Point-of-Care Ultrasound for Pulmonary Concerns in Remote Spaceflight Triage Environments

Benjamin D. Johansen; Rebecca S. Blue; Tarah L. Castleberry; Erik L. Antonsen; James M. Vanderploeg

INTRODUCTION: With the development of the commercial space industry, growing numbers of spaceflight participants will engage in activities with a risk for pulmonary injuries, including pneumothorax, ebullism, and decompression sickness, as well as other concomitant trauma. Medical triage capabilities for mishaps involving pulmonary conditions have not been systematically reviewed. Recent studies have advocated the use of point-of-care ultrasound to screen for lung injury or illness. The operational utility of portable ultrasound systems in disaster relief and other austere settings may be relevant to commercial spaceflight.

METHODS: A systematic review of published literature was conducted concerning the use of point-of-care pulmonary ultrasound techniques in austere environments, including suggested examination protocols for triage and diagnosis.

RESULTS: Recent studies support the utility of pulmonary ultrasound examinations when performed by skilled operators, and comparability of the results to computed tomography and chest radiography for certain conditions, with important implications for trauma management in austere environments.

DISCUSSION: Pulmonary injury and illness are among the potential health risks facing spaceflight participants. Implementation of point-of-care ultrasound protocols could aid in the rapid diagnosis, triage, and treatment of such conditions. Though operator-dependent, ultrasound, with proper training, experience, and equipment, could be a valuable tool in the hands of a first responder supporting remote spaceflight operations.

KEYWORDS: sonography, lung, medical protocol, spaceflight, telemedicine, edema, endotracheal tube, pneumothorax, ebullism, high altitude.

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Ultrasound has traditionally been seen as a suboptimal modality for diagnosis and treatment of pulmonary injury or illness.[6,10,38] Sound waves do not penetrate well through an aerated lung, resulting in an interrupted image with limited anatomical correlation. Even so, various lung signs and patterns have been recognized that correlate with lung injury or illness.[38,39] Pulmonary ultrasound is rapidly gaining recognition as a bedside diagnostic tool in emergency departments and intensive care units.[39] Experts are now recommending the use of ultrasound as an adjunct for the clinical monitoring and management of a number of thoracic pathologies, including trauma, pneumothorax, effusions, edema, and parenchymal disease.[39]

Some researchers have suggested that the diagnostic accuracy of pulmonary ultrasound, when performed by trained personnel, can be equivalent or even superior to computed tomography (CT) and chest radiography in a number of lung disorders.[16,39,44] Further, improvements in technology have made ultrasound equipment more compact, portable, and durable, and therefore increasingly useful in austere conditions.[22,23] Ultrasound has been successfully used in a variety of environments, including hot and dusty military operations, cold and high-altitude sites, and humid jungle settlements.[22,24] Ultrasound is the only imaging modality on the International Space Station (ISS), allowing astronauts to perform imaging examinations with the aid of expert guidance from the ground.[6,24,40]

From the University of Texas Medical Branch, Galveston, TX, and the Center for Space Medicine, Baylor College of Medicine, Houston, TX.

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Address correspondence to: Benjamin Johansen, D.O., M.P.H., Department of Preventive Medicine and Community Health, University of Texas Medical Branch, 301 University Blvd, Galveston, TX 77555-1110; bdjohans@utmb.edu.

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The versatility of ultrasound makes it an ideal tool to augment care in limited-resource environments. For example, pulmonary ultrasound can help rapidly identify causes of acute respiratory failure.[16,39] It can also aid in treatment through verification of the correct placement of an endotracheal tube and demonstration of bilateral pleural sliding following intubation.[34] Ultrasound helps avoid intrathoracic structures and confirm instrument placement during invasive procedures such as chest tube insertion, thoracentesis, and tracheostomy.[4,31,32] It can also contribute to the diagnosis of rare conditions, such as altitude-related pulmonary decompression sickness and ebullism.[2,9,21]

