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

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

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

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Ultrasound has traditionally been viewed as a less than optimal modality for diagnosis and treatment of the pulmonary system, as air-interfaces disrupt ultrasound views. Researchers have recently identified various lung signs and patterns indicative of lung injuries and illness improving the utility of pulmonary ultrasound. The compact size and ease of use of portable ultrasound machines has helped personnel involved in disaster relief, military operations, and, more recently, in support of operations on the International Space Station. With a goal towards longer duration missions, eventual exploration of Mars, and the development of the commercial space industry participants of varying ages and medical comorbidities will engage in activities with risk for pulmonary injuries such as pneumothorax, ebullism, and decompression sickness. The use of protocols to rapidly perform a pulmonary ultrasound exam could aid in triage and treatment of these participants. A systematic review of published literature on human studies was conducted involving the use of point-of-care pulmonary ultrasound techniques, ultrasound use in austere environments, and suggested examination protocols for triage and diagnosis. Recent studies support the utility and comparability of pulmonary ultrasound examinations to computed tomography and chest radiography, allowing for successful use in a wide variety of austere environments. Pulmonary injury and illness are among the potential health risks facing astronauts during orbital and suborbital space activities. The implementation of point-of-care ultrasound protocols could aid in the rapid diagnosis, triage, and treatment of such injuries should they arise. Ultrasound, with proper training and equipment, can be an invaluable tool to a medical first responder supporting spaceflight operations.

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List of Abbreviations

ACS	American College of Surgeons
AGE	Acute Gas Embolism
AP	Anteroposterior
ATLS	Advanced Trauma Life Support
BLUE	Bedside Lung Ultrasound in Emergency
CT	Computed Tomography
DCS	Decompression Sickness
DICE	Disappearance/Intrathoracic, Continuation/Extrathoracic
DTIC	Defense Technical Information Center
eFAST	Extended Focused Assessment with Sonography in Trauma
FAST	Focused Assessment with Sonography in Trauma
GSBS	Graduate School of Biomedical Science
HAPE	High Altitude Pulmonary Edema
ISS	International Space Station
NASA	National Aeronautics and Space Administration
UTMB	University of Texas Medical Branch
PE	Pulmonary Embolism
PLAPS	Posterolateral Alveolar or Pleural Syndrome
TDC	Thesis and Dissertation Coordinator

Chapter 1: Introduction

Ultrasound has traditionally been seen as a less than optimal modality for diagnosis and treatment of pulmonary injury or illness.(Gargani and Volpicelli 2014; Stefanidis et al. 2011) Sound waves are not well transmitted through an air-filled lung; thus, the presence of air in pulmonary tissue results in an interrupted, black image to the user. However, with technological improvements, various lung signs and patterns have been more recently recognized for identifying lung injury or illness.(Stefanidis et al. 2011) Pulmonary ultrasound is quickly becoming a valuable bedside diagnostic tool in many emergency departments and intensive care units. When performed by trained personnel, diagnostic results are nearly equivalent to those of computed tomography (CT) and chest radiography for most lung disorders.(Lichtenstein and Meziere 2008; Zanobetti et al. 2011) Through improvements in technology, ultrasound equipment has become more compact, portable, and durable, making it ideal for use in austere conditions.(Nelson et al. 2011) Ultrasound has been successfully used in a multitude of environments ranging from the hot temperatures and dusty military operations in Iraq, cold and high-altitude environments of Nepal, and humid Amazon jungle settlements.(Nelson et al. 2011b; Otto et al. 2009) Ultrasound is currently the only imaging modality on the International Space Station (ISS), allowing astronauts to perform various imaging examinations including eyes, kidneys, vasculature, and abdominal organs, with the aid of expert guidance from the ground.(Otto et al. 2009; Wagner et al. 2014)

The versatility of ultrasound makes it an ideal tool to aid in point-of-care diagnosis and treatment. Prior studies have demonstrated that pulmonary ultrasound can rapidly provide the diagnosis of causes of acute respiratory failure, including pulmonary edema, chronic obstructive pulmonary disease exacerbation, status asthmatics, pulmonary embolism (PE), high altitude pulmonary edema (HAPE), and pneumothorax.(Lichtenstein and Meziere 2008) It can aid in treatment of respiratory failure by verification of the correct placement of an endotracheal tube and evidence of bilateral pleural sliding following intubation.(Sim et al. 2012) Ultrasound helps avoid intrathoracic structures and confirm placement during invasive procedures such as chest tube insertion, thoracentesis, and tracheostomy.(Chun et al. 2004; Salz et al. 2010; Salamonsen et al. 2013) Further uses theoretically include assisting the diagnosis of rare conditions such as altitude-related pulmonary decompression sickness and ebullism.(Murray et al. 2013; Balldin et al. 2002)

