demonstration of this modality in spaceflight. As a first step toward developing this capability, this article describes the methodology and results of the first-ever radiographs of a human subject in microgravity via the use of ultra-portable diagnostic x-ray imaging.

METHODS

Selection of a commercial off-the-shelf, Food and Drug Administration-approved, ultra-portable, wireless digital x-ray system was performed (Impact Wireless, Complete Battery-Powered Portable Digital Radiography System, MinXray, Inc., Northbrook, IL, United States). The selection was based on availability, portability, prior Food and Drug Administration approval, off-the-shelf capability, and having already undergone systems impact testing, including vibrational, temperature, altitude simulation, shock, external short circuit, and overcharge testing. The battery-powered x-ray generator (TR90BH) used by the selected system measures 21.9 × 19 × 44.0 cm and has a mass of 7.7 kg. The battery that powers this TR90BH generator is a custom-built rechargeable Li-ion battery M910BL with specifications of 57.6V, 1700 mAh, 97.92 Wh. It is charged using a custom pin block charger with an AC adaptor. Approximately 100 to 400 exposures per charge can be obtained with this unit depending on the output technique used. The CsI wireless image receptor measures 38.4 × 46.0 × 1.5 cm with a mass of 3.7 kg, an active area of 35.6 × 42.7 cm, and a pixel size of 0.140 × 0.140 mm. During on-the-ground testing and protocol development, a torso-harness system was created for securing the x-ray generator to the operator to stabilize the TR90BH during flight while maximizing targeting capability. The harness features a metal plate that is mounted to the back of the generator, allowing the generator to be secured to a heavy-duty, hinged arm designed for videography equipment.

Prior to flight, the two technicians who acted as x-ray generator operator and receiver operator/anatomic target rehearsed the protocol for 48 h. During this preflight testing phase, the TR90BH generator, harness system, and positioning relative to the hand-held receptor were tested, along with the associated laptop computer and imaging software. For this testing, an x-ray line phantom was secured with medical tape directly onto the surface of the imaging receptor. Radiographs of the line phantom were then obtained to act as terrestrial gravity (1 G) control images.

Next, this imaging system was flown on a parabolic research flight aboard a modified Boeing 727 operated by ZeroG Incorporated (Exploration Park, FL, United States). The parabolic research flight consisted of six sets of parabolas with five parabolas in each for a total of 30 parabolas. In terms of the variable gravity fields experienced during the flight, lunar gravity (1/6 G) was created during the first three parabolas. The remaining 27 parabolas were microgravity (0 G) exposures between 20 and 30 s in length. Only images of the line phantom were obtained during the limited lunar gravity parabolas (**Fig. 1**).

The technician and equipment positioning for the parabolas were as follows. For the first set of six parabolas, both the technician operating the generator (hereafter technician 1) and the technician holding the receiver and acting as the anatomic target (hereafter technician 2) were seated and wearing seatbelts. The seatbelts were standard commercial airline lap belts. They were worn for safety while the technicians became accustomed to the altered gravity fields and tested the equipment in the parabolic flight environment. During the second set of six parabolas, technician 2 unbelted and placed their foot in a foothold to reduce target motion while technician 1 remained seated. During the third set of six parabolas, both technicians were unbelted. Both had one foot in a foothold during image x-ray generation and image creation. During the fourth set of parabolas, technician 2 was floated to the ceiling by the ZeroG flight crew. Technician 2 then hugged the detector against their chest and pelvis to reduce motion of the target relative to the receptor, while technician 1 lay on the floor of the craft, aiming the x-ray beam up at the anatomic targets. During parabola set five, technician 1 floated without the aid of a foothold while technician 2 stabilized themselves with a foothold and braced an iPad (iPad Mini 5th Generation, Apple Inc., Cupertino, CA, United States) against the detector. Parabola set six was reserved to repeat any unsuccessful imaging attempts. No repetitions were necessary.