With the development of the commercial human spaceflight industry, spaceflight will be offered to more diverse participants in terms of age and health status.[26] Further, commercial human spaceflights are intended to launch from remote sites around the world.[9] These facilities are far from formalized medical care, similar to the remote launch and landing environments used by the National Aeronautics and Space Administration (NASA) and its international partners. Should a mishap occur, a rapid triage evaluation will be required to inform field care and evacuation decisions.[30] Some spaceflight-related pulmonary injuries, such as barotrauma, may necessitate alternative treatment modalities to standard trauma resuscitative practices.[9,21] Given the current lack of prehospital imaging support of triage and decision-making, portable ultrasound may help identify injury, assist prehospital management techniques, and stabilize a patient for transfer to definitive care.[9,21]

When used by an experienced practitioner, ultrasound could help in making a rapid presumptive diagnosis and aid triage responses for spaceflight operations.[6,16] Protocols already exist to rapidly diagnose life-threatening pulmonary injury that can be used by medical first responders in remote locations providing immediate care for spaceflight-related injuries. These protocols could be adapted to account for the unique stressors of spaceflight and to augment the rapid triage of spaceflight participants with potential injury.

This article will outline previous studies in the application of ultrasound technology in austere and remote environments not dissimilar to spaceflight. Protocols and novel applications to rapid response and prehospital medical care after spaceflight mishap will be addressed, focusing on use of ultrasound for pulmonary pathology.

METHODS

A systematic review was conducted in PubMed, Web of Science, the Defense Technical Information Center, and Google Scholar for all available literature on human and animal studies involving ultrasound for diagnosis of pulmonary injury or compromise, as well as the use of ultrasound in austere environments. The search terms included "pulmonary," "ultrasound," "point-of-care," "lung," "austere environment," "aerospace," "ebullism," "pneumothorax," "high altitude," "pulmonary edema," "contusion," and "endotracheal tube." All titles obtained from these criteria were reviewed. Studies published in a language other than English without available translation and articles regarding ultrasound that did not specifically address out-of-hospital applications or pulmonary conditions were discarded. All other articles were reviewed in their entirety.

Using these methods, 124 references were identified that met search criteria and addressed the topics of interest. Of these, 15 were published in languages other than English without available translations, and 65 addressed concerns outside the scope of this article, such as pulmonary hypertension and cardiothoracic ultrasound techniques for in-hospital sonographic applications. The remaining 45 studies were included in the review. Literature obtained includes in vitro and in vivo studies, case studies, technical reports, white papers, and review articles.

RESULTS

From the operational perspective, ultrasound is an imaging modality with a number of important advantages. These include general safety, absence of ionizing radiation, unlimited repeatability, and versatility that allows a single operator to examine a wide range of anatomical sites and parameters.[8] The modern digital systems are very portable and boast a large image storage space without the need for accessories or disposable parts.[8]

There are a number of known disadvantages for portable ultrasound devices, including overall fragility that requires protective packaging for transport. Most systems are not designed or tested for use in extreme environments and may not function well.[14] The piezoelectric crystal array of the probe is quite fragile and any impact may cause performance degradation.[30] Battery life is limited and alternative charging modalities, such as solar-powered arrays, are not immediately available. Although basic sonography can be learned in a short amount of time, some scanning techniques require specific training and skill for adequate imaging.[6,30,37] Even so, it is not always necessary for the operator to have a background in medical ultrasound or the ability to interpret images; as some studies (discussed below) have demonstrated, minimally trained operators are capable of obtaining high-quality images that can be interpreted by remotely located experts.

Use of Ultrasound in Austere Environments

The versatility of ultrasound allows for use in a wide variety of applications and environments.[20] Portable ultrasounds have been employed following natural disasters, helping with patient triage and resource management with varying degrees of success and limitations.[5,20,33] For example, a hand-held device was used in a 2010 disaster response following a devastating Haitian earthquake.[33] While the device was useful in screening patients during triage, it could only capture static images, rendering it unreliable for more detailed cardiopulmonary evaluations.[33] Even so, of the images obtained on 51 patients, 76% of scans influenced treatment decisions, with the remaining 24% resulting in equivocal or indeterminate findings.[33] In 2005, emergency physicians used a portable ultrasound machine after a hurricane disaster in Guatemala, performing 137 scans for a variety of complaints.[5] Ultrasound mandated emergent treatment in 6% of patients and ruled out a potential diagnosis in a further 42% of scans, demonstrating that point-of-care ultrasound can provide on scene diagnostic and triage capability for a variety of clinical scenarios.[5]

