Ultrasound applications in mass casualties and extreme environments

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A mass-casualty incident is one in which the number of patients with injuries exceeds the available medical resources to care for them in a timely manner. In such a situation, the numerous advantages of ultrasonography make it an ideal triage tool for helping clinicians rapidly screen patients. Experiences during the 1988 Armenian earthquake and the 1999 Turkish earthquake demonstrated the proficiency of ultrasound in providing rapid clinical data to the physicians caring for the mass-casualty patients. Wireless and satellite transmission of ultrasound images also has been shown to be feasible and may be applied to mass-casualty situations. In addition, ultrasound applications have been demonstrated to aid in the diagnosis of various conditions, including pneumothorax, in the International Space Station. Ultrasound's portability, reproducibility, accuracy, and ease of use will make it an important diagnostic instrument for future space missions. (Crit Care Med 2007; 35[Suppl.]:S275–S279)

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A mass-casualty incident is an event where the number of ill or injured patients exceeds the available local or regional healthcare resources for the timely provision of adequate care in order to minimize injury or death. A mass-casualty incident may result from a man-made or natural disaster. During a mass-casualty incident involving trauma patients with multiple injuries, the large caseload may lower the quality of care given to individual patients. From a trauma-care perspective, the goal of a hospital disaster plan is to provide severely injured patients with a level of care that approximates the care given to similar patients under normal conditions. Effective triage of these casualties is often hindered by shortages in time, personnel, and medical equipment. Moreover, during a mass casualty, patients may present to the emergency department with acute, nontraumatic problems that are related to the disaster. These would include patients presenting with chest pain, shortness of breath, abdominal pain, or undifferentiated hypotension.

The use of ultrasonography as a triage tool in these mass-casualty situations has numerous advantages. Ultrasound may be applied to a broad category of trauma patients. In many studies, the focused assessment with sonography in trauma (FAST) examination has been demonstrated to be highly accurate, sensitive, and specific (1–10). New handheld units make this technology portable; ultrasound examinations can now be performed in makeshift triage areas and in the prehospital setting. It generally takes 4 mins or less to perform an ultrasound trauma-screening examination (5), which also facilitates performing serial examinations on patients to monitor their status. Ultrasound is noninvasive. No contrast materials need to be administered to the patient, and there is no radiation exposure involved. Moreover, ultrasound is safe for patients who are pregnant, have a coagulopathy, or have had previous abdominal surgery.

These features of ultrasonography make it especially appealing to emergency physicians and critical care specialists, who will encounter many challenges in a mass-casualty incident. Every emergency department and hospital will be overwhelmed with patients affected by the event. Admission rates will be high, which will challenge the hospital infrastructure's capacity. Diagnostic capabilities within the hospital's radiology department will be hard-pressed to meet the challenge of these high patient volumes. A large percentage of the trauma patients will have multiple blunt or crush injuries, including some patients who may be pregnant. Patients may present with cardiovascular disease exacerbated by the mass-casualty incident. Additionally, some patients may present with undifferentiated hypotension. The applications of ultrasound may assist clinicians in any of these scenarios. The use of ultrasound, and specifically the FAST examination, also has been advocated in medical environments outside of the traditional hospital setting that encounter mass-casualty incidents (e.g., on an aircraft carrier) (11).

Two studies have been published that have described experiences in utilizing ultrasound as a triage tool in the early stages of mass-casualty incidents. A 1991 study described the Armenian experience after an earthquake in December 1988 destroyed three large cities and >100 villages in Armenia (12). This natural disaster resulted in >25,000 deaths and roughly 150,000 casualties in a region where the population approximated 700,000 people. The capital, Yerevan, was the only preserved city with enough hospital beds and medical facilities to deal with such a mass-casualty incident. The event congested the city's lone computed tomography (CT) scanner with head-

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trauma cases, and there was no magnetic resonance imaging capability within Yerevan.

The majority of the trauma patients were transported to the largest hospitals in Yerevan within the first 3 days after the earthquake. The insufficient diagnostic capabilities of the medical community placed unprecedented strains on the receiving hospitals. The authors of this report noted that there were 30 ultrasound machines altogether in the city. For the 1,000-bed Republic Hospital, which was located in the center of the city, two triage rooms were set up in the lobby of the hospital to screen patients; an ultrasound machine was placed in each. Six physicians performed all of the ultrasound examinations. The goal of the treating physicians was to sonographically examine all admitted trauma patients. When the caseload did not permit this, priority was given to patients who were hemodynamically unstable, had altered mental status, or had clinical evidence of torso injuries, hematuria, low urinary output, or major extremity trauma (12).