During the first set of six parabolic intervals, technician 1 discovered that during microgravity the springs in the arm of the torso harness system used for securing the generator forced the generator away from their body. To compensate for this, between parabola sets 1 and 2, technician 1 disconnected the generator's mounting plate from the arm and safely stowed the

Fig. 1. A) Two of the authors pose in microgravity aboard a parabolic flight with the ultra-portable x-ray generator and image receptor. B, C, D) Example image acquisitions of the two technicians in various positions. Photo credit: Steve Boxall, Zero Gravity Corp., 2022.

arm. Thereafter, the generator's angle and distance from their body were allowed to be freely determined by technician 1 as they acquired images. Throughout the flight, the x-ray generator remained tethered to technician 1 by a nylon safety cable during all phases of flight.

The imaging target protocol proceeded as follows. During parabola set one, where the first three parabolas were lunar gravity and the final two were microgravity, the line pair phantom was imaged. After the generator was removed from the harness during the straight and level flight between parabola sets one and two, the phantom was again imaged during parabolas six and seven. The phantom was then removed from the receptor surface and secured. During parabolas 8–10, technician 2 placed their hand directly on the image receptor surface and the first human radiographs were obtained in microgravity. During the third through fifth sets of parabolas, technician 2 moved themselves and the detector into various positions relative to one another and to the generator to allow for imaging of multiple body parts, including the hand, knee, chest, cervical spine, and pelvis (**Fig. 2**). By the start of parabola set six (parabola 26), 21 images had been acquired, including 6 phantom images and 15 images of human anatomy. All images were acquired at 90 kVp and 1.65 to 4 mA, with a source-to-image distance ranging from approximately 1.0 to 1.7 m. Images were wirelessly transferred from the imaging receptor to a secured laptop computer in flight after each acquisition using MinXray imaging software. Each image was inspected visually between parabolas to ensure a minimum quality before moving to the next image in the protocol.

After landing, further quantitative and qualitative assessment of the acquired images was performed. Nonblinded qualitative assessment was performed by three board-certified fellowship-trained radiologists employed at an academic training program (two with body imaging fellowship training and one with musculoskeletal imaging fellowship training) using a Barco Nio (MDNC-3421; Barco, Poperinge, Belgium) PACS monitor. Quantitative assessment was performed by a radiology imaging physicist. The presampling modulation transfer function was measured by fitting an error function to the supersampled edge of the line phantom (**Fig. 3**). Contrast-to-noise ratio was measured for a low-contrast target with respect to the background.

RESULTS

The phantom and human radiographs obtained on the ground, in simulated lunar gravity, and in microgravity environments

Fig. 2. The first radiograph of a human acquired in microgravity (left) with one of the earliest radiographs acquired by Wilhelm Roentgen (right).

were deemed to be qualitatively diagnostic by the radiologists for the pathology expected to be evaluated by radiography. Quantitatively, the phantom radiographs had no statistically significant difference in spatial resolution or contrast resolution. For all imaging conditions, the spatial resolution appeared comparably sharp. Line pairs up to the Nyquist frequency of 3.6 line-pairs/mm were clearly visible for all imaging environments, and the presampling modulation transfer functions were comparable (**Fig. 4**). Average contrast-to-noise ratio for the low-contrast target was 2.44 and consistent across imaging conditions, with no statistically significant differences (Fig. 4).

