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CROSSROADS

Ultrasound: From Earth to Space

Jennifer Law*, Paul. B. Macbeth

ABSTRACT: Ultrasonography is a versatile imaging modality that offers many advantages over radiography, computed tomography, and magnetic resonance imaging. On Earth, the use of ultrasound has become standard in many areas of medicine including diagnosis of medical and surgical diseases, management of obstetric and gynecologic conditions, assessment of critically ill patients, and procedural guidance. Advances in telecommunications have enabled remotely-guided ultrasonography for both geographically isolated populations and astronauts aboard the International Space Station. While ultrasound has traditionally been used in spaceflight to study anatomical and physiological adaptations to microgravity and evaluate countermeasures, recent years have seen a growth of applications adapted from terrestrial techniques. Terrestrial, remote, and space applications for ultrasound are reviewed in this paper.

Keywords: Ultrasound, Spaceflight, Telemedicine, Telesonography, Remote consultation

INTRODUCTION

The use of ultrasound to diagnose and facilitate therapeutic interventions has become routine in many areas of medicine and surgery (1). With advances in computing power and probe design, ultrasound systems have become a widely available imaging modality. Traditionally, ultrasound is best known for its assessment of pregnancy and fetal growth. A growing number of applications have developed to include detailed assessments of almost every organ system. Clinicians have also identified benefits in trauma, critical care, and remote diagnostics. Ultrasound is an ideal diagnostic tool as it is noninvasive, low-cost, and highly portable. Image generation and interpretation, however, is highly user-dependent. As a result, ultrasound has traditionally been limited to expert users. With new advances in ultrasound technology and personnel training, the use of ultrasound has expanded beyond these traditional boundaries and has become an extension of the physical examination to many. Bedside ultrasound assessments have enhanced physicians’ capabilities to accurately diagnose and understand patient physiology with the benefit of real-time feedback (2).

In this review we discuss the development of ultrasound technology and its expanded assessment of patients. A detailed description of its applications will be highlighted with discussion of its remote capabilities and utility for human space exploration.

BACKGROUND

History of ultrasound. The origins of ultrasonography can be traced back as far as the early 1800s, when Swiss physicist Jean-Daniel Colladon accurately determined the speed of sound through water. In the late 1800s, Pierre Curie and Jacques Curie demonstrated the connection between voltage and pressure in crystalline materials now known as the piezoelectric effect. This breakthrough led to the creation of the modern ultrasound transducer. It was not until the late 1930s when Austrian psychiatrist Dr. Karl Dussik demonstrated the clinical utility of ultrasound by generating images of brain tumors. A decade later, Dr. George Luwig characterized the differences of sound waves in different tissues. Early clinical applications primarily focused on clinical assessment of pregnancy and fetal development. As the technology matured, more clinical applications

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were identified. In the late 1970s, Europeans began using ultrasound in the assessment of critically ill trauma patients. It was nearly 15 years later when this application became more widespread in North America. Within the last two decades, ultrasound technology and technique have matured, allowing for wide availability. New techniques and applications continue to be developed.

How ultrasound works. In contrast to radiography, computed tomography (CT), and magnetic resonance imaging (MRI), the acquisition and interpretation of ultrasound images are interconnected, as the ultrasonographer must be able to identify important structures and pathologies while scanning. As such, ultrasonographers require an understanding of the basic physical principles of ultrasound. Fundamentally, ultrasound image generation relies on the interaction of ultrasound waves with different tissues. Ultrasonography is based on the piezoelectric effect where quartz crystals are electrically stimulated, causing the crystals to change shape and produce sound waves. Conversely, when reflected sound waves hit the crystals, they produce electrical signals, which are used in combination to generate an image. Image generation relies on impedance differences between different tissues. These tissue interfaces result in the reflection of transmitted ultrasound waves, creating an echo. Many of the objects seen in ultrasound images are due to the physical properties of ultrasonic beams, such as reflection, refraction, and attenuation. The ultrasound computer measures the time to detect the reflected wave, then calculates the distance to the reflected surface. These signals and calculations are then combined to generate a two-dimensional real-time image on the screen. In a typical ultrasound, millions of pulses and echoes are sent and received each second. A probe is positioned on the surface of the body and moved to obtain various views. Ultrasound waves pass easily through fluids and soft tissues, however they are unable to penetrate bone or gas. Therefore, ultrasound is of limited use for examining regions surrounded by bone, or areas that contain gas or air. Despite this, ultrasound has been used to examine most parts of the body. Understanding these interactions is important for establishing a clinical diagnosis.