With the development of the commercial space industry, spaceflights will be offered to participants of varying ages and medical comorbidities.(Pattarini et al. 2014) Medical practitioners supporting these flights will need to be equipped to respond to a wide variety of medical issues that may result from the physical demands of spaceflight or the physical condition of the participants. Commercial spaceflight programs are being developed in remote sites around the world. These facilities are far from formalized medical care and are similar to the remote launch environments utilized by the National Aeronautics and Space Administration (NASA) and its international partners. In the event of a medical emergency, a rapid set of triage decisions are required when responding to a patient in the field.(Russell and Crawford 2013) When used by an experienced practitioner, ultrasound could help in making a rapid presumptive diagnosis and aid in decision-making during triage responses to spaceflight operations.(Lichtenstein and Meziere 2008)

The development of protocols to rapidly diagnose life-threatening pulmonary injury will be necessary for medical first responders providing immediate care for spaceflight-related injuries. One example of such a protocol is the Bedside Lung Ultrasound in Emergency (BLUE) protocol.(Lichtenstein and Meziere 2008) It is utilized as a rapid prehospital or emergency room examination that can be completed in less than three minutes to evaluate a patient for the main causes of acute respiratory failure.(Lichtenstein 2014) Protocols like these should be adapted in preparation for the rapid triage of spaceflight participants with pulmonary injury related to this unique environment, including injuries of traumatic etiology, altitude-related concerns, or injury resulting from barotrauma. This article will outline previous studies in the application of ultrasound technology in austere and remote environments, not dissimilar to spaceflight. The specificity of various sonographic techniques for the evaluation of common pulmonary pathologies will be explored. Finally, protocols and novel applications for the use of ultrasound in rapid response and medical care for spaceflight activities will be discussed, outlining areas requiring further research.

Chapter 2: Methods

A systematic review was conducted in PubMed, Web of Science, the Defense Technical Information Center (DTIC), 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, 117 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 63 addressed concerns outside the scope of this article, such as pulmonary hypertension and cardiothoracic ultrasound techniques for in-hospital sonographic applications. The remaining 39 studies were included in the review. Literature obtained includes *in-vitro* and *in vivo* studies, case studies, technical reports, white papers, and review articles.

Chapter 3: Results

USE OF ULTRASOUND IN AUSTERE ENVIRONMENTS FOR MASS CASUALTY RESPONSE

Ultrasound is an ideal tool to triage patients in the event of a mass casualty incident, where traditional imaging techniques are unavailable or are overwhelmed by patient volume.(O.J. Ma et al. 2007) As a screening modality, ultrasound is portable, non-invasive, carries no risk of radiation exposure, and allows for a thorough triage examination in a relatively short amount of time.(O.J. Ma et al. 2007) Its versatility allows for use in a wide variety of applications including pregnancy, undifferentiated hypotension, trauma, and is an ideal modality for transport to and use in extreme environments.(O.J. Ma et al. 2007)

Portable ultrasounds have been employed following natural disasters, particularly in remote environments, and the technology has helped to improve patient triage and resource management, though with varying degrees of success and limitations.(Shorter and Macias 2012) For example, a hand-held Signos® ultrasound device was utilized in 2010 during disaster response following a devastating Haitian earthquake.(Shorter and Macias 2012) While the device was useful for patient management decisions and decreased the number of patients transferred to higher levels of care due to screen-out capabilities, it was limited in that it could only capture static images, rendering it unreliable for more detailed cardiopulmonary evaluations.(Shorter and Macias 2012) Even so, researchers report that, of the images obtained on 51 patients, 76% of scans influenced treatment decisions (with the remaining 24% resulting in equivocal or indeterminate results).(Shorter and Macias 2012)

In 2005, emergency physicians responding to a hurricane disaster in Guatemala brought a SonoSite Micromaxx® portable ultrasound machine.(Dean et al. 2007) Responders performed 137 scans including basic echocardiography, evaluation of lungs and pleura, abdominal evaluation of aorta, biliary tract, kidneys, and serosal cavities.(Dean et al. 2007) They also performed pelvic scans, orthopedic and soft tissue evaluations, and venous imaging.(Dean et al. 2007) In 6% of patients, ultrasound mandated emergent treatment; in 42% of scans, ultrasound ruled out the diagnosis in question, demonstrating that point-of-care ultrasound can provide reliable information in a rapid manner for a wide variety of clinical scenarios, allowing diagnostic and triage capability on scene.(Dean et al. 2007)

