# Handheld Sonographic Cardiovascular Imaging Under Hypergravity Conditions

Rebecca S. Blue; Karen M. Ong



**INTRODUCTION:** Real-time cardiovascular imaging during hypergravity exposure has been historically limited by technological and physical challenges. Previous efforts at sonographic hypergravity imaging have used fixed ultrasound probes; the use of hand-held ultrasound, particularly performed by minimally trained laypersons, has been less explored. Here we will discuss handheld sonography to self-visualize carotid vascular and cardiac changes during hypergravity.

**METHODS:** Three subjects with variable ultrasound experience ranging from no familiarity to extensive clinical experience used handheld ultrasound at rest and under stepwise $+G_z$ hypergravity exposures (maximum $+3.5\ G_z$) to visualize carotid vascular changes. Subxiphoid cardiac ultrasound was obtained by the most experienced subject. Subjects had variable prior hypergravity experience; all were trained in anti-G straining techniques. Sonographically inexperienced subjects underwent a brief (< 5 min) familiarization with the ultrasound probe, user interface, and desirable viewing window immediately prior to centrifugation; real-time coaching was provided. Ultrasound images were correlated to self-reported symptoms and hemodynamic data.

**RESULTS:** Handheld ultrasound performed as desired; all subjects were successful at obtaining ultrasound images with adequate capture of windows of interest. Subxiphoid imaging efforts were limited by probe overheating and associated with variable quality of imaging due to probe displacement from straining techniques; the subject noted transient, mild discomfort and ecchymosis after imaging in the subxiphoid region.

**DISCUSSION:** Even individuals with minimal or no ultrasound experience successfully obtained usable images under centrifuge conditions. While there were some limitations, this technical demonstration provides initial validation of handheld sonography as an available tool for real-time cardiovascular imaging in a hypergravity environment.

**KEYWORDS:** ultrasound, vascular, jugular, cardiac, subxiphoid, human centrifuge, commercial spaceflight, spaceflight participant.

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Handheld ultrasound imaging provides real-time, noninvasive imaging in variable and even nonclinical environments. The development of increasingly portable, handheld ultrasound devices, and the iteration of increasingly user-friendly interfaces, has made sonography an accessible technique for even early practitioners.[22] In spaceflight, ultrasound is commonly used given relatively lightweight imaging options, broad applications for multiple uses, and relative ease of use.[11,14,16] Currently, ultrasound is the only imaging capability available on the International Space Station, with crewmembers receiving some preflight training and real-time remote guidance from ground support to perform a wide variety of clinical and research imaging.[13,17] Studies have demonstrated additional feasibility of handheld ultrasound for spaceflight, with use of a handheld ultrasound on the International Space Station and other transit vehicles for monitoring, research, and diagnostic evaluation of various clinical applications.[3,7]

Use of ultrasound in space analog environments, such as human centrifuge, is not new; studies have demonstrated the utility of static ultrasound in human centrifuges for many decades, with early reports of transcranial Doppler during

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centrifuge to detect cerebral blood flow and anticipate hypergravity-related events such as G-induced loss of consciousness (G-LOC) and effectiveness of anti-G straining maneuvers (AGSM).[4,12,23] Asynchronous vascular evaluation, with ultrasound imaging before and after centrifuge exposure, has similarly been used to correlate AGSM effectiveness to risk of G-LOC or evidence of hypergravity tolerance.[1,2,5] Static ultrasound has been used to evaluate vascular responses, such as alterations of carotid arterial diameter and jugular wall distension or peripheral vascular autoregulation, during hypergravity exposures in human and nonhuman primate subjects.[6,8,21] Similarly, static ultrasound has been used to obtain four-chamber apical echocardiographic views on human subjects in a centrifuge; while such imaging has been successful, it required a substantial equipment burden and preconfiguration of the centrifuge gondola as well as expert management of equipment, with no ability of the subject(s) to address real-time technical limitations.[10,20] Human studies have been limited due to the need for subjects to remain as still as possible, often precluding the ability for dynamic AGSM.[6] A more interactive ultrasound capability may better provide dynamic vascular evaluation, feedback regarding effectiveness of straining, and even real-time cardiac assessment of hemodynamic response to hypergravity stressors. To our knowledge, real-time hand-held ultrasound for vascular and cardiac imaging has not been performed during human centrifuge exposure.