Following the Armenian earthquake in 1988, physicians used available ultrasound machines where other imaging modalities were lacking to perform screening examinations of disaster victims.[20] Within the first 72 h, 750 patients were admitted to the hospital and 400 received ultrasound examinations; of these, 304 demonstrated no clinically significant pathology and could be screened out with little to no use of other limited resources.[20] In the remaining 96 patients, ultrasound demonstrated significant pathology requiring treatment.[20] Only four false negative cases were reported, all with retroperitoneal or hollow viscus injuries, areas of the body in which ultrasound has some limitation, resulting in lower sonographic sensitivity.[20]

Remote Ultrasound Interpretation and Minimal Provider Training

To help widen the diagnostic capabilities of ultrasound, images can be sent wirelessly from a remote site to physicians for interpretation.[11,20] A 2003 study evaluated the image clarity and diagnostic accuracy of field performance and interpretation of limited thoracic and abdominal sonographic exams, known as a "focused assessment with sonography in trauma" or FAST, which identify fluid (usually blood) around the heart and abdominal organs after traumatic injury.[20] FAST examinations were performed on patients with free pericardial or intraperitoneal fluid in a remote hospital prior to patient transport, with images transmitted to the receiving hospital.[20] The study found that real-time wireless transmission produced quality images that were easily interpreted by the remote reading physician, allowing for preliminary diagnostic capabilities prior to transport to definitive care.[20]

Further, ultrasound can be successfully performed by personnel without medical background when images are sent via satellite for interpretation by trained physicians.[11,20] A study was performed by astronauts aboard the ISS in which a crewmember with limited ultrasound and medical experience obtained images via remote guidance from a trained ground operator for probe placement and ultrasound settings.[20] This study, performed in a controlled setting, demonstrated no significant differences between the FAST exams performed in orbit and those performed on Earth by trained sonographers.[20] A similar study used the same ISS protocol, with untrained operators performing thoracic ultrasound exams under remote expert guidance in isolated high-altitude locations, to further demonstrate remote imaging capability.[24] The minimally trained, nonexpert operators were remotely guided through ultrasound protocols and were able to identify classic pulmonary findings, such as lung tissue sliding and "B-lines" (hyperechoic reflections perpendicular to the pleural line, signifying pulmonary edema), necessary to diagnose pulmonary edema and rule out pneumothorax.[24] In addition, researchers examined the durability and limits of portable ultrasound in the extreme environment of Mt. Everest.[24] The study exposed the ultrasound equipment to high altitudes of up to 8230 m (27,000 ft), with a 1524 m/min (5000 ft/min) ascent, and temperatures as low as −7°C (19°F).[24] The portable computer and video streaming device used to communicate with remote-guidance operators was shown to function equally well at both high and low altitudes, without limitations from cold exposure.[24]

Confirmation of Advanced Airway Interventions

Endotracheal intubation is a potentially life-saving procedure, but carries the risk of morbidity and mortality associated with unrecognized esophageal or main-stem bronchus intubation, especially in environments where immediate radiographic confirmation is unavailable.[19,34,41] In prehospital emergency scenarios, patient positioning during intubation may be less than ideal, ambient noise levels from prehospital environments and transport vehicles make lung auscultation virtually impossible, and alternative confirmatory equipment is not available.[4,6] Prehospital providers, therefore, must rely on direct visualization and limited auscultation to confirm endotracheal tube (ETT) placement. While direct visualization of the tube passing through the vocal cords, with auscultation confirming bilateral breath sounds, is considered good evidence of successful placement, up to 55% of right main-stem intubations are not detected by these actions alone.[34,41] Capnography is often used for confirmation, but studies report only 93% sensitivity in distinguishing endobronchial from endotracheal placement using capnography alone.[34] Similarly, continuous end-tidal CO_2 monitoring relies on adequate pulmonary blood flow for accuracy, but sensitivity can be as low as 72% in patients experiencing a low flow state such as traumatic shock.[41] In the hospital, these techniques would be followed by radiographic verification; unfortunately, this confirmation is generally unavailable in a remote field environment.[34,41]