Of the 750 patients admitted to the hospital in the first 72 hrs, 400 of them received ultrasound examinations in the hospital lobby or at the bedside in the emergency department. Additionally, 78 had a follow-up ultrasound examination performed, and 35 patients underwent serial examinations. Altogether, 530 ultrasound examinations were performed (12).

Of the 400 patients who were screened sonographically, 304 of them demonstrated no clinically significant pathology. In almost 25% of the cases (96 patients), some pathology was demonstrated by ultrasound. With the exception of three patients, all of the non-head-injury trauma patients were treated without the use of CT. The presence of free intraperitoneal fluid was the most common finding in the trauma cases with an abnormal ultrasound examination. Sixteen patients underwent operative intervention based solely on findings of the clinical evaluation and ultrasound examination. Four false-negative ultrasound examinations were noted by the authors of the report. These four cases were a patient who presented with gross hematuria and was found to have a ruptured kidney on laparotomy, a patient with a large retroperitoneal hematoma who developed an ileus and jaundice, a patient with a subcapsular hematoma of the spleen found at 1-month follow-up, and an obese patient with a massive hemothorax (12).

These four false-negative cases highlight the limitations of ultrasound in the trauma setting. Ultrasound has a low sensitivity for detecting retroperitoneal injuries or hollow viscus injuries. The technology also becomes more limited when it encounters obesity, subcutaneous emphysema, or underlying ascites. Ultrasound usually is unable to locate and define the exact etiology of intraabdominal bleeding. Its main limitation remains that it is highly operator-dependent (12).

Another study described Turkey's experience with a mass-casualty incident. In August 1999, an earthquake struck northwestern Turkey, including the cities of Golcuk, Izmit, and Yalova. This earthquake resulted in almost 17,000 deaths and >100,000 injuries. Of the 5,302 patients admitted to hospitals, 639 had renal complications secondary to their crush injuries, and 477 ultimately underwent hemodialysis because they developed acute renal failure (13).

Physicians at the treating hospitals used ultrasound as a triage tool in assessing these patients with renal complications. Renal Doppler ultrasonography is a noninvasive, accurate, and rapid diagnostic tool that provides helpful renal hemodynamic information. It uses parameters such as the resistive index that is estimated from intrarenal blood flow impedance. The renal resistive index increases as a reflection of renal vasoconstriction (13).

The initial Doppler studies were performed within 32 hrs after the earthquake and follow-up Doppler ultrasonography was performed 6 wks later. The ultrasound studies were performed with a Toshiba 270-SSA unit with a 3.75-MHz convex transducer for both spectral and color displays. The sample volume of the Doppler system was placed in the interlobar arteries, and the blood-flow–velocity waveform was recorded as peak systolic velocity (S) and end-diastolic velocity (D). The resistive index (RI) was calculated as $RI = S - D/S$ by the Toshiba software within the unit (13).

The authors of this 2001 study found that the renal resistive index significantly increased in patients with severe acute crush injury. The resistive indices correlated significantly with the number of hemodialysis sessions, requirement for hemodialysis, and the duration of oligoanuria. The diagnostic information provided by these triage ultrasound examinations helped guide the treating physicians' management of the fluid replacement, urine alkalization, and intravenous mannitol administration of the casualty victims. The authors concluded that measurement of the renal resistive index by Doppler ultrasonography might provide predictive information about recovery from acute renal failure resulting from crush injury (13).

While the studies describing the Armenian and Turkish experiences helped provide some initial data for the use of ultrasound as a triage tool in the hospital setting, further investigation was needed to evaluate the feasibility of satellite transmission of ultrasound images to a hospital from a remote field site. Two studies have described the potential feasibility of sending ultrasound images to a hospital over a wireless system. A 2003 study evaluated the image clarity and diagnostic accuracy of transmitting FAST examination images from a field environment via wireless and satellite transmission. Using a handheld ultrasound unit, FAST examinations were performed on three patients with free pericardial or intraperitoneal fluid and two control subjects in a remote military support hospital. A miniature vest-mounted video transmitter attached to the handheld ultrasound unit transmitted wireless ultrasound video 20 meters to a receiving antenna. The ultrasound images were then redirected via satellite to a medical center (14).

The investigators found that real-time wireless transmission reliably produced images without a decline in quality or interpretability (14). A potential application for this technology may be to help redirect triage of trauma cases in mass-casualty incidents. If FAST images can be sent via satellite to a receiving hospital, patients can be diverted to an appropriate trauma center, where operative teams already would be armed with the ultrasound examinations' results.