Here we will discuss demonstration of a commercial off-the-shelf, portable, handheld ultrasound with tablet interface during human centrifuge exposure. Sonography was performed by three individuals of variable pre-existing ultrasound skill, including an attending-level physician with regular point-of-care ultrasound use in clinical practice, a resident with introductory familiarization to sonography but limited clinical experience, and a nonmedical layperson unfamiliar with use of ultrasound, to determine whether pre-existing or extensive training is necessary for effective real-time imaging of vascular structures during hypergravity. The experienced clinician additionally performed subxiphoid cardiac imaging as a demonstration of capability.

## METHODS

Three subjects ages 35–45 yr volunteered to participate in a demonstration of sonographic utility during hypergravity exposure in a human centrifuge at the National AeroSpace Training and Research (NASTAR) Center in Southampton, PA, United States. Subjects included Subject 1, female, a trained and practicing physician with extensive experience in use of point of care ultrasound for clinical applications; Subject 2, female, a resident physician with prior familiarization training to ultrasound but limited clinical use; and Subject 3, male, a nonmedical layperson with no prior ultrasound or clinical experience. These individuals had variable prior experience in a centrifuge: Subject 1 had extensive pre-existing experience in human centrifuges, AGSM technique, and human centrifuge research; Subject 2 had recent (< 1 mo) familiarization training in a human centrifuge and AGSM as well as a limited prior acrobatic flight familiarization, but no extensive hypergravity experience; and Subject 3 had participated in one prior familiarization human centrifuge experience approximately 5 yr prior to participation. Subjects 2 and 3 were provided refresher training in AGSM technique, including lower extremity muscle contraction and the "Hook" (L-1 closed glottis variant) maneuver, prior to centrifuge profiles.

Sonography was performed using a commercial off-the-shelf, portable, handheld ultrasound (Butterfly IQ™, Butterfly Network Inc., Guilford, CT, United States). Vascular imaging was performed by all three subjects on the right internal jugular vein. Prior to centrifuge profiles, appropriate ultrasound probe positioning was identified and marked for subject reference (see **Fig. 1**). For window identification, the jugular valve was first identified (point 1), followed by the base of the skull (point 4), then two equidistant points between points 1 and 4 (points 2 and 3). Subjects' skin was marked at point 2 and probe placement at the marked location was confirmed by medical monitors prior to centrifuge profiles. Subjects 2 and 3 were then familiarized with jugular ultrasound and provided time to

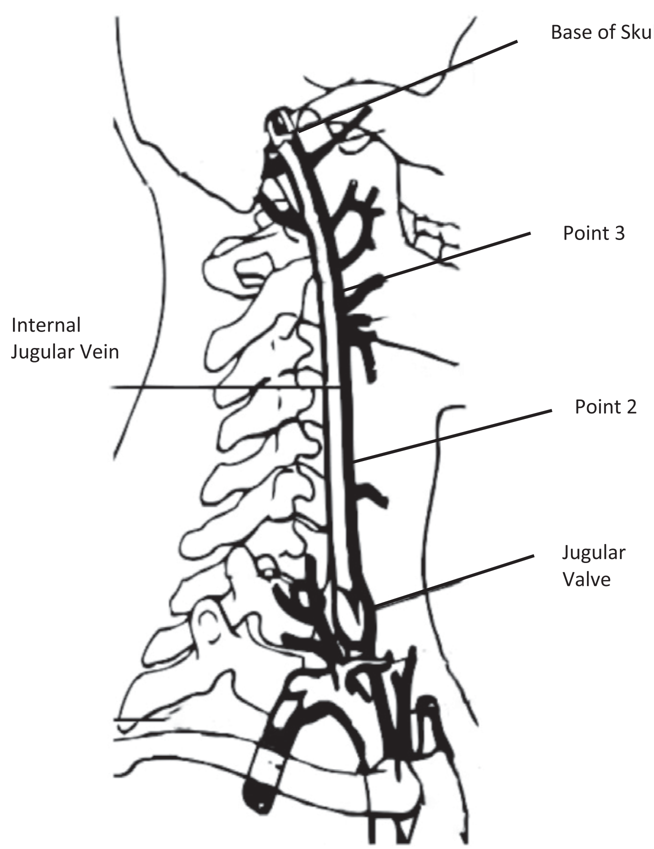


**Fig. 1.** Jugular imaging window. The jugular imaging window was identified by the following landmarks: the jugular valve was first identified (point 1), followed by the base of the skull (point 4), then two equidistant points between points 1 and 4 (points 2 and 3). Point 2 was marked for ease of identification during centrifuge profiles.

practice maintaining a field of view inclusive of vasculature during AGSM and at rest (< 10 min).