The use of ultrasound to confirm ETT position has been evaluated in cadaveric studies.[19] ETT position is confirmed by placing the ultrasound probe longitudinally over the cricothyroid membrane, allowing for identification of the larynx by visualizing two hyper-echoic laryngeal lines in a longitudinal plane.[19] Visualization of a "snow-storm" appearance between these two lines confirms successful intubation, and lack of this sign and visualization of tube movement posterior to the two laryngeal lines signifies an esophageal intubation.[19] Initial studies reported a sensitivity of 97.1% and specificity of 100%, demonstrating the utility of ultrasound for confirmation of successful intubation.[19] A lower sensitivity of 51.4% and specificity of 91.4% was reported for identification of esophageal intubation.[19] Even so, these findings suggest that the use of ultrasound may be a rapid and accurate method of detecting dynamic ETT placement during the intubation process, though the study was limited by small sample size and cadaveric modeling.[19]

Controlled trials have since been performed to identify the utility of ETT detection in live humans.[41] One study on 33 subjects reported a sensitivity of 100% and specificity of 100% in confirmation of successful endotracheal intubation, though this study was limited to dynamic evaluations of low-risk patients in nonemergent conditions and a controlled operating room environment.[41] In another study of 115 patients requiring emergent intubation, 31 of these during cardiopulmonary resuscitation, bedside ultrasound was used to identify bilateral lung sliding (gliding of parietal and visceral pleura visualized by ultrasound of the intercostal space during ventilation) to exclude mainstem intubation.[34] Sensitivity was reported ranging from 90–93%, and specificity from 42–100% dependent upon clinical scenario (with cardiac arrest patients resulting in 100% specificity, noncardiac arrest patients only 43%).[34] This technique is not without concerns, as there was a possibility that lung sliding could be seen in nonparalyzed patients of single-lung intubation with preserved spontaneous respiratory effort.[34] This may be the etiology of the false positive cases noted among patients who were not in the cardiac arrest group.[34] A similar study evaluating 13 elective intubation and 2 emergent cases expanded sonographic findings to include the presence or absence of lung sliding, enhancement of this movement with color power Doppler, and "comet-tail" artifacts (horizontal movement of the visceral pleura).[4] These features were assessed in all phases of the intubation process with successful identification of right main-stem intubation when sliding was absent in the contralateral lung.[4]

In situations of head trauma and airway compromise, where patients cannot be stabilized with placement of an ETT, percutaneous tracheostomy may be required.[18] Identifying anatomical landmarks prior to tracheostomy placement in the field can be challenging due to head and neck trauma, less-than-ideal patient positioning, and the presence of obstructive equipment (such as a helmet or harness) on a patient.[18,21] When performed by a trained operator, ultrasound can improve identification of vasculature and anatomical landmarks prior to intervention.[18] In a longitudinal plane, tracheal rings sonographically appear as consecutive hypoechoic ovoid structures, whereas in a transverse plane they appear as a crescent-shaped structure superimposed on reverberation artifact representing the tracheal air column.[18] Proper identification of appropriate landmarks, such as the cricoid and thyroid cartilage, cricothyroid membrane, and tracheal rings, can ensure accurate placement of a tracheostomy and assist in selection of an appropriate tracheostomy tube.[18]