Following the Armenian earthquake in 1988, physicians utilized available ultrasound machines where other imaging modalities were lacking to perform screening examinations of disaster victims.(O.J. Ma et al. 2007) Within the first 72 hours, 750 patients were admitted to the hospital with 400 receiving ultrasound examinations; of these, 304 demonstrated no clinically significant pathology and could be screened out with little to no use of other, limited resources.(O.J. Ma et al. 2007) In the remaining 96 patients, ultrasound demonstrated significant pathology requiring treatment.(O.J. Ma et al. 2007) Only four false negative cases were reported, all with retroperitoneal or hollow viscous injuries, areas of the body in which ultrasound has some limitation resulting in lower sonographic sensitivity.(O.J. Ma et al. 2007)

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 further interpretation.(O.J. Ma et al. 2007) 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 (generally blood) around the heart and abdominal organs after traumatic injury.(O.J. Ma et al. 2007) A SonoSite Micromaxx® portable ultrasound was used to perform FAST examinations on patients with free pericardial or intra-peritoneal fluid in a remote hospital prior to patient transport, with images then transmitted to the receiving hospital.(O.J. Ma et al. 2007) 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.(O.J. Ma et al. 2007)

Further, ultrasound can be successfully performed by non-professional personnel when images are sent via satellite for interpretation by trained physicians.(O.J. Ma et al. 2007) 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.(O.J. Ma et al. 2007) The study demonstrated no significant differences between the FAST exams performed in orbit and those performed on earth by trained sonographers.(O.J. Ma et al. 2007) Of note, the FAST exams performed were on known uninjured subjects; this study did not address the ability of a trained or untrained sonographer to identify fluid collections under microgravity conditions.(O.J. Ma et al. 2007) A similar study utilized the same ISS protocol, with untrained operators performing thoracic ultrasound exams under remote expert guidance in isolated high-altitude locations, to further demonstrate this capability.(Otto et al. 2009)

In addition, researchers examined the durability and limits of portable ultrasound in the extreme environment of Mt. Everest.(Otto et al. 2009) The study exposed the ultrasound equipment to high altitudes of up to 27,000ft, with a 5,000ft/min ascent, and severe temperatures as low as -7°C. (Otto et al. 2009) 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 exposure to cold temperatures.(Otto et al. 2009) The minimally trained, non-expert ultrasound operators were remotely guided through ultrasound protocols without difficulty, and were able to identify classic pulmonary findings, such as lung tissue sliding and “comet tails” (hyperechoic reflections perpendicular to the pleural line, signifying pulmonary edema), necessary to diagnose pulmonary edema and rule out pneumothorax.(Otto et al. 2009)

Confirmation of Endotracheal Tube Placement

Endotracheal intubation is a potentially life-saving procedure, but carries significant risk when performed in less-than-ideal scenarios. In particular, there is a higher morbidity and mortality with unrecognized esophageal or main-stem intubation, which is of high risk in environments where immediate confirmatory radiographic imaging is unavailable.(Werner et al. 2007; Sim et al. 2012; G. Ma et al. 2007) It can be particularly difficult to confirm proper endotracheal tube placement in prehospital and operational emergency settings for a number of reasons. First, as patient positioning during intubation may be less than ideal, ambient noise levels from prehospital environments (particularly emergency transport vehicles) make examination for breath sounds with a stethoscope virtually impossible, and secondly alternative confirmatory equipment may not be remotely available.(Chun et al. 2004) Instead, many prehospital providers must rely on direct visualization and auscultation for tube confirmation.

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 auscultation alone. (Werner et al. 2007; Sim et al. 2012) CO_2 Capnography is often utilized as a confirmatory modality, but is also limited as it cannot distinguish endobronchial from endotracheal placement, with studies reporting only 93% sensitivity.(Sim et al. 2012) Similarly, continuous end-tidal CO_2 monitoring relies on adequate pulmonary blood flow for accuracy, which can be compromised in patients experiencing a low flow state such as cardiogenic shock, with sensitivity reported at only 72%.(Werner et al. 2007) For this reason, these techniques are often followed by radiographic verification.(Sim et al. 2012) Unfortunately, chest radiography is not generally available when intubation occurs in a remote field environment.(Werner et al. 2007; Sim et al. 2012)