The tablet user interface was secured during profiles in a hard-mounted metal frame and hard case located in direct eyesight of the subject performing sonography. While ultrasound vasculature settings were preloaded on the tablet, participants were required to perform minimal tablet interface actions during centrifugation, including initiating and terminating sonographic video recordings. After subjects were loaded and secured in the gondola, an experienced sonographer then confirmed placement of the handheld probe on the pre-marked location and confirmed adequate window acquisition and transverse view of vasculature on the tablet interface prior to closing the gondola and initiating profiles. Subjects then participated in centrifuge profiles consisting of 5-s acceleration to peak $+G_z$, 5-s hold at peak $+G_z$, and 5-s deceleration to idle speed. Subjects held the ultrasound probe in place without external support throughout centrifuge profiles.

Subjects first experienced a $+2.15\text{-}G_z$ peak for familiarization and to ensure they were able to maintain adequate control of the ultrasound probe under hypergravity. During this initial exposure, subjects were instructed to relax with no use of AGSM. Subsequent profiles included a peak of $+3.5\ G_z$. Subjects were allowed to opt into a maximum of six total peak exposures but could terminate participation at any time. Profiles were experienced with subjects relaxed, with preemptive initiation of AGSM at approximately $+2\ G_z$ (prior to peak exposure), and with late AGSM after reaching peak ($+3.5\ G_z$) exposure. In repetitive profiles, subjects were allowed to experiment with variable conditions, including isokinetic lower extremity contraction without Hook, use of the Hook maneuver with or without isokinetic extremity contraction, and intermittent contraction of musculature. Subjects were monitored at all times in the gondola by video, and Subjects 2 and 3 were provided real-time coaching via two-way voice communication by an experienced sonographer who could visualize the tablet screen via gondola video.

Subject 1 additionally performed subxiphoid cardiac imaging. After being secured in the gondola, the subject placed the handheld probe inferior to the xiphoid tip of the sternum, with pressure applied to hold the probe against the abdomen and posteriorly toward the spine, allowing for the probe to be angled superiorly along the frontal plane and posterior to the sternum. The subject confirmed adequate visualization of a four-chamber subxiphoid cardiac view prior to profile initiation. Additional profiles as above were performed both relaxed and with use of AGSM.

## RESULTS

All subjects successfully obtained vascular imaging of the right internal jugular vein during centrifuge profiles (**Fig. 2** and **Fig. 3**). Imaging was adequate and demonstrated appropriate jugular collapse and distension during relaxed and AGSM-inclusive exposures, respectively. Transient loss of landmarks occurred, particularly with inferior migration of the ultrasound probe during hypergravity onset or slight window shifts induced by muscle contraction, but subjects were able to reposition probes in real-time to reidentify and maintain appropriate windows. No episodes of near or complete loss of consciousness (G-LOC) occurred.

Inexperienced sonographers (Subjects 2 and 3) reported ease of use of the handheld ultrasound, additionally reporting adequacy of the brief familiarization training provided prior to participating in profiles. Repetitive profiles did result in some minor upper extremity fatigue; even so, subjects reported no difficulty in maintaining probe position despite noted fatigue. Subjects reported no pain or persistent discomfort after termination of the centrifuge experience. Subjects noted that jugular dilation was easily identified real-time by watching the tablet application during straining maneuvers. One subject reported increasing their AGSM effort when they were unsatisfied with the visualization of a partially dilated vein. Subject 3 was able to demonstrate rapid jugular expansion under hypergravity conditions with isokinetic leg contraction alone; Subjects 1 and 2 demonstrated poor filling with isokinetic muscle contraction but improved dilation with the addition of the Hook maneuver.

Subject 1 noted increased difficulty in maintaining subxiphoid cardiac views compared to jugular ultrasound (**Fig. 4**). In particular, positioning the relatively large probe (measuring 163 × 56 × 35 mm) for a subxiphoid window was difficult in an upright posture with restraints attached and tightened. Further, the subject noted mild abdominal discomfort with AGSM due to the probe positioning and noted probe interference with abdominal muscle use during strain. Subxiphoid window loss occurred during the Hook maneuver respiratory exchange, though the subject was able to reacquire an adequate window quickly. On the third acceleration profile, the ultrasound probe abruptly terminated imaging, with an error notice stating that the probe battery had overheated. Total cardiac imaging at that time was approximately 4 min of probe use, with ≤ 30-s video segments intermittently obtained.

