Laura Drudi (M.D., C.M. candidate 2013) is a third year medical student at McGill University. Her interest in combining her two passions of space and medicine has led her to conduct aerospace medicine research. She will be taking a one year's leave of absence from the Faculty of Medicine and will be pursuing a Diploma of Space Studies and an MSc in Experimental Surgery prior to completing her MD. She hopes to work for the manned space program as a flight surgeon and to further continue her research in space life sciences.

Gregory E Stewart (BMSc MD CCFP(c)) completed medical school at The University of Ottawa and is now a resident at The University of Western Ontario in the Rural Family Medicine Program in Goderich. As a pilot and traveler as well as a physician in training, he investigated “Medical Education for Exploration Class Missions” because he was interested in learning about the medical concerns of long duration space travel and how a CMO operates in this extreme environment.

Ultrasound: From Earth to Space

Jennifer Law*, Paul. B. Macbeth

ABSTRACT: Ultrasoundography 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 ultrasoundography for both geographically isolated populations and astronauts aboard the International Space Station. While ultrasound has traditionally been used in space-flight 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

1To whom correspondence should be addressed

Dr. Jennifer Law
University of Texas Medical Branch
Division of Aerospace Medicine
Email: jelaw@utmb.edu
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 or 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. Ultrasound 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 community continues to strive to detect these reflected waves, 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. 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).

Medical and surgical applications. Ultrasound is increasingly being used in the emergency department for medical resuscitations. New 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 function 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 cholestasis and cholecystitis, appendicitis, hydropsphrosis, 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 abrupton. 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 for many 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

Ultrasoundography 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 expert interpretation is 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 has translated into results in programs to provide tele-ultrasound 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 networks enabled the medical community to provide ultrasound images for interpretation by a remotely located expert (29).

Existing telesonography programs have focused mainly towards emergency department and 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 California 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 and ultrasound transmission, the receiving physicians are able to monitor the remote clinical personnel through the assessment of a trauma patient. These technologies have also been described in providing diagnostic capabilities in the battlefield (38).

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 physician 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 telemetering than with the use of a procedure manual.

Robotic-guided ultrasound. The capabilities of ultrasound-guided 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, 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 anatomic or physiological changes in microgravity and evaluate countermeasures (43), it 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).

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 and hemothorax (48) and other indicated percutaneous aspiration of intraperitoneal fluid to treat peritonitis (49) have also been demonstrated in porcine models in parabolic flight.

Sonography can be used 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 ultrasound systems to remotely provide the expert with tactile feedback. Currently, these systems are prohibitively expensive and used primarily on a research basis.

Ultrasound: From Earth to Space

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-transmissibility 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 does extend 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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Jennifer Law (M.D.) is an aerospace medicine resident and the 2011-2012 chief resident of aerospace medicine at the University of Texas Medical Branch (UTMB) in Galveston, Texas. She received her Bachelor of Science degree in electrical engineering from the Massachusetts Institute of Technology and Medical Doctor degree from the University of Southern California. She subsequently completed her residency at the University of California-Davis and currently moonlights as a clinical instructor in the emergency department at UTMB. Prior to her medical career, she worked at NASA’s Jet Propulsion Laboratory on the Mars Exploration Rovers project and supported pre-launch operations at the Kennedy Space Center. She has authored a number of publications in the fields of aerospace medicine, emergency medicine, and trauma.

Paul McBeth (M.A.S.C.) is currently a General Surgery residency at the University of California, where he earlier completed his MD. He began his career as an engineer and completed a Masters of Applied Science degree in electrical engineering from the University of British Columbia where he studied surgical robotics and human factors. He served as a Robotics Research Engineer where he assisted in the design and development of a MR compatible, image-guided neurosurgical robot system. Dr. McBeth is also a graduate of the International Space University. His research interests include applications of remote ultrasound and the resuscitation of critically ill patients.