TERRESTRIAL APPLICATIONS

Ultrasound is an essential tool for diagnostics and interventional procedures and has been used to characterize almost every organ system in a variety of patient populations and specialties.

Trauma. The Focused Assessment with Sonography for Trauma (FAST), originally described in 1999 by consensus definition, is used to rapidly evaluate patients with blunt or penetrating thoracoabdominal trauma (3). The FAST examination is based on evaluation of dependent portions of the peritoneal cavity—the splenorenal, hepatorenal, and rectovesical/rectovaginal recesses—for evidence of free fluid (as illustrated in Figure 1) and the pericardium for evidence of pericardial effusion or tamponade. The purpose of this assessment is to extend the physical examination to rapidly identify diagnoses that require emergent interventions such as laparotomy or pericardiocentesis. In the setting of an unstable patient, the use of ultrasound for rapid diagnostic assessment is far superior to conventional CT or MRI modalities. The FAST examination is widely used in North America and has become standard teaching for emergency medicine and surgical trainees. Recently this evaluation technique has been expanded to include examination of the pleural surfaces to assess for the presence of fluid (hemothorax) and air (pneumothorax). This technique is referred to as the extended FAST (EFAST) originally described by Kirkpatrick, et al (4, 5). Other descriptions of using ultrasound in assessment of trauma patients include identification of intraperitoneal free air (6) and pulmonary contusion (7), assessment of elevated intracranial pressures by sonographic characterization of the optic sheath (8), identification of a ruptured globe (9), and diagnosis of maxillofacial fractures (10). Despite these advances in application and technique, further development is ongoing (11-18).

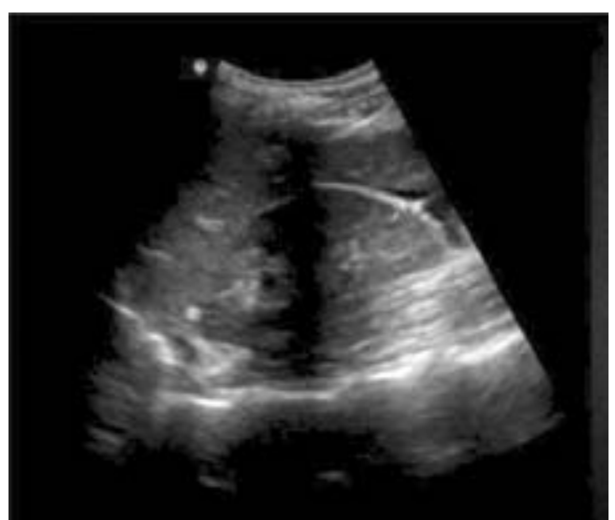

Figure 1: A positive Focused Assessment with Sonography for Trauma (FAST) examination. Ultrasound image demonstrating a small amount of free fluid adjacent to the liver in Morrison's pouch.

Medical and surgical applications. Ultrasound is increasingly being used in the emergency department for medical resuscitations. Various protocols have been described to evaluate the undifferentiated hypotensive patient, generally involving sonographic windows of the abdomen, heart, abdominal aorta, inferior vena cava, and pleura (19-21). In less emergent settings, comprehensive transthoracic or transesophageal echocardiograms are used to evaluate the anatomical structure and functioning of the heart, yielding information including valve integrity, ejection fraction, and disease states such as endocarditis, hypertrophic cardiomyopathy, and pericardial effusion. Other applications for ultrasound include diagnosis of arterial and venous thrombosis, biliary tree disease such as cholelithiasis and cholecystitis, appendicitis, hydronephrosis, testicular torsion, and soft tissue infections.

Obstetric and gynecological applications. Ultrasound, which does not expose patients to ionizing radiation, has traditionally been the modality of choice for the confirmation of intrauterine pregnancy, monitoring of fetal growth, and evaluation of pregnancy-related complications including placenta previa and abruption. Ultrasound also enables excellent visualization of the uterus and adnexa to diagnose such conditions as uterine fibroids, ovarian cysts, and ovarian torsion.

Procedural guidance. The application of ultrasound in interventional procedures has seen significant growth. Its use has become an established component of interventional procedures to assist physicians in the safer delivery of invasive procedures such as central venous access, arterial lines, chest tube placements, percutaneous fluid drainage including thoracentesis and paracentesis, abscess identification and drainage, and regional nerve blocks (1, 22). The use of ultrasound for central line placements has reduced procedure-related complications and is now considered standard of practice in many institutions (23). Ultrasound has also been shown to significantly improve speed, patient satisfaction, and safety for difficult peripheral vascular access in the emergency department (24, 25). Ultrasound guidance for fracture reduction is currently under investigation (26). Demonstration of remote guidance of interventional procedures has been described and is presented further in the next section.