Following the profiles, the subject noted minor but persistent discomfort of the abdominal wall musculature; 24 h after centrifuge profiles a minor, faint ecchymosis (1 × 2 cm) was noted on the superior abdominal wall at the site of probe placement. Ecchymosis resolved within 3 d of centrifugation and was not associated with any functional or physical limitation for the subject.

## DISCUSSION

Ultrasound vascular imaging was successful under hypergravity conditions when performed by individuals of variable skill, with even a novice user of no sonographic or hypergravity experience able to obtain adequate imaging. In fact, imaging obtained by Subject 3 was arguably more stable with less window loss than that obtained by Subjects 1 and 2. Subject 3 was the only male volunteer; he had longer upper extremities than the other subjects and was able to make use of the arm rest where the female

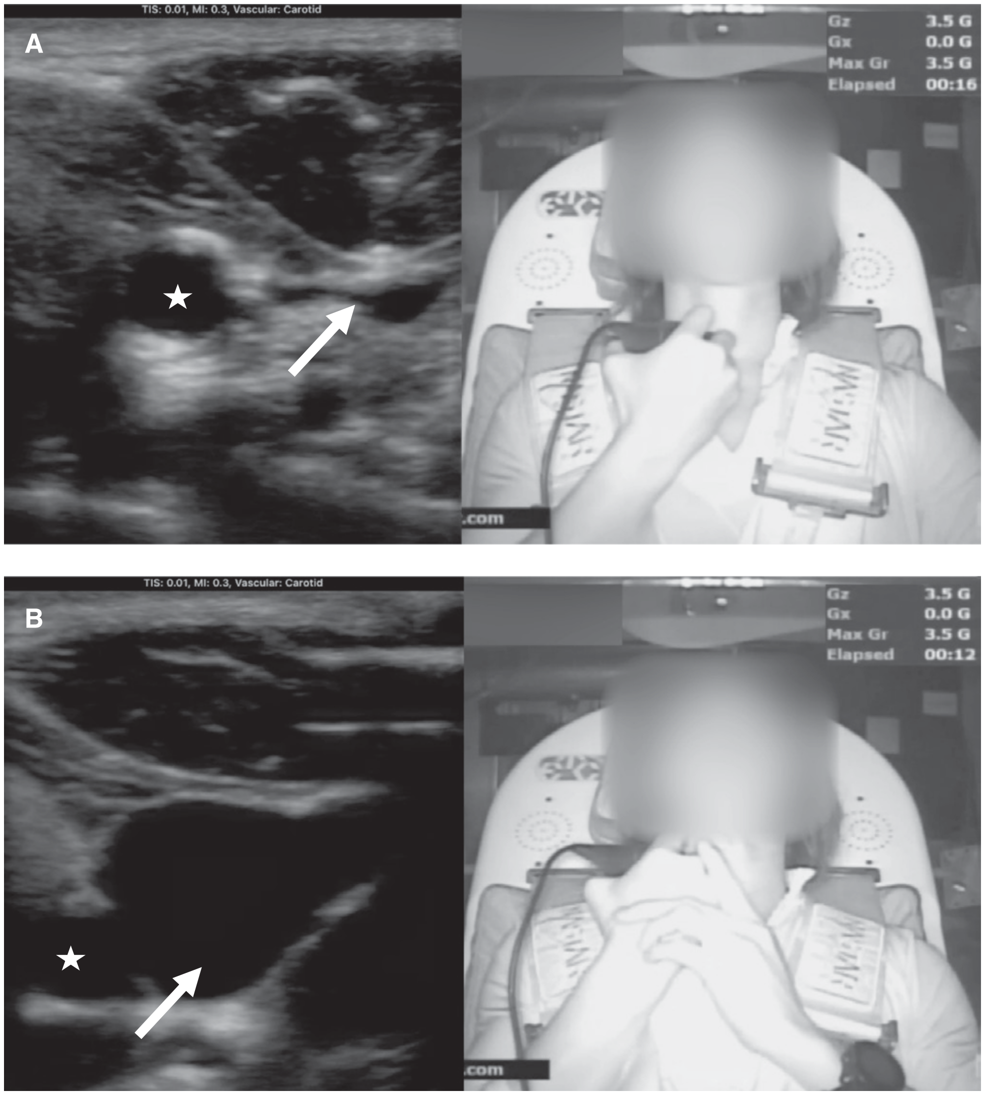


**Fig. 2.** Jugular imaging by minimally experienced sonographer (Subject 2). A) Jugular vein as imaged by a minimally experienced sonographer while relaxed at +3.5 $G_z$. B) Jugular venous distention as imaged by a minimally experienced sonographer performing an anti-G straining maneuver at +3.5 $G_z$. The carotid artery is marked by a star; the jugular vein is indicated by a white arrow.