Ultrasound Guidance in Intrathoracic Procedures

Sonography can help to accurately position needles for thoracic decompression or thoracostomy tubes for the treatment of pneumothorax and drainage of pleural fluid collections.[6,18] Significant chest wall thickness due to edema or truncal obesity may lead a medical responder to underestimate an appropriate needle insertion depth, and the presence of other concurrent medical conditions may add complexity to such procedures.[18] Tools found on many ultrasound machines to freeze an image and measure a distance with caliper functions provide accurate calculations for needle insertion depth prior to initiating the procedure.[18] Such measurements only remain accurate when positioning is unchanged between the time of measurement and the insertion of the needle. Other capabilities of many state-of-the-art machines, such as color Doppler, may help avoid complications or identify altered landmarks due to body habitus or comorbidity.[18] For example, one study involving 50 patients demonstrated that the intercostal artery could be reliably identified with thoracic ultrasound.[31] Two ultrasounds were used, a portable device and a more complex system used in hospital settings, to evaluate prone-positioned patients.[31] Color Doppler was used via linear probe in three chest locations to identify the vessel as a pulsatile structure within the intercostal space, and findings were compared with CT images using vessel extraction software that tracked the course of the vessel.[31] CT scanning identified the intercostal artery in 128 of 133 positions.[31] A pulsatile vessel with a waveform characteristic of an intercostal artery on pulse-wave Doppler was located in 114 of 133 positions.[31] It was noted that vessel identification was more rapid with the higher-end ultrasound, taking 14 s on average, compared to the average portable machine time of 40 s, though there was discrepancy in locating the exact position of the vessel.[31] When compared to CT, ultrasound had increased ability to locate vessels lying behind the overlying rib by placing the probe at an upward angle, though slightly decreased reliability overall.[31] The study demonstrated that intercostal arteries could potentially be identified by a trained individual using a portable ultrasound machine when alternative imaging modalities are unavailable.[31]

Following thoracostomy tube insertion, verification of placement is necessary to identify appropriate intrathoracic or inadvertent extrathoracic tube position.[32] An extrathoracically malpositioned tube can result in life-threatening complications for the hemodynamically unstable and those requiring positive pressure ventilation.[11] In a study using an ultrasound with a linear-array 10-MHz transducer, researchers described a sonographic finding in a cadaveric model that verified intrathoracic chest tube position with 100% sensitivity and specificity.[32] At the insertion site, a subcutaneous hyperechoic arc is noted that is created by the tube; disappearance of the hyperechoic arc when moving the probe cephalad indicated that the thoracostomy tube had entered the pleural space, resulting in proper intrathoracic placement.[32] If the hyperechoic arc remained, continuing the full length of the chest tube, this sign confirmed extrathoracic placement.[32] These findings were referred by the researchers as the "Disappearance/Intrathoracic, Continuation/Extrathoracic" sign.[32] Limitations of the study included the use of a small number of unembalmed cadaveric subjects, which may be difficult to relate to a live population with a diversity of body habitus and differences in anatomy.[32]

Pulmonary Edema

As described previously, pulmonary ultrasound techniques can be used to effectively diagnose pulmonary edema by identifying and quantifying the artifact known as "B-lines" or "ring-down artifact."[7,16,39] B-lines arise from the pleural line and extend to the bottom of the ultrasound screen without fading, moving horizontally with lung sliding.[16,39] They represent subpleural areas with decreased air and increased fluid content, suggesting pulmonary congestion.[16] Studies have validated the advantages of using B-lines for detecting pulmonary edema compared to other traditional imaging techniques such as radiography and CT scan.[19,39,43]

One study examined the correlation between the quantity of B-lines and indicators derived from other modalities, such as chest radiography, wedge pressure, and the indicator dilution method of extravascular lung fluid, and found that sonographic exams were faster than wedge or dilution methods while correlating closely with traditional measurements.[1] Importantly, this study concluded that ultrasound data were of sufficient accuracy to detect interstitial pulmonary edema before manifestation of clinical symptoms.[1] In a much larger study, a multicenter, prospective trial examined the use of pulmonary ultrasound for the diagnosis of decompensated heart failure.[27] The researchers found that sonography had higher sensitivity and specificity for the diagnosis when compared to traditional examinations or radiography for the evaluation of acute dyspnea, suggesting that lung sonography could be an important supplementary diagnostic tool for such evaluations.[27]

