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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 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. Beside 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 ultrasoundography 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 Lewig 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 have emerged.
Ultrasound: From Earth to Space

**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 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 cholelitiasis and cholecystitis, appendicitis, hydrenephrosis, 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 plaenenta 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 many minimally invasive procedures to help 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 time, 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 and central vascular access in the emergency department (24, 25). Ultrasonography 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 expertise 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 for imaging modality available. Seven programs 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 also 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 toward the development of 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 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 in 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...

**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 was first described 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 pouch. In contrast to 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 electrostatically 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 interference 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 bone or gas. Despite this, ultrasound has been used to examine most parts of the body. Understanding these interactions is important for establishing a clinical diagnosis.

**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.
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 these techniques were feasible and that the success rates were similar to those achieved in the same procedures performed on Earth. Ultrasound was found to be a valuable tool for diagnosing and managing medical conditions in space.

Two robotic systems, the Telerobotic Ultrasound System, and the Haptic Technologies Ultrasound System, were developed and integrated into the Hubble Space Telescope. These systems allow for remote guidance from experts, for diagnostic purposes. Several groups are working on the development of robotic systems for space applications. Remote control allows for the expert to guide the ultrasound probe and obtain high-quality images. The success rates for these procedures were comparable to those achieved in the same procedures performed on Earth.

Ultrasound-guided prostate biopsies were also performed successfully in space. This procedure involves the use of an ultrasound probe to guide the placement of needles into the prostate gland for the purpose of obtaining tissue samples. The procedure is used to detect prostate cancer, which is a common cause of death in developed countries. Ultrasound-guided prostate biopsies were performed on the International Space Station (ISS) and the Space Shuttle. The success rates were comparable to those achieved on Earth, and the procedure was found to be safe and effective.

REFERENCES
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