The use of ultrasound to confirm endotracheal tube position was first done in cadaveric studies, placing the ultrasound probe longitudinally over the cricothyroid membrane.(G. Ma et al. 2007) This allowed for identification of the larynx by visualizing two hyper-echoic laryngeal lines in a longitudinal plane.(G. Ma et al. 2007) A successful endotracheal intubation is determined by visualization of a “snow-storm” appearance between these two lines, and lack of a this sign and visualization of tube movement posterior to the two laryngeal lines signified an esophageal intubation.(G. Ma et al. 2007) Initial studies reported a sensitivity of 97.1% and specificity of 100%, demonstrating the utility of ultrasound for confirmation of successful intubation. A lower sensitivity of 51.4% and specificity of 91.4% was reported for identification of esophageal intubation.(G. Ma et al. 2007) These findings suggest that the use of ultrasound may be a rapid and accurate method of detecting dynamic endotracheal tube placement during the intubation process, though the study was limited by small sample size and cadaveric modeling.(G. Ma et al. 2007)

Controlled trials have since been performed to identify the utility of endotracheal tube detection in live humans.(Werner et al. 2007) 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 non-emergent conditions and a controlled operating room environment.(Werner et al. 2007) Another study evaluated ultrasound to visualize lung sliding to confirm proper endotracheal tube placement following emergency intubation.(Sim et al. 2012) In the evaluation of 115 patients, 31 of which required intubations during active cardiopulmonary resuscitation, bedside ultrasound was used to identify lung sliding, (gliding of parietal and visceral pleura visualized by ultrasound of the intercostal space during ventilation) to exclude main-stem intubation.(Sim et al. 2012) Sensitivity was reported ranging from 90-93%, and specificity from 43-100% dependent upon clinical scenario (with cardiac arrest patients resulting in 100% specificity, non cardiac arrest patients only 43%).(Sim et al. 2012) This technique is not without concerns, as there was a possibility that lung sliding could be seen in patients of one-lung intubation with preserved spontaneous breathing having not received a paralytic.(Sim et al. 2012) This may be the etiology of the false positive cases noted among patients who were not in the cardiac arrest group.(Sim et al. 2012)

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, each of which was imaged during all phases of the intubation process including pre-oxygenation, anesthesia induction resulting in apnea and bag-mask ventilation, endotracheal intubation, and initiation of positive pressure ventilation.(Chun et al. 2004) These findings successfully identified right main-stem intubation when appropriate signs were absent.(Chun et al. 2004)

ULTRASOUND GUIDANCE IN INTRATHORACIC PROCEDURES

Ultrasound can aid in the avoidance of intercostal structures, such as nerves and vessels, and organ puncture helping to accurately position chest tubes for the treatment of pneumothorax and drainage of pleural fluid collections.(Lyn-Kew and Koenig 2013) Tools found on many ultrasound machines to freeze an image and measure a distance with caliper functions allow accurate calculation of needle insertion depth prior to initiating the procedure.(Lyn-Kew and Koenig 2013) Individuals with significant chest wall edema due to trauma or truncal obesity may cause a medical responder to underestimate an appropriate needle insertion depth.(Lyn-Kew and Koenig 2013) Other capabilities of many state of the art machines such as color doppler may help avoid intercostal vasculature.(Lyn-Kew and Koenig 2013)

Laceration of the intercostal artery during thoracentesis or chest tube insertion has the potential for serious complications.(Salamonsen et al. 2013) A study involving 50 patients demonstrated that the artery could be reliably identified with routine thoracic ultrasound when compared with CT images.(Salamonsen et al. 2013) Two ultrasounds were used, including a portable General Electric e Logiq 500™ device and a Phillips iU22™ machine, to evaluate prone-positioned patients.(Salamonsen et al. 2013) Color doppler was used via linear probe in three chest locations to identify the vessel as a pulsatile structure within the intercostal space.(Salamonsen et al. 2013) These findings were compared with CT images using vessel extraction software that tracked the course of the vessel.(Salamonsen et al. 2013) A positive CT result was defined as successful location of a vessel within the space and a negative result indicated that the vessel was located behind the overlying rib.(Salamonsen et al. 2013) The intercostal artery was identified in 128 of 133 determined CT scanning positions.(Salamonsen et al. 2013) A pulsatile vessel with a waveform characteristic of an intercostal artery on pulse wave