It should be noted that B-lines and "comet-tails" (or "comets" or "lung comets") are not the same, despite their frequent interchangeable use in point-of-care ultrasound publications and even official tutorials. These two artifacts may be very different in their imaging pattern, underlying physics, and significance. The original "comet-tail artifact" in organized radiology is a frequent normal finding, a short, fading reverberation artifact that does not propagate and amplify all the way down the image. Comet-tails are useful in positively identifying the pleural surface while ruling out pneumothorax and confirming the horizontal movement of the visceral pleura. Comets also frequently accompany foreign bodies and cholesterol or calcium deposits elsewhere in the human body. Pulmonary B-lines, on the other hand, are a largely pathological finding and involve, besides reverberation, a resonance effect in the fluid-rich interstitial spaces within the still-aerated lung tissue, generally indicative of pulmonary congestion. It is acceptable to consider B-lines as a subtype of comet-tails, as suggested by Lichetenstein,[16] while recognizing that not every comet-tail is a B-line. "B-lines" is the preferred term for indicating pathology according to 2012 consensus recommendations on pleural and lung ultrasound.[39] In order to avoid further propagation of this already-widespread confusion, we recommend distinction in the interpretation and use of these terms, and avoidance of the nonspecific term of "comet-tails" when true B-lines are discussed. We use the term B-lines in this text to describe any fully extending, nonfading artifact that meets the definition of B-lines published in the recommendations;[39] use of the term comet-tail is limited to indicating horizontal movement of pleura (such as when ruling out pneumothorax).

High Altitude Pulmonary Edema

In 2006, researchers demonstrated successful diagnosis of high altitude pulmonary edema (HAPE) via ultrasound by the identification of B-lines, which correlated with significantly lower oxygen saturation in the HAPE patients compared to the control subjects.[7] Further, reduction in B-lines with resolution in HAPE suggests that ultrasound can provide a real-time visual representation of extravascular lung fluid, perhaps even more sensitive than conventional radiography, which often lags behind clinical resolution.[7] Similar studies identified early evidence of HAPE prior to clinical symptoms.[29] Thus, sonographic B-lines can be interpreted as a preclinical sign of pulmonary edema, allowing for earlier intervention and prevention of clinical deterioration.[29]

Pneumothorax and Pulmonary Contusion

Chest radiography is the most common modality used to diagnose and screen for pneumothorax, but it is not without limitations, and may be false-negative in as many as 30–40% of patients.[17] CT is the current gold standard, but is limited by its accessibility and imaging time, which can potentially delay the diagnosis or treatment.[17] Ultrasound has been demonstrated to be successful in real-time diagnosis of pneumothorax at bedside, with studies showing equal or better accuracy when compared to conventional radiography.[6,17,39]

One retrospective study reviewed ultrasound evaluations that identified the absence of lung sliding as well as the presence of "A-lines" (hyperechoic horizontal lines parallel to the pleural line at regular intervals), which represent a normal or excessive amount of air.[1,10,17] A third examination sign evaluated was the presence of a "lung point," the transition point between the sonographic pattern of pneumothorax (absence of lung sliding) into a normal pattern of lung sliding.[10,17,39] The presence of A-lines without B-lines is considered pathognomonic for pneumothorax; the presence of a lung point represented direct visualization of the pneumothorax and provides information about the magnitude of the pneumothorax.[17,39] The study evaluated 43 cases and 237 controls and demonstrated a 100% sensitivity and 78% specificity for identification of occult pneumothorax by absence of lung sliding alone.[17] Absent lung sliding plus A-sign resulted in 95% sensitivity and 94% specificity, where lung point examination resulted in a 79% sensitivity and 100% specificity.[17] Ultrasound is also useful in reducing the need for repeat radiography or confirmational CT scans when diagnosing occult pneumothorax.[17,39] Other studies have evaluated adding a pulmonary component to the standard FAST examination.[12] Results suggested that sonographic exam can be more sensitive than chest radiography alone when compared to the gold standard of CT.[12,39]

In patients with traumatic injuries requiring immobilization, limiting chest radiography to anteroposterior supine views only, small pneumothoraces are missed in up to 30–50% of patients on initial evaluation.[3] The use of ultrasound alone in these immobilized patients has been shown to successfully identify even small pneumothoraces, with a sensitivity of 98.1% and specificity of 99.2%.[3]

Ultrasound evaluation of pneumothorax is not without its limitations. Bullous emphysema, pleural adhesions, fibrosis, and extensive subcutaneous emphysema are conditions that can result in the absence of lung sliding and can be confused for a pneumothorax.[3,6,39] Evaluations are best performed and interpreted by trained practitioners with repeated sonographic technique over multiple thoracic areas to ensure visualization of the pathology.[3,6]