In 2004, another study evaluated the feasibility and diagnostic accuracy of sending echocardiographic images from a field hospital via wireless and satellite transmission. Twelve patients with previously diagnosed cardiac structural disease had transthoracic echocardiography performed with a handheld echocardiographic instrument at a remote military field hospital. The echocardiographic images were transmitted via a commercial satellite to a medical center, where they were interpreted in real time by a boardcertified cardiologist. The echocardiographic studies were compared with each other before and after satellite transmission. The technical quality and diagnostic accuracy of the study images were compared with conventional hospital transthoracic echocardiograms. The investigators found excellent agreement between the on-site and satellite-transmitted echocardiographic images. There was an overall average of 95% concordance, with a high degree of agreement demonstrated in technical quality (83%) and assessments of left-ventricular ejection fraction (100%), pericardial effusion (100%), and left-ventricular size (92%). The investigators demonstrated that they could reliably transmit and interpret normal and abnormal echocardiographic images without any drop in quality. In a mass-casualty incident, this triage application would provide real-time cardiac assessment for patients suffering from chest trauma or a cardiovascular emergency (15).

Real-time wireless transmission of ultrasound images may potentially play a role on the battlefield. Previous studies have examined the role of ultrasonography under these conditions (16, 17). Ultrasound under battlefield conditions has been demonstrated to be as sensitive, specific, and accurate in the diagnosis of hemoperitoneum as in civilian conditions. A 1999 Croatian study reported that ultrasonography under war conditions had a sensitivity of 86%, specificity of 100%, and accuracy of 97% for detecting free intraperitoneal fluid. This compared favorably to ultrasound's sensitivity, specificity, and accuracy of 88%, 100%, and 95%, respectively, under civilian conditions in Croatia (17).

Three questions need to be addressed with respect to ultrasound's future in mass-casualty care. First, what is the most effective and efficient use of portable ultrasound technology in battlefield conditions? Second, medical mobile units with ultrasound equipment are gaining popularity in some communities; how can this capacity be efficiently mobilized as a triage tool in a mass-casualty incident? Third, can we effectively train healthcare personnel other than physicians to administer accurate ultrasound examinations, in order to expand our triage resources in a mass-casualty incident?

In summary, the use of sonographic screening in mass-casualty incidents is a rapid and effective means of identifying intraabdominal and intrathoracic injuries, which will complement the clinical evaluation of the patient. Sonographic screening should be utilized before invasive or more time-consuming procedures are ordered. Because of its portability, ultrasound is an ideal instrument for physicians working in the emergency department and critical care settings. In addition, establishing real-time wireless transmissions of ultrasound images to or from a medical center also should be considered. Wireless and satellite transmission of ultrasound images is feasible and may be applied to mass-casualty situations. This telecommunications technology illustrates how ultrasound can be of great benefit as an initial triage instrument.

Ultrasound Applications in Extreme Environments

Space travel places extreme and conflicting demands on medical care. The International Space Station (ISS), a low-earth-orbit facility which has been continuously inhabited since November 2, 2000, currently is the centerpiece of global space exploration, but many other government and commercial initiatives are under way. Given that support resources might be days—conceivably, even months—away from the injured space traveler, on-site medical care should be of the highest quality. Weighing against that need is the prohibitive cost of transporting equipment into space. The National Aeronautics and Space Administration (NASA) estimates the expense of transporting equipment aboard the space shuttle to be $10,000 per pound. Cost-efficient single-use rockets cost approximately $2000 per pound to place payload in low earth orbit. This limits the use of bulky traditional imaging technology such as plain radiography or computed tomography.

Traumatic injury in space is of great concern because of its impact on the mission and crew members (18). The greatest risk for blunt or penetrating injury is during extra-vehicular activity, such as space-station construction, vehicle docking, or payload delivery (19). Enormous expense and effort are required to evacuate an ailing crew member in space (20). This places a premium on the accurate diagnosis of medical conditions. The only imaging tool aboard the ISS is the ATL HDI-5000 Ultrasound System (Philips Medical Systems, Bothell, WA) (21). Terrestrial studies have shown the use of ultrasound to be both sensitive and specific for the diagnosis of many medical conditions (1–10, 22, 23). Several recent studies have been performed to evaluate the use of ultrasound in a microgravity environment using nonphysician operators.