Doppler was located in 114 of 133 positions.(Salamonsen et al. 2013) It was noted that vessel identification was more rapid with the higher end machine, taking 14 seconds on average, compared to the average portable machine time of 40 seconds, though there was discrepancy in locating the exact position of the vessel.(Salamonsen et al. 2013) 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.(Salamonsen et al. 2013) Increased body habitus provided an additional challenge for vessel identification and increased scanning time, particularly with the portable ultrasound machine.(Salamonsen et al. 2013) Overall the study demonstrated that intercostal arteries can be identified reliably in seconds by a trained individual using a portable ultrasound machine when alternative imaging modalities are unavailable.(Salamonsen et al. 2013)

Following completion of chest tube insertion, verification of placement is necessary to identify intrathoracic or extrathoracic tube position.(Salz et al. 2010) A tube that is malpositioned in the extrathoracic cavity can result in life-threatening complications for the hemodynamically unstable and those requiring positive pressure ventilation.(Salz et al. 2010) Clinical, tactile clues to verify intrathoracic placement include passing a finger parallel to the tube into the pleural space and rotating the tube without resistance, while visual signs include the presence of condensation or draining fluid within the tube.(Salz et al. 2010) Even with the above signs present, imaging is routinely used for definitive verification.(Salz et al. 2010) Most commonly a single anteroposterior portable chest radiograph is obtained; however, even with imaging it can still be difficult to confirm correct placement.(Salz et al. 2010) In a study using a SonoSite Titan® 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(Salz et al. 2010) At the insertion site, a subcutaneous hyperechoic arc is noted that is created by the chest tube; disappearance of the hyperechoic arc when moving the probe cephalad indicated that the chest tube had entered the pleural space, resulting in proper intrathoracic placement.(Salz et al. 2010) If the hyperechoic arc remained, continuing the full length of the chest tube, this sign confirmed extrathoracic placement.(Salz et al. 2010) These findings were referred by the researchers as the "Disappearance/Intrathoracic, Continuation/Extrathoracic" (DICE) sign.(Salz et al. 2010) 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.(Salz et al. 2010)

In situations of head trauma and airway compromise, where patients are unable to be stabilized with placement of an endotracheal tube, percutaneous tracheostomy may be required.(Lyn-Kew and Koenig 2013) 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 need to remove safety equipment (such as a helmet or harness) from a patient.(Lyn-Kew and Koenig 2013) Ultrasound can improve identification of vasculature and anatomical landmarks prior to intervention.(Lyn-Kew and Koenig 2013) 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.(Lyn-Kew and Koenig 2013) 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.(Lyn-Kew and Koenig 2013)

Pulmonary Edema

Chest radiography has traditionally been used to make a diagnosis of interstitial pulmonary edema, yet has weak correlations with extravascular lung fluid measurements.(Agricola et al. 2005) As described previously, pulmonary ultrasound techniques can be used to effectively diagnose pulmonary edema by identifying comet-tail artifacts, also known as “B-lines”.(Lichtenstein and Meziere 2008; Fagenholz et al. 2007) A comet tail is a vertical hyperechoic line that arises from the pleural line, extends to the bottom of the ultrasound screen without fading, and moves horizontally with lung sliding.(Lichtenstein and Meziere 2008) It represents decreasing air volume and increasing density within the alveolar spaces, suggestive of pulmonary congestion.(Lichtenstein and Meziere 2008) Studies have validated the significance of the lung comet sign for detecting pulmonary edema compared to other traditional imaging techniques such as radiography and CT scan. (Wimalasena et al. 2013; G. Ma et al. 2007)

One study examined the correlation between these comet-tail images with chest radiography, wedge pressure, and the indicator dilution method of extravascular lung fluid.(Agricola et al. 2005) Sonographic exams were found to be expedient, as each ultrasound image took less than five minutes to obtain, and far more rapid than more invasive evaluations of wedge pressure (requiring placement of an indwelling catheter) or the dilution method (requiring measurements of cardiac output, cardiac preload volume, and monitoring of pulmonary fluid).(Agricola et al. 2005) Detection of extravascular lung water <500ml by sonographic technique had a 90% sensitivity and 89% specificity, while detection of extravascular lung water >500ml had a 90% sensitivity and 86% specificity.(Agricola et al. 2005) Sonographic images correlated closely with measurements of wedge pressure and extravascular lung fluid.(Agricola et al. 2005) In addition, researchers report ultrasound is sensitive and accurate enough to provide reliable detection of interstitial pulmonary edema prior to manifestation of clinical symptoms.(Agricola et al. 2005)