Pulmonary contusions are a common result of blunt trauma injuries and can go undiagnosed in emergency evaluations.[36] Studies have demonstrated that trained sonographic operators can identify, via the presence of lung sliding, the presence or absence of pneumothorax even in the presence of pulmonary contusion.[6,28] Use of additional lung findings, such as comet-tails, can assist in the exclusion of pneumothorax with high sensitivity.[6,17,35] Further, the presence of B-lines has been shown to be characteristic of early pulmonary contusion, providing sonographically confirmed and presumptive diagnoses in clinical scenarios suggestive of traumatic contusion.[35,36,39]

Lung contusions are known to evolve over the course of three stages: the first from acute traumatic damage to the lung parenchyma, the second to edema 1–2 h after the initial trauma, and the final occurring as pulmonary air spaces fill with blood, inflammatory cells, and tissue debris.[36] Studies have demonstrated that diagnosis is more accurate with ultrasound during stages 1 and 2 compared to radiography.[36] Prior research has shown that, while chest radiography may yield sensitivity as low as 27%, ultrasound examinations can make a diagnosis of even early lung contusions with 94% sensitivity and 96% specificity.[36]

Prehospital Protocols for Post-Spaceflight Recovery

There are multiple pulmonary injuries that might be seen following a spaceflight mishap, including those related to a sudden decompression of a vehicle.[9] For example, ebullism is the spontaneous evolution of liquid water to water vapor at body temperature when ambient pressure is 47 mmHg or less; this condition has a high potential for morbidity and mortality.[21] Sequential treatment steps involve repressurization, high-frequency percussive ventilation, addressing other barotraumas and decompression sickness, field medical support, and safe transfer for definitive medical care.[21] Ultrasound could aid in verifying ETT position to secure the airway for percussive ventilation prior to hospital transfer.[21,34] Ultrasound evaluation could provide clues to support other clinical signs of barotrauma, such as pneumothorax.[6,10,17] In the event of a tension pneumothorax, ultrasound could help in prehospital needle thoracostomy and chest tube placement.[18,31,32]

Many ultrasound protocols designed for rapid pulmonary evaluation in the prehospital environment could be applied to triage after a spaceflight mishap. One example is the Bedside Lung Ultrasound in Emergency (BLUE) protocol.[16] The BLUE protocol is a rapid prehospital or emergency room examination that can be completed by trained providers in less than 3 min to evaluate patients experiencing severe dyspnea or acute respiratory failure.[13,14,16] The protocol uses pulmonary signs, combined when indicated with venous analysis, to help identify specific pulmonary diagnoses with 90.5% accuracy.[13,15] Standard thoracic examination points include anterior lung sliding, anterior B-lines, and "posterolateral alveolar or pleural syndrome."[13,15] The BLUE protocol is performed when clinical doubts remain after a complete physical examination.[15] Although originally designed for use in critical care units, protocols like these can be performed in a variety of environments, including prehospital.[15,16]

DISCUSSION

A substantial body of peer-reviewed literature supports the use of pulmonary ultrasound imaging, performed by experienced operators, as a useful modality for rapid evaluation and guidance of treatment in the prehospital environment. The use of protocols for the evaluation and management of pulmonary injury and disease have proven to be reliable when performed by a trained operator. Given the often complex prehospital presentations of trauma patients, ultrasound holds a potential as a supplemental diagnostic tool in the field. This is especially important in the setting of a spaceflight mishap that may put patients at risk for unusual pulmonary injuries related to barotrauma in addition to common traumatic injuries. In a review of autopsies performed on pilots involved in fatal general aviation accidents, lung injury accounted for 37.6% of all organ injuries and 58% of all thoracic injuries.[42] Lung injuries after survivable spaceflight-related accidents would be expected to show similar pulmonary injury statistics. As spaceflight operations frequently take place in remote environments far away from a well-equipped emergency room or trauma center, the addition of ultrasound to current prehospital management capabilities may provide significant benefits to providers responding to spaceflight mishaps.