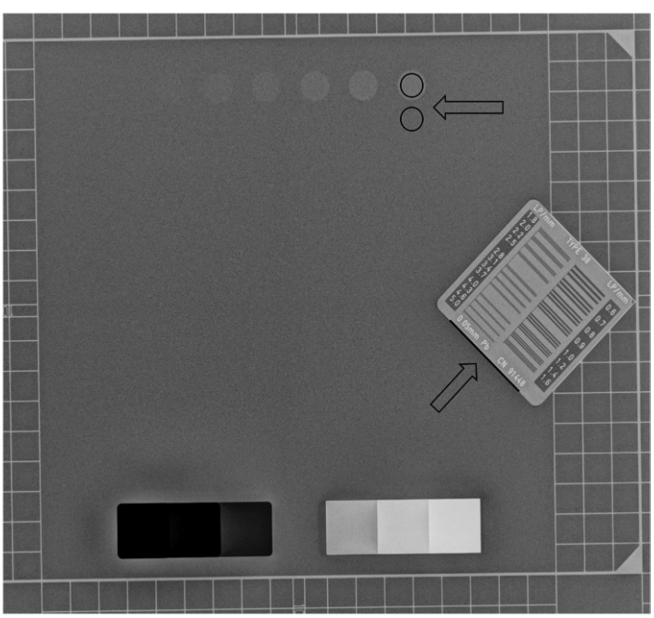

Fig. 3. The presampling modulation transfer function was measured by fitting an error function to the supersampled edge of the line-pair phantom (black line indicated by arrow). The contrast-to-noise ratio was measured for a low contrast target with respect to the background (black circles indicated by arrow).

DISCUSSION

This pathfinding study demonstrates a feasible approach to the performance of multiple radiographic exams in microgravity and reduced gravity environments. Both limited qualitative and basic quantitative assessments of contrast and spatial resolution relative to ground controls suggest diagnostic quality exams can be performed in flight with this commercial off-the-shelf equipment. The preflight training for successful utilization of this ultra-portable unit was accomplished within a few days before flight and images were wirelessly transferred and available for instant interpretation after acquisition. This radiography system and methodology produced images with diagnostic adequacy while minimizing mass, space, power, training, and dose relative to previously proposed radiography units for spaceflight.

Human iatrogenic radiation exposure is an important consideration for medical equipment on exploration class missions, particularly as astronauts traveling beyond the Van Allen belts will be exposed to higher ambient radiation doses. For example, a Mars mission may expose the crew to up to 1 Sv (1000 mSv) of radiation, while exposures range on average from 0.153 to 0.231 $mSv \cdot d^{-1}$ on the ISS and 0.3 $mSv \cdot d^{-1}$ on the lunar surface, depending on available shielding.[14,18] When compared to the daily background dose, the dose associated with in-flight radiography would be relatively small and carry a lower risk profile in comparison. For example, the typical effective dose to a patient for a chest radiograph is 0.1 mSv and 0.001 mSv for a hand radiograph. There would briefly be even lower doses of scattered radiation immediately surrounding the imaged patient,

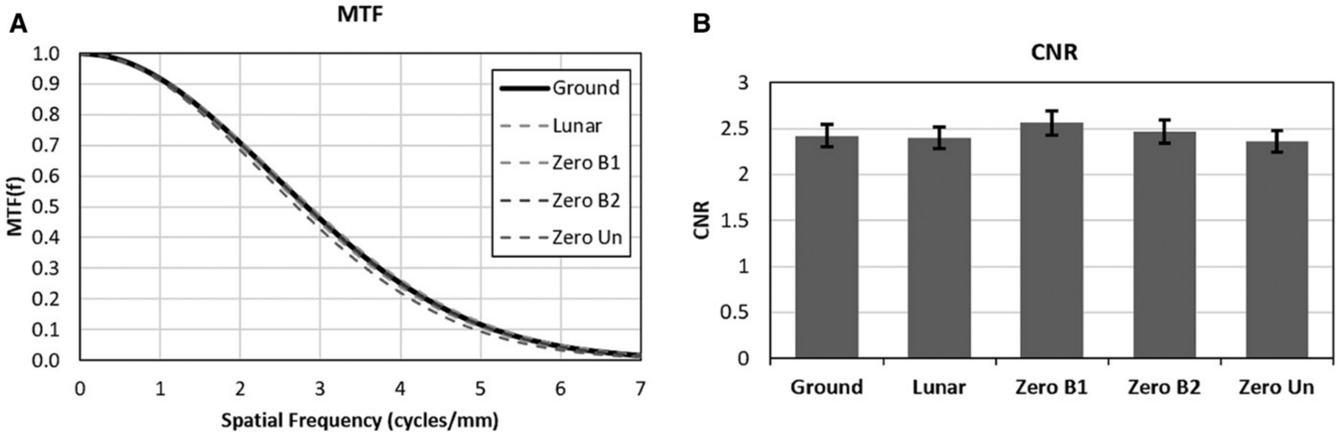

Fig. 4. A) Modulation transfer function (MTF) and B) contrast-to-noise ratio (CNR) at 1 G and at varying levels of reduced gravity.