HIGH ALTITUDE PULMONARY EDEMA

In 2006, researchers demonstrated successful diagnosis of HAPE via ultrasound by the identification of comet-tails, which correlated with significantly lower oxygen saturation in the HAPE patients compared to the controlled subjects.(Fagenholz et al. 2007) The results demonstrated ultrasound is an effective diagnostic and monitoring tool for HAPE, potentially even superior to conventional radiography and often more available in remote, high-altitude locations.(Fagenholz et al. 2007) Further, reduction in comet-tails with resolution in HAPE suggests that ultrasound is able to provide a more accurate real-time visual representation of extravascular lung fluid than conventional radiography, which often lags behind clinical resolution.(Fagenholz et al. 2007) With a trained operator, the comet-tail technique could be combined with echocardiography examination to estimate pulmonary artery pressure and left ventricular function, differentiating between HAPE and other causes of pulmonary edema such as left ventricular failure (as cardiac function should be preserved in HAPE patients).(Fagenholz et al. 2007) Similar studies identified early evidence of HAPE prior to clinical significance and onset of symptoms.(Pratali et al. 2010) Thus, sonographic comet-tails can be interpreted as a preclinical sign of pulmonary edema prior to more overt clinical signs and symptoms experienced by the patient, allowing for earlier intervention and prevention of clinical sequelae.(Pratali et al. 2010)

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 missed diagnosis has been identified in as many as 30-40% of patients.(Lichtenstein et al. 2005) CT is the current gold standard, but is limited by its fixed location, accessibility, and imaging time, which can potentially cause delays in diagnosis or treatment.(Lichtenstein et al. 2005) Ultrasound has been demonstrated to be successful for real-time imaging and diagnosis of pneumothorax at bedside, with studies showing equal or better accuracy when compared to conventional radiography.(Lichtenstein et al. 2005)

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 in the alveoli.(Agricola et al. 2005; Gargani and Volpicelli 2014; Lichtenstein and Meziere 2008; Lichtenstein et al. 2005) 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.(Lichtenstein et al. 2005; Gargani and Volpicelli 2014) The presence of A-lines without B-lines (comet-tails) is considered a pathognomonic sign of pneumothorax; the presence of a lung point represented direct visualization of the pneumothorax and provides information about the dimensions of the pneumothorax.(Lichtenstein et al. 2005) 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.(Lichtenstein et al. 2005) 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.(Lichtenstein et al. 2005) This study illustrates that ultrasound is a useful bedside tool with the potential to reduce the need of repeat radiography or confirmational CT scans when diagnosing occult pneumothorax.(Lichtenstein et al. 2005)

Other studies have demonstrated the utility of adding a pulmonary component to the standard FAST examination conducted when evaluating a trauma patient.(Kirkpatrick et al. 2004) Results suggested that sonographic exam can be more sensitive than chest radiography alone when compared to the gold standard of CT.(Kirkpatrick et al. 2004) In particular, in patients with traumatic injuries requiring immobilization and limiting chest radiographic imaging to anteroposterior (AP) supine views only, it has been found that small pneumothoraces are missed in up to 30-50% of patients on initial radiographic evaluation.(Blaivas et al. 2005) Research has demonstrated that the use of ultrasound alone in these immobilized patients can successfully identify even small pneumothoraces, with a sensitivity of 98.1% and specificity of 99.2%.(Blaivas et al. 2005) Further, operators have been demonstrated to be capable of predicting the size of the pneumothorax, which greatly assists in clinical decision making (such as determining the need for a thoracostomy tube or other interventions).(Blaivas et al. 2005)

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.(Blaivas et al. 2005) Further, evaluations particularly of complicated cases are best performed by trained operators with repeated sonographic technique over multiple thoracic areas, including the anterior, lateral, and posterior chest, to ensure visualization of the pathology.(Blaivas et al. 2005)

Pulmonary contusions are a common result of blunt trauma injuries and can go undiagnosed in emergency evaluations.(Soldati et al. 2006) Concern has been raised regarding whether or not pulmonary contusions have the potential to limit the accuracy of ultrasound when examining a patient for pneumothorax.(Platz et al. 2009) However, most 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.(Platz et al. 2009) Use of additional lung findings, such as comet-tails, can assist in the exclusion of pneumothorax with high sensitivity.(Soldati et al. 2010; Lichtenstein et al. 2005) Further, the presence of comet-tails, often interpreted as pulmonary edema as described above, has been shown to be characteristic of early pulmonary contusion, providing sonographically-confirmed and presumptive diagnoses in clinical scenarios supportive of traumatic contusion.(Soldati et al. 2006; Soldati et al. 2010)