volunteers were required to support the ultrasound probe without a stabilizing support structure, factors which may have contributed to image stability. Further, the simplicity of the transverse vascular window, pre-marked with the probe positioning confirmed before the centrifuge profile initiation, likely further enabled the unfamiliar subject's ability to hold a static window and maintain imaging. Rare vascular window loss observed with all subjects was easily compensated for, with minimal familiarization required to allow Subjects 2 and 3 to recognize window loss and enable reacquisition during the profile.

Real-time identification of jugular dilation during hypergravity and AGSM was a validating finding, providing contemporary feedback to identify adequacy of AGSM and, in one case, imaging drove increased AGSM effort to address unsatisfactory venous dilation. This suggests that such visualization is a useful adjunct to AGSM training and identification of inadequate strain. While handheld sonography is not likely to be standardized for use in all hypergravity training, use of such adjunctive imaging could be considered in cases where adequacy of strain is questionable or lacking, or where individuals need alternative feedback to improve technique. The use of sonographic imaging as an asynchronous educational tool (for example, video demonstration to novices for better understanding of physiology prior to centrifuge exposure) may additionally prove useful in some circumstances.

Subxiphoid imaging was more challenging for several reasons. Upright positioning is not ideal for obtaining subxiphoid windows due to decreased probe mobility in an individual flexed at the hip. The added challenges of maneuvering around a five-point harness led to awkward hand and probe positioning and uncomfortable pressure of the probe against the abdominal wall. Use of a smaller probe for cardiac imaging may be more successful. Body habitus is an additional consideration; in an individual with increased abdominal girth, a subxiphoid view may not be achievable in an upright and restrained condition. Parasternal windows may be easier to obtain in some