so the area should be cleared of other crew during acquisition. While not in operation, the x-ray generator unit does not produce radiation and, therefore, there is no unexpected exposure. The generator unit itself is embedded with shielding so that, during acquisition, radiation exposure to the surrounding area not within the beam is minimal. This shielding is included in the off-the-shelf measurements of size and mass. This shielding would also provide partial protection from galactic cosmic radiation for the unit electronics, which is a known concern in flight. Additionally, the electronics could be radiation hardened further as necessary, as is sometimes performed for other sensitive equipment. While lithium-ion batteries such as that in the generator are already used aboard the ISS, a safety and compatibility evaluation of the particular battery specifications used to power this or any other x-ray generator would be needed before any orbital flight.

This study is not without limitations. Parabolic flight is an imperfect simulation of spaceflight in low Earth orbit or in cis- and translunar space. The ambient radiation environment, vibration load, cabin volume, equipment available for subject positioning, and vehicular sources of electromagnetic interference could all potentially contribute to degradations or limitations in image quality in spaceflight relative to parabolic flight. However, the time limitations for positioning and exposure imposed by the short periods of microgravity in parabolic flight would be removed, facilitating these exams. Second, this proof-of-concept work used a single healthy human technician as an anatomic target, and limited exam types were performed. Appropriate patient positioning in altered gravity may be particularly difficult in a scenario where the subject is acutely ill. Furthermore, it is expected that reduced or absent gravity may limit x-ray sensitivity and specificity for pathology with some gravity-dependent findings, such as pneumothorax and small bowel obstruction.[16] We observe the need to perform additional suborbital and low Earth orbit flights to replicate our findings and ensure that diagnostic quality images are consistently reproducible with different operators and subjects.

Opportunities to perform further testing of x-ray imaging in altered gravity environments should be pursued. Private and state-sponsored exploration class missions returning to the lunar surface and beyond to Mars are rapidly shifting from the realm of science fiction to science fact. As mission length and crew complement increase, so too does the risk of a medical or surgical emergency. NASA has developed a series of risk assessment tools to evaluate and help mitigate these potential conditions through optimization of the mission medical kit.[15] Depending on the constraints of the kit, medical imaging equipment will likely be included on long-duration missions on the lunar and Martian surfaces. Dozens of the conditions of highest concern require imaging for confident diagnosis and/or definitive management.[1,17] While handheld ultrasound demonstrates utility for a majority, radiography would allow for superior or simplified evaluation for a subset of these, including musculoskeletal trauma, dental and oromaxillofacial disease, and thoracic pathology, some of which have already occurred during spaceflight.[12] While ultrasound has been favored historically due to its lack of ionizing radiation, versatility, small size, low mass, and interventional utility, providing a terrestrial standard of care on another planetary surface will necessitate additional modalities, especially those which can enhance or complement the capabilities of handheld ultrasound. In addition to clinical use, modifications of terrestrial radiography techniques, such as dual-energy x-ray absorptiometry, may assist in answering critical research questions in flight, such as changes in bone mineral density during long-duration missions. Other benefits include the ability to perform in-flight nondestructive testing and evaluation of equipment, including but not limited to malfunctioning solar panels or potential hull damage, such as occurred on Expedition 56/57.[6]

Development and testing of portable radiography equipment for spaceflight have long been proposed, though no urgent use case has yet necessitated implementation, particularly given the successful extensive adaptations of in-flight ultrasound and the ability to rapidly evacuate from low Earth orbit. However, since first suggested in the 1980s for the never-constructed Space Station Freedom, the radiation dose, mass, size, and power requirements of portable digital radiography have decreased substantially, altering the calculus for its inclusion in future technical demonstrations in low Earth orbit and for potential permanent use in large off-world habitats. To this end, this work paves the foundational steps of acquiring radiographs with ultra-portable units in a reduced gravity environment. Our results suggest that widely available commercial off-the-shelf units are sufficient for this task and ready for trial in suborbital or orbital demonstration flights. The authors hope that this is a small but concrete first step toward a bright future for space radiology.

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