Lung contusions are known to evolve over the course of three stages: the first caused by the trauma itself resulting in acute damage to the lung parenchyma, the second being an edematous phase occurring 1-2 hours after the initial trauma, and the final occurring as pulmonary air spaces fill with blood, inflammatory cells, and tissue debris.(Soldati et al. 2006) Traditional radiography has been shown to be most accurate in this final phase; in contrast, sonography has been demonstrated to more accurately diagnose pulmonary contusions during earlier stages (1 and 2) when compared to conventional radiography.(Soldati et al. 2006)

In hospital settings, lung contusions are most often diagnosed with CT, as chest radiography has been demonstrated to be only useful in the diagnosis of severe pulmonary trauma and late-stage disease and, as described above, is likely to miss more subtle or early cases.(Soldati et al. 2006) The ability to identify pulmonary contusion early, even in the prehospital environment, could improve patient management, help guide appropriate treatment, and determine the need for intervention. Prior research has shown that, while chest radiography may yield sensitivity as low as 27%, ultrasound examinations can make a diagnosis of lung contusion with 94% sensitivity and 96% specificity.(Soldati et al. 2006) Further, ultrasound examinations of pulmonary findings can be completed in less than 60 seconds, taking less than 3 minutes for a complete thoracic and abdominal examination, and can be performed in prehospital settings unlike most radiographic imaging.(Soldati et al. 2006) In contrast, CT examination can take over 20 minutes for an evaluation (including the transport time to and from the CT scanner).(Soldati et al. 2006)

PREHOSPITAL PROTOCOLS FOR SPACEFLIGHT AND SIMILAR ENVIRONMENTS

Many protocols designed for rapid, emergent evaluations for the prehospital environment could be utilized for field evaluation and triage in the spaceflight industry. The BLUE protocol is a rapid ultrasound algorithm used as a guide to establish the diagnosis of patients experiencing severe dyspnea.(Lichtenstein 2009; Lichtenstein and Meziere 2008) It uses pulmonary signs, combined when indicated with venous analysis, to create seven defined profiles corresponding with specific pulmonary diagnoses such as pneumothorax, pulmonary edema, pulmonary embolism, pneumonia, chronic obstructive pulmonary disease, and asthma, yielding 90.5% accuracy.(Lichtenstein 2015; Lichtenstein 2009) Standard thoracic examination points are used to allow for reproducible examination of specific pulmonary signs, including anterior lung sliding, anterior comet tails, and “posterolateral alveolar or pleural syndrome” (PLAPS).(Lichtenstein 2009; Lichtenstein 2015)

The BLUE protocol should be performed when clinical doubts remain after a complete physical examination.(Lichtenstein 2015) When performed by trained sonographers, the BLUE protocol can be completed in three minutes using a universal ultrasound probe.(Lichtenstein 2009) Although originally designed for use in critical care units, due to its simplicity in examination points and use of a single ultrasound probe it has the capability of being performed in any number of environments.(Lichtenstein and Meziere 2008; Lichtenstein 2015) Similar protocols for various environments and clinical scenarios have been developed as currently there is no method considered the gold standard.(Lichtenstein 2015)

One such protocol developed for injuries unique to spaceflight is for the treatment of ebullism. Defined as the spontaneous evolution at body temperature of liquid water in tissues to vapor when ambient pressure is 47 mmHg or less, ebullism has a high potential for morbidity and mortality.(Murray et al. 2013) Sequential steps in treatment involve repressurization, reversal of anoxia, preventing decompression sickness (DCS), field medical treatment and support, ruling out consequences of barotrauma, and safe transfer for definitive medical care.(Murray et al. 2013) Portable ultrasound may help experienced first responders in the field provide prehospital treatment and stabilize the patient for transfer.(Murray et al. 2013) Securing the airway and providing high frequency percussive ventilation is of utmost priority if the patient is unconscious or impaired.(Murray et al. 2013; Pattarini et al. 2013) Ultrasound could be used to verify the position of the endotracheal tube following rapid sequence intubation.(Sim et al. 2012; Murray et al. 2013) Once a secure airway is established, a trauma evaluation should be performed, evaluating for evidence of traumatic injuries including pneumothorax.(Murray et al. 2013) Evaluation for the presence or absence of lung sliding, A-lines, lung point, and comet tails can provide clues to support other clinical signs of pneumothorax.(Lichtenstein et al. 2000; Lichtenstein et al. 2005; Gargani and Volpicelli 2014; Murray et al. 2013; Lichtenstein and Meziere 2008) In the event of a tension pneumothorax, ultrasound may help in needle thoracostomy and chest tube placement.(Salz et al. 2010; Lyn-Kew and Koenig 2013; Salamonsen et al. 2013) Similar utilization of ultrasound technique could add to the clinical decision making for an unconscious patient with unknown injuries after a spaceflight mishap, ruling out various etiologies of disease that could have led to loss of consciousness.(Murray et al. 2013) A field medical protocol developed for the approach of an unconscious patient outlines specific considerations for individuals exposed to high altitude and -Gz exposure.(Pattarini et al. 2013) Removal of a helmet or pressure suit should be done with caution by trained individuals looking for signs of suspected suit breach that could lead to ebullism.(Pattarini et al. 2013) Other signs such as signs of blunt or penetrating trauma that could lead to pneumothorax must be considered.(Pattarini et al. 2013) Ultrasound may eventually be utilized in the evaluation of other forms of trauma, including acute gas embolism (AGE), DCS, and cardiovascular compromise, though protocols for such evaluations have yet to be developed or field-tested.