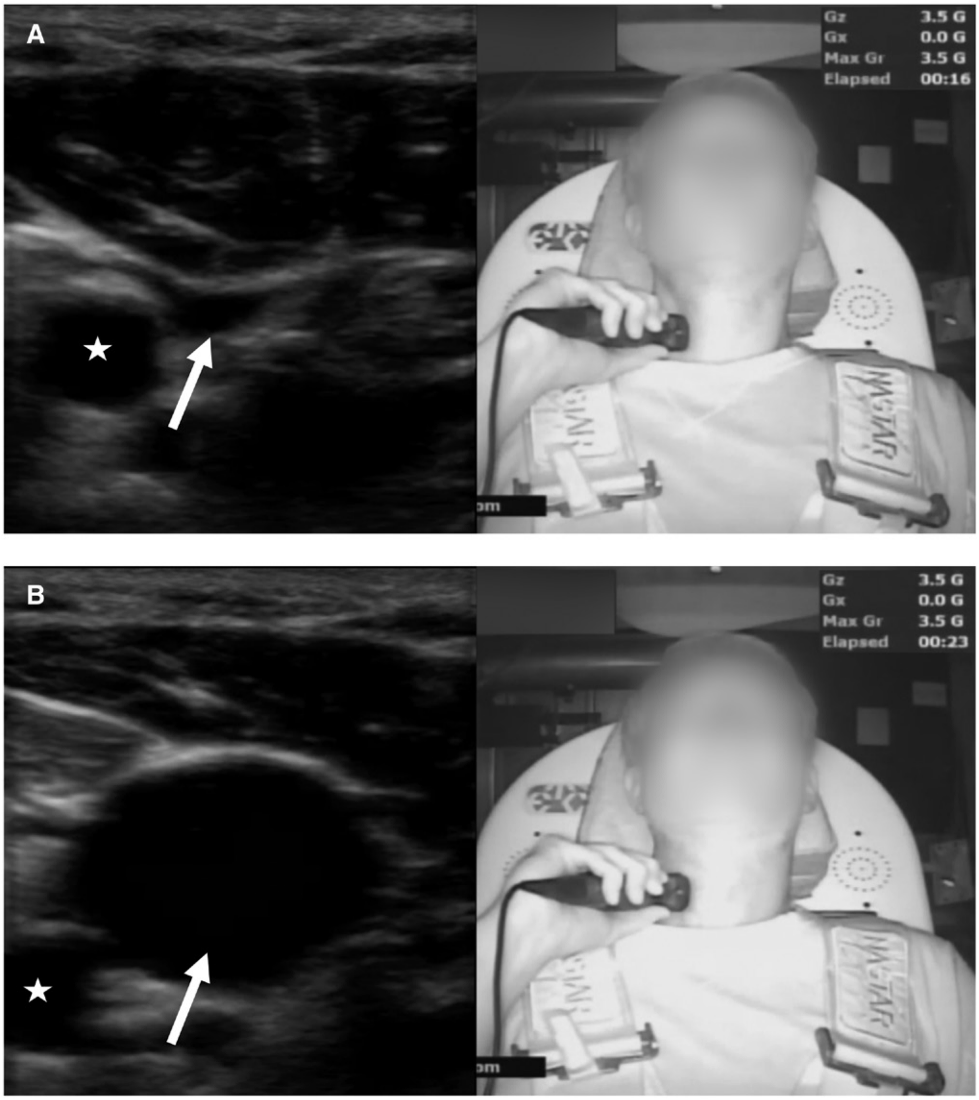


**Fig. 3.** Jugular imaging by a novice sonographer (Subject 3). A) Jugular vein as imaged by a novice sonographer while relaxed at +3.5 $G_z$. B) Jugular venous distension as imaged by a novice sonographer performing an anti-G straining maneuver at +3.5 $G_z$. The carotid artery is marked by a white star; the jugular vein is indicated by a white arrow.

individuals but could require more exposure of a subject, which may be less ideal for a training scenario, particularly for nonprofessionals or commercial customers. Body habitus may similarly limit parasternal imaging.

Cardiac imaging is energy intensive, with increased thermal output compared to other imaging modalities.[9] In this demonstration, cardiovascular imaging quickly led to battery overheating and loss of imaging capability. Similar challenges of battery overheating have been identified in other aeromedical uses of portable ultrasound.[15] While the pursuit of real-time cardiac imaging during hypergravity for a future commercial spaceflight participant with cardiac history may someday be of interest, real-time hypergravity cardiac sonography is likely to remain more of a scientific interest than a clinical need in the near-term future.

Future applications of vascular sonography in dynamic hypergravity environments may similarly be limited to research or special interest activities for the near future but are worth considering regardless. Comparison of ultrasound findings in spaceflight compared to analog environments may provide improved understanding of the limitations of terrestrial analogs for training and research purposes. Sonography may be useful in calculating aortic compliance and identifying vascular alterations (and timeframe of onset) in variable physiological conditions, including preexisting conditions or use of pharmaceuticals, euvolemia vs. dehydration, and others. For example, improving the understanding of vascular flow dynamics in the heart, the thorax, the abdomen, or the extremities may allow for improved modeling of G-tolerance, with potential applications such as prediction of tolerance for future spaceflight participants with variable age, condition, and medical history. Real-time imaging may additionally shed light on observed clinical effects of spaceflight or analog conditions, such as hypergravity-induced dysrhythmias.[18,19]