At trauma centers in the United States, the FAST examination has become routinely used to evaluate trauma patients (24). Because of imaging limitations aboard ISS, the efficacy of the FAST examination for screening traumatic injuries in microgravity environments has come under increased scrutiny. Ultrasound is an imaging tool that is noninvasive, repeatable, and transmittable via satellite. It involves no ionizing radiation, which is of particular benefit to space travelers, who are exposed to high levels of environmental radiation. Terrestrial FAST examinations rely on gravitational pooling of fluid by imaging the most dependent portions of the peritoneum for free fluid. A 2003 study by Kirkpatrick and co-investigators, which examined the feasibility of the FAST examination in microgravity, used a porcine model and a microgravity environment created aboard a KC-135 aircraft using parabolic flight. The animals were scanned with a HDI-5000 ultrasound system using a 5–2 MHz curved array transducer (21). A ground-based study was used to develop the techniques used in parabolic flight. A peritoneal lavage catheter was inserted, and varying amounts of normal saline were instilled. Scans of the peritoneal cavity were obtained in the perihepatic space, pelvis, and perisplenic areas. An additional rapid survey of the midline abdominal area (abdominal sweep) was taken. Images were obtained in zero gravity (0 *g*) and hypergravity (1.8 *g*). On-board sonographers performed the examinations. The images were recorded and shown to a panel of expert sonologists in a blinded fashion (21). Sonologists judged the imaging at 0 *g* or 1.8 *g* to be no more technically difficult than that in normal gravity (1 *g*). Overall, the blinded reviewers found that 80% of images were of adequate quality to determine the presence or absence of free fluid. The total proportion of indeterminate images was unrelated to weightlessness or hypergravity. The on-board sonographers were able to easily detect injected fluid in all imaging locations during real-time evaluation. However, when the images were examined retrospectively by blinded review, the amount of fluid injected correlated with the sonographic estimation of intraperitoneal fluid in only the pelvis and perihepatic space. One explanation for this could be anatomical differences between porcine and human models. Overall, the perihepatic space was the area most accurately scanned during weightlessness. The probability of a positive fluid diagnosis ranged from 9% with no actual fluid present to 51% with 500 mL of fluid present (21).

Another study examined the ability of nonphysician crew members with modest training in ultrasound operation to obtain high-quality FAST images using remote guidance. The scan was conducted by a crew member in the Human Research Facility in ISS's Destiny Module. Images were transmitted via satellite to NASA's Mission Control Center in Houston, TX. A radiologist with extensive experience in ultrasound and remote guidance conducted the examination by viewing downloaded images and instructing the crew member to adjust settings and probe position. The study concluded that there were no significant differences between the FAST examinations performed in orbit and those performed in standard terrestrial conditions (25).

Two reports have examined the use of ultrasound in microgravity to diagnose pneumothoraces and hemothoraces (20, 26). A 2001 report investigated the ability of ultrasound to measure the extent of pneumothorax in a porcine model. In this study, each animal had a 16-French Cordis introducer inserted into its right chest cavity with varying amounts of air insufflated. Ultrasound images were obtained using an HDI-5000 ultrasound machine with a broadband 12–5 MHz linear probe or a Sonosite 180 (Sonosite, Inc.; Bothell, WA) with a broadband 5–2 MHz probe. Anterior, posterior, and lateral images were obtained. The presence of a pneumothorax was determined by the absence of lung sliding, which is the to-and-fro movement of the visceral-parietal interface during respiration. A microgravity environment was created using parabolic flight aboard a NASA KC-135 research aircraft. Images were obtained during level flight (1 *g*) and parabolic flight (0 *g*) (26).

During examinations in level flight, there was a progressive loss of lung sliding from the anterior window to the lateral window, and finally to the posterior window; this loss of lung sliding was seen as insufflation increased. After insufflation of 150 cm^3, the loss of lung sliding or partial lung sliding was noted anteriorly, but not posteriorly. The loss of posterior lung sliding became evident at 250 cm^3. During microgravity, there was no anterior to posterior progression of lung sliding, and all three windows appeared to have equal sensitivity. This study concluded that ultrasound for pneumothorax appeared to be more sensitive in the microgravity environment, perhaps because of a more uniform distribution of air in the absence of gravity (26).

A 2004 report further evaluated the differences in sonographic characteristics of pneumothoraces and hemothoraces in both ground models and microgravity. A HDI-5000 ultrasound system with a broadband 4–7 MHz linear probe was used to perform the examinations. Air was introduced into the chest cavity using a manner similar to the previous study and microgravity was recreated using parabolic flight. In the pneumothorax ground model, between 50 mL and 200 mL of air was introduced with progressive loss of lung sliding from the anterior to posterior interface respectively. In the microgravity studies, the pneumothorax model showed loss of lung sliding in all fields after 100 mL of air. No anterior to posterior progression of lung sliding was seen (20).