Chapter 4: Discussion

With a goal towards longer duration missions and eventual exploration of Mars current spaceflight operations are expanding our knowledge of an individuals long-term exposure to microgravity. Commercial organizations within the aerospace industry are developing suborbital spacecraft that will eventually introduce participants from a wide variety of medical backgrounds to the rigors of spaceflight. Many of these participants could be more advanced in age with the potential for health risks not represented in career astronauts. Preexisting pulmonary disease is among the many potential health risks that supporting medical personnel must be prepared to manage, independent of further risk posed by the spaceflight itself, including barotrauma or traumatic injury from a vehicular mishap. Within both current and future space operations an emergent decompression of the spacecraft would place participants at a high risk of sustaining lung related injuries, such as pneumothorax, pulmonary edema, and ebullism. Further injury may be sustained due to blunt trauma in the event of a crash. 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.(Wiegmann and Taneja 2003)

Spaceflight operations frequently take place in remote environments far away from the comforts of a well-equipped emergency room or trauma center. In cooperation with the Russian Federal Space Agency current NASA manned missions launch and land in remote areas of the Republic of Kazakhstan. Commercial companies such as Virgin Galactic and SpaceX are developing facilities in desert areas of New Mexico and west Texas. The capability to rapidly diagnose and triage life-threatening injuries could prove critical in providing successful medical support to these missions. Portable ultrasound could be an invaluable tool at the disposal of field medical personnel responding to an emergent situation.

Ultrasound examination protocols have been established to guide practitioners in providing a rapid screening exam for life threatening injuries. The FAST exam, described above, is the most common and widely known protocol, and this protocol can be expanded to include the lungs and rule out pneumothorax (then termed the "extended FAST" or "eFAST" exam). Similarly, the BLUE protocol was developed for use in patients experiencing severe dyspnea who will be admitted to an intensive care unit, though its use has been expanded to other clinical evaluation scenarios.(Lichtenstein 2014) Incorporating ultrasound into protocols developed for spaceflight operations, such those developed for the diagnosis and treatment of ebullism and for an unconscious patient with unknown injury, could aid in the diagnosis of pulmonary injury or confirm successful procedural technique, such as endotracheal intubation.(Pattarini et al. 2013; Murray et al. 2013) Ultrasound protocols could be employed during prehospital field recovery to provide a rapid and systematic assessment of injuries. 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 treatment on site.

Following a spaceflight-related mishap or medical emergency, initial assessment of an injured spaceflight participant by medical personnel should be similar to any initial trauma evaluation. A primary survey evaluating airway, breathing, circulation and signs of trauma according to Advanced Trauma Life Support (ATLS) protocols should be addressed first.(Pattarini et al. 2013) When appropriate interventions such as airway stabilization to include intubation and vascular access for medications and fluid administration for the treatment of shock should take place immediately.(Pattarini et al. 2013) Ground or air transportation should be arranged for expeditious transfer to the nearest American College of Surgeons (ACS) Level I Trauma Center.(Pattarini et al. 2013) Once the patient is deemed stable, further assessment with ultrasound could be useful in determining a differential diagnosis of injury and confirming position of equipment such as an endotracheal tube.

A focused evaluation of cardiac, pulmonary, and abdominal systems employing established protocols such as eFAST and BLUE could help to rule out any life threatening injuries that would require immediate attention. A comprehensive pulmonary analysis would include examination in the anterior, lateral, posterior, and apical zones. The ability to safely maneuver the patient and maintain a secure airway may stipulate certain limitations.(Gargani and Volpicelli 2014) To rapidly rule out pneumothorax in an unstable patient the exam should begin at the nondependent zones for air collection.(Gargani and Volpicelli 2014) This corresponds to the anterior-inferior chest in a patient who is