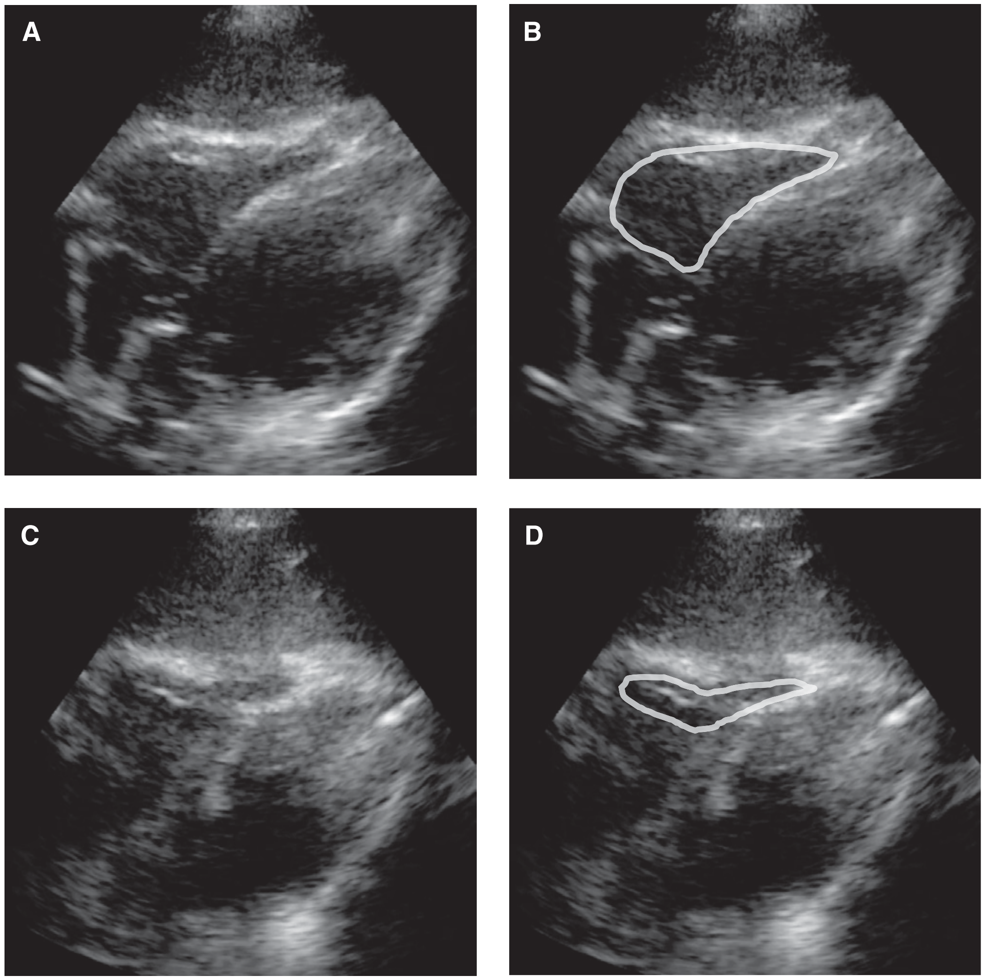


**Fig. 4.** Subxiphoid cardiac imaging by an experienced sonographer (Subject 1). A) Subxiphoid imaging at rest before profile initiation. B) The same image is presented with a white outline of right ventricle volume. C) Subxiphoid imaging while relaxed at +3.5 $G_z$. D) The same image is presented with a white outline of right ventricle volume. Note the relative collapse of the right ventricle and the partial loss of the ideal cardiac imaging window due to challenging probe management under hypergravity conditions.

While handheld sonographic imaging is limited by the factors described above, real-time imaging in unique and unfamiliar environments may provide improved physiological understanding, particularly as layperson engagement in aerospace activities increases. Further, such imaging may provide substantial educational benefits in both real-time and asynchronous efforts. This technical demonstration provides validation of handheld sonography as an available and underutilized tool for real-time cardiovascular imaging in a hypergravity environment. As technology continues to evolve, use of smaller and more user-friendly devices will continue to expand opportunities for improved visualization and associated understanding of aerospace environments and the humans within them.

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## REFERENCES

1. Albery WB, Ten Eyck RP, Wolfe M. Female exposure to high G: echocardiographic evaluation for chronic changes in cardiac function. Aviat Space Environ Med. 1998; 69(9):857–861.
2. Choi HS, Sul JG, Yi KS, Seo J-M, Chung KY. Ultrasonographic finding of internal jugular vein during anti-G straining maneuver: is it associated with gravity-induced loss of consciousness? Eur J Appl Physiol. 2010; 109(4):625–630.