REMOTE ULTRASOUND

Ultrasonography is inherently well suited for remote application with transmission of signals for expert interpretation. The development of remote ultrasound capabilities has expanded beyond terrestrial based activities to include applications in human spaceflight on the International Space Station (ISS). The benefits to patients on Earth are delivery of diagnostic and interventional capabilities in geographically isolated sites, where experts are not always available or there is a need for second opinion when diagnosis is difficult. In many remote locations, ultrasound may exist as the only potential imaging modality available. Several studies have documented utility using ultrasound for the detection of chronic, sub-acute and acute medical problems in isolated areas where advanced imaging capabilities are not available (27). Recent literature suggests that non-radiologist operators can reliably perform focused ultrasound examinations to facilitate on-site diagnosis (28).

Ground-based. Geographically isolated patients often have limited access to health care resources including ultrasound services. This lack of access has resulted in programs to provide telesonography to remote communities. The portability and low cost of ultrasound equipment make it ideal for this application. Global telecommunication networks, using ISDN (ground based) or D or V SAT (satellite) protocols, allow transmission of communications signals between almost any two points on Earth. These established global networks enable transmission of ultrasound images for interpretation by a remotely located expert (29).

Existing telesonography programs have focused mainly towards diagnosis of chronic or sub-acute medical conditions and follow-up assessments (30-33). Applications in remote areas of Australia and Canada have demonstrated its use for assessment of pregnancy and fetal health (34, 35). Recent advances have allowed for remote diagnostic and intervention guidance in critically ill patients (36, 37). A program based in Calgary, Alberta, has created a telemedicine link between a remote resuscitating hospital and the emergency department of a tertiary care trauma centre in the management of acutely injured patients. Using two-way video conferencing and one-way ultrasound transmission, the receiving physicians are able to mentor the remote clinician through the assessment of a trauma patient. These technologies have also been described in providing diagnostic capabilities in the battlefield.

NEEMO. Remote ultrasound has been evaluated and tested aboard Aquarius, an underwater habitat off the Florida Keys, as part of the NASA Extreme Environment Mission Operations (NEEMO). The life sciences mission NEEMO 7 investigated the role of ultrasound examination of the abdominal organs and structures. Ultrasound-trained and untrained aquanaut crewmembers conducted a series of diagnostic and interventional procedures under remote guidance from experts over 3,000 km away (38). Researchers demonstrated that mean efficiencies were slightly higher with telementoring than with the use of a procedure manual.

Robotic-guided ultrasound . The capabilities of ultrasound using an audio/video link with a remote expert have also been augmented with robotic control and guidance of the ultrasound probe. Several groups are working on the development of master-slave type remote ultrasound diagnostic systems (39-41). These systems, based on a communications link between two robotic systems, allow the expert ultrasonographer to extend a virtual hand onto the ultrasound probe. The motion of a master manipulator is controlled by the expert and is reproduced by a slave manipulator carrying an ultrasound probe. Haptic technologies have also been developed and integrated into these systems to remotely provide the expert with tactile feedback. Currently, these systems are prohibitively expensive and used primarily on a research basis.

SPACE APPLICATIONS

Ultrasound is currently the only medical imaging method available aboard the ISS, which hosts an ultrasound system in its Human Research Facility (HRF) that is capable of high-definition sonographic imaging for cardiac, vascular, general/abdominal, thoracic, musculoskeletal, and other ultrasound applications, with remote guidance from experts in the Mission Control Center (MCC) (42). While to date ultrasound has been primarily used to characterize anatomical or physiological changes in microgravity and evaluate countermeasures (43), terrestrial applications for ultrasound are increasingly being adapted for spaceflight, for diagnostic purposes. In microgravity, organs may shift position and free fluid does not pool in dependent areas, so many existing ultrasound techniques require modification. Parabolic flight offers the opportunity to refine adapted techniques before they are used in space.

Cardiovascular. Prolonged exposure to microgravity can result in cardiac deconditioning and orthostatic intolerance upon return to Earth due to fluid shift and loss. The first ultrasound system in space, Argument, was flown on Salyut 6 and 7 to study chamber sizes and left ventricular systolic function. More advanced systems, ranging from the American Flight Echograph to the HRF Ultrasound System (HRF US), have subsequently enabled more complete evaluation of the heart in flight. On ISS Expedition 7, a study demonstrated the feasibility of coupling the HRF US to the cycle ergometer to perform stress echocardiography (42). To measure fluid shift, systems such as the French Compact Doppler System have been used to evaluate cerebral and femoral blood flow before flight, during reentry and landing, and post-flight (43).