Well-studied, evidence-based ultrasound protocols exist that are directly transferable to an aerospace mishap recovery setting to augment rapid and systematic assessment of injuries. The FAST exam is the most common and widely known protocol and can be expanded to include the lungs to rule out pneumothorax. Similarly, the BLUE protocol was developed for use in patients experiencing severe dyspnea admitted to an intensive care unit, though its use has been expanded to other clinical evaluation and prehospital scenarios.[14] Inclusion of ultrasound in the assessment for and treatment of ebullism or barotrauma could aid in decision-making for procedures, including endotracheal intubation, needle decompression, or tube thoracostomy.[9,21,25] A successful ultrasound examination as an adjunct to prehospital clinical evaluations may help identify the need for timely transfer of a patient to the nearest medical facility or allow for initial on-site treatment.

The operational circumstances surrounding an aerospace mishap create less than ideal conditions for the medical responder to perform a rapid yet adequate evaluation and initial treatment. The mishap recovery site may involve more than one victim, various hazards, and likely chaotic initial response patterns. In demanding conditions, it is even more important to ensure adequate preparedness of the providers for systematic and accurate assessment, including the use of ultrasound equipment and techniques. Those performing point-of-care ultrasound exams should therefore be closely familiar with the equipment and have demonstrated proficiency in obtaining and interpreting images from a wide variety of acutely ill patients with different body habitus.

The main limitation of proper ultrasound use is operator experience. While the literature reviewed suggests that, in the hands of an experienced and trained operator, ultrasound can be equivalent or superior in certain cases to conventional imagery techniques, there appears to be a gap in the adoption of ultrasound for this purpose. Despite ultrasound devices being found in a variety of health care settings, its use has not yet achieved a more streamlined point-of-care approach to diagnosis and treatment. In many circumstances, ultrasound has increased the number of examinations performed due to instrument checks, interpretational doubts, and need for conformational imaging with more conventional techniques.[37] This phenomenon could be due in part to a lack of adequate formalized training among operators with a variety of backgrounds and disciplines. In order for the successful integration of ultrasound into point-of-care diagnosis and treatment, operators need to be familiar with the normal and abnormal appearance of tissues, sonographic findings unique to each examination, and a standardized methodology for diagnosis and treatment. Variability in body habitus, examination environments, and sonographic equipment only contributes to the complexity of such examinations and may lead to operator error. An increase in research is recommended to further define this gap in the adoption of point-of-care ultrasound use. The establishment of structured training and proficiency programs with subsequent performance evaluation of trained operators may help to increase the knowledge needed for the adoption of ultrasound as a first-choice imaging tool.

At the same time, multiple studies support the ability of minimally trained operators to perform simple, yet adequate imaging needed for rapid triage.[11,20,24] While this may not be ideal for thorough evaluations, minimally trained operators may be able to demonstrate simple clinical findings in field scenarios that aid in decision-making when no other imaging modalities are available. More evidence, beyond anecdotal case reports and experiments, is needed to establish the contribution of ultrasound performed by minimally trained first responders to the outcomes of traumatic accidents in prehospital environments. Current literature upholds the major benefit of ultrasound in such settings when performed and interpreted by a well-trained operator.

Ultrasound imaging is rapidly gaining acceptance as a valuable tool in the examination of the pulmonary system, and the accuracy of sonographic data obtained and interpreted by experienced operators in many cases compare to, or exceed, that of conventional imaging techniques. The portability of ultrasound equipment lends its use to a greater variety of operational environments, making it a useful piece of equipment to include in remote activities such as spaceflight-related field operations. The literature herein suggests that inclusion of ultrasound use in prehospital aerospace triage settings, with concomitant expertise within the medical response team, can provide important diagnostic and treatment advantages and improve the medical care provided.

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Authors and affiliations: Benjamin D. Johansen, D.O., M.P.H., Rebecca S. Blue, M.D., M.P.H., Tarah L. Castleberry, D.O., M.P.H., and James M. Vanderploeg, M.D., M.P.H., University of Texas Medical Branch, Galveston, TX; and Erik Antonsen, M.D., Ph.D., Department of Emergency Medicine, Center for Space Medicine, Baylor College of Medicine, Houston, TX.

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