3. Cowing K. Space Health Institute demonstrates self-reliant performance of the Butterfly iQ portable handheld ultrasound system in space. SpaceRef 2021. [Accessed 8 May 2023]. Available from https://spaceref.com/press-release/space-health-institute-demonstrates-self-reliant-performance-of-the-butterfly-iq-portable-handheld-ultrasound-system-in-space/.
4. Dinakar S, Agarwal A. An analysis of transcranial Doppler to interpret changes in cerebral circulation under +Gz. Indian J Aerosp Med. 2020; 63:61–64. [Accessed 9 May 2023]. Available from https://indjaerospacemed.com/an-analysis-of-transcranial-doppler-to-interpret-changes-in-cerebral-circulation-under-gz/.
5. Eiken O, Keramidas ME, Sköldefors H, Kölegård R. Human cardiovascular adaptation to hypergravity. Am J Physiol Regul Integr Comp Physiol. 2022; 322(6):R597–R608.
6. Frett T, Petrat G, Arz M, Leguy C. Quantitative evaluation of a telerobotic system for vascular ultrasound measurement on a short arm human centrifuge. Microgravity Sci Technol. 2021; 33(1):14.
7. Gliadkovskaya A. Butterfly takes flight: hand-held ultrasound pushed to the limits to test its use for space missions. Fierce Healthcare. 2023. [Accessed 8 May 2023]. Available from https://www.fiercehealthcare.com/health-tech/butterfly-networks-iq-handheld-scanner-goes-space-nasa-spacex.
8. Green NDC, Brown MD, Coote JH. Failure of vascular autoregulation in the upper limb with increased +Gz acceleration. Eur J Appl Physiol. 2007; 100(6):621–626.
9. Jenkins S, Shiha MG, Yones E, Wardley J, Ryding A, et al. Cardiovascular examination using hand-held cardiac ultrasound. J Echocardiogr. 2022; 20(1):1–9.
10. Jennings T, Tripp L, Howell L, Seaworth J, Ratino D, Goodyear C. The effect of various straining maneuvers on cardiac volumes at 1 G and during +Gz acceleration. Wright Patterson Air Force Base (OH): Harry G. Armstrong Aerospace Medical Research Laboratory; 1989. TR No: ADA262335. [Accessed 9 May 2023]. Available from https://apps.dtic.mil/sti/pdfs/ADA262335.pdf.
11. Johansen BD, Blue RS, Castleberry TL, Antonsen EL, Vanderploeg JM. Point-of-care ultrasound for pulmonary concerns in remote spaceflight triage environments. Aerosp Med Hum Perform. 2018; 89(2):122–129.
12. Krutz R. Correlation of eye-level blood flow velocity and blood pressure during +Gz acceleration. Brooks Air Force Base (TX): School of Aerospace Medicine; 1973. TR No: AD770560. [Accessed 4 Jan. 2024]. Available from https://apps.dtic.mil/sti/pdfs/AD0770560.pdf.
13. Law J, Macbeth PB. Ultrasound: from Earth to space. McGill J Med. 2011; 13:59.
14. Martin DS, South DA, Garcia KM, Arbeille P. Ultrasound in space. Ultrasound Med Biol. 2003; 29(1):1–12.
15. Melanson SW, McCarthy J, Stromski CJ, Kostenbader J, Heller M. Aeromedical trauma sonography by flight crews with a miniature ultrasound unit. Prehosp Emerg Care. 2001; 5(4):399–402.
16. Pavela J, Sargsyan A, Bedi D, Everson A, Charvat J, et al. Surveillance for jugular venous thrombosis in astronauts. Vasc Med. 2022; 27(4): 365–372.
17. Sargsyan AE, Hamilton DR, Jones JA, Melton S, Whitson PA, et al. FAST at MACH 20: clinical ultrasound aboard the International Space Station. J Trauma. 2005; 58(1):35–39.
18. Suresh R, Blue R, Mathers C, Castleberry T, Vanderploeg J. Dysrhythmias in laypersons during centrifuge-simulated suborbital spaceflight. Aerosp Med Hum Perform. 2017; 88(11):1008–1015.
19. Suresh R, Blue R, Mathers C, Castleberry T, Vanderploeg J. Sustained accelerated idioventricular rhythm in a centrifuge-simulated suborbital spaceflight. Aerosp Med Hum Perform. 2017; 88(8):789–793.
20. Tripp LD, Jennings TJ, Seaworth JF, Howell LL, Goodyear C. Long-duration +Gz acceleration on cardiac volumes determined by two-dimensional echocardiography. J Clin Pharmacol. 1994; 34(5):484–488.
21. Werchan PM, Schadt JC, Fanton JW, Laughlin MH. Total and regional cerebral blood flow during recovery from G-LOC. Aviat Space Environ Med. 1996; 67:751–758.
22. Wilkinson JN, Saxhaug LM. Handheld ultrasound in training—the future is getting smaller! J Intensive Care Soc. 2021; 22(3):220–229.
23. Wood EH, Sturm RE. Human centrifuge non-invasive measurements of arterial pressure at eye level during Gz acceleration. Aviat Space Environ Med. 1989; 60(10, Pt 1):1005–1010.