In the hemothorax ground model, aliquots of dyed normal saline were introduced through a thoracostomy tube. Results showed that the fluid tended to collect in the posterior windows at 25 mL of fluid. Fluid appeared in the anterior windows when the injected volume exceeded 100 mL. In microgravity, a layer of fluid was evident in both windows after injection of 50 mL of fluid (20).

Ultrasound evaluation of the thoracic cavity shows promise in excluding pneumothorax and hemothorax in microgravity. In situations where chest radiography and CT scanning are virtually impossible, ultrasound diagnosis can help avoid the high cost of emergent medical evacuation in space travel.

A medical emergency aboard ISS may necessitate endotracheal intubation. Endotracheal tubes may be misplaced into the esophagus or may be inserted too far into a mainstem bronchus. Ultrasound has been used to evaluate endotracheal tube placement in a manner similar to that used to identify a pneumothorax. One study evaluated 15 patients using a Sonosite 180 with a high-frequency 10–5 MHz linear array transducer (27). The patients underwent endotracheal intubation and images were obtained to evaluate for comet-tail artifacts and lung sliding. A comet-tail artifact is a normal artifact believed to arise from hyperechogenic reverberation from the pleural line. Images were obtained in the third or fourth intercostal space bilaterally during preoxygenation, induction, and endotracheal intubation, and immediately after intubation.

In 13 elective-surgery patients, a comet-tail artifact was present throughout the procedure, thus implying normal pleural apposition. Lung sliding was absent during all apneic periods, suggesting a lack of motion between the visceral and parietal pleura interfaces. In two trauma patients, comet-tail artifact, but not lung sliding, was visualized in the left hemithorax, suggesting a right mainstem intubation. This was later confirmed using chest radiography (27).

The use of ultrasound is not limited to visceral organs. It also has the capability of evaluating muscles, tendons, and joint spaces. Space flight typically includes healthy individuals less likely to possess chronic health problems. However, even the most resilient musculature can be prone to injury because of the decrease in mass of bone, tendons, and muscle in microgravity (28).

A 2005 study evaluated the ability of a nonphysician crew member to obtain diagnostic-quality sonographic images of the shoulder (28). The crew member received limited ultrasound training and conducted the ultrasound aboard ISS with real-time guidance from experienced, ground-based sonologists. The evaluations were performed rapidly (within 15 mins) and accurately. The ultrasound frames demonstrated excellent quality of all shoulder views. It was determined that these images could be used to exclude substantial shoulder musculoskeletal injury. This study supported the notion that nonphysician crew members with modest training could perform complex ultrasound tasks when guided by experienced sonologists.

Facial trauma and ocular emergencies also pose a risk to astronauts. Because of a lack of ophthalmologic equipment aboard ISS, ultrasound will likely play an important role in diagnosing eye emergencies. Emergency-department bedside ultrasound has been shown to be sensitive and specific for the detection of ocular pathology (23). One study carried out in ISS analyzed the ability of nonphysician crew members to obtain ultrasound images of the eye. These crew members underwent limited ultrasound training before their mission. The ultrasound examination was conducted aboard ISS and transmitted via satellite to a radiologist at NASA's Mission Control Center. The radiologist viewed the images and instructed the crew member on how to adjust machine settings and probe placement. The images obtained in this study were of excellent quality and were similar to images taken by an expert sonographer during a baseline examination. The investigators concluded that crew members performing ultrasound could provide essential information for guiding clinical decision-making (29).

To further assess the role of ultrasound imaging in space travel, additional study should be conducted in three areas. First, interrater reliability should be analyzed for the interpretations of the ultrasound images transmitted from ISS. Second, feasibility should be assessed for ultrasound detection of bony fractures by nonphysician crew members. Third, the learning curve should be studied for ultrasound training of nonphysician crew members.

Commercial interests have begun assessing excursions into low earth orbit. NASA and other national space agencies plan to complete construction of ISS by 2010, develop improved spacecraft, establish a Moon station, and eventually send men to Mars. Severe budget and payload constraints will be ubiquitous as space travel increases in frequency and duration. Commercial flights could add the complication of space travelers with average or poor health. Because of its portability, reproducibility, accuracy, and ease of use, ultrasound will continue to play an important role in aerospace medicine in the future.

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