Musculoskeletal. Many musculoskeletal complaints such as back pain, contusion, and strain are common among space crews. Ultrasound has demonstrated that the intervertebral distance between L1 and L5 increases significantly in microgravity (44), which may be one of the contributing factors to back pain in space. Ultrasound can theoretically be used to evaluate any tendon, ligament, and bursa (42). A specific protocol for sonographic evaluation of the shoulder, including the articular cartilage surface and the biceps and supraspinatus tendons was demonstrated by the Expedition 9 crew (45).

Trauma. Blunt and penetrating trauma can occur when astronauts engage in tasks such as extravehicular activity, habitat construction, and vehicle operations. The FAST examination has been evaluated both in parabolic flight and aboard the ISS. In the former case, fluid was introduced to the peritoneal cavity of restrained porcine models and it was found that fluid in the subhepatic space was the most sensitive in microgravity (46). In the latter case, a crewmember was able to perform the exam on herself without difficulty (47). Sonographic diagnosis of pneumothorax, hemothorax (48) and ultrasound-guided percutaneous aspiration of intraperitoneal fluid to treat peritonitis (49) have also been demonstrated in porcine models in parabolic flight.

Genitourinary. Urinary tract infections, urosepsis, urinary retention, and nephrolithiasis have all occurred in past space flights. The HRF US has been used to conduct renal and bladder surveys for evaluation of the renal anatomy, vascular flow, and ureteral patency (50, 51). Ultrasound-guided percutaneous bladder catheterization to relieve urinary obstruction was demonstrated in porcine models in parabolic flight, which can be adapted to space in case luminal catheterization is not possible (52).

Ocular. Ocular foreign bodies are a common problem in microgravity, where small particles float freely, sometimes undetected. During the Shuttle-Mir Program, there was also an incidence of blunt trauma to the orbit when a bungee cord restraint system broke (53). Recently, a non-physician crewmember was able to use the HRF US to perform a comprehensive

ocular examination on himself with remote guidance from the MCC, visualizing the anatomical structures of the globe, iris, and pupil (54).

Sinuses. Astronauts in space are predisposed to sinusitis due to cephalad fluid shift and altered drainage of the sinuses in microgravity; superinfection of the sinuses may result in acute bacterial rhinosinusitis. Beninnger et al. introduced fluid to porcine sinuses in parabolic flight and found that in microgravity, fluid could be visualized on ultrasound as a 2 to 3 mm thick air-fluid interface distributed along the entire sinus cavity. The authors further noted that ultrasound-guided sinus drainage procedures were possible (55).

Decompression sickness. Space crews are susceptible to decompression sickness (DCS) when they transition from one environment to a more hypobaric environment, such as an extravehicular (EVA) suit. When the ambient pressure decreases, nitrogen dissolved in the bloodstream comes out of solution and forms bubbles, which may circulate in the body or get trapped, causing local symptoms. Nitrogen bubbles are readily seen on Doppler ultrasound. An in-suit system has been recommended by the NASA Medical Operations EVA Integrated Product Team to better understand bubble formation and arterialization in flight to quantify the risk of DCS (56).

Future applications. For future Exploration Class missions, astronauts will require autonomous medical capabilities given communication delays between the crew and medical support staff on the ground; real-time remote guidance will likely be replaced by one or more trained physician-astronauts onboard. Timely evacuation to Earth will not be possible. Thus, ultrasound will play a greater role in the medical armamentarium for diagnosis and treatment of medical contingencies in space. Sargsyan et al. (42) has catalogued an extensive list of ultrasound applications that have been tested in microgravity and/or with remote guidance, as well as those that are potentially feasible in space. In addition to the previously described applications, more novel uses for ultrasound include evaluation for dental periapical abscesses, thyroiditis, and retroperitoneal hematoma. Finally, low-intensity ultrasound has been suggested to promote bone formation in vitro (57) and may one day be used as a countermeasure against microgravity-induced osteopenia.

CONCLUSION

Ultrasound is a well-proven diagnostic modality on Earth and is becoming increasingly useful in space. Its versatility, portability, noninvasiveness, lack of ionizing radiation, and tele-transmittability make ultrasound an ideal imaging method for space crews. Although ultrasound does not provide the same resolution for evaluating gas-filled or osseous structures as CT or MRI, the role of ultrasound continues to expand, both on Earth and in space. New applications being investigated for spaceflight may be adapted for use on Earth, especially in remote environments that do not have ready access to advanced imaging modalities or expert radiologists, and vice versa. Indeed, ultrasound shows much promise in benefitting both astronauts and patients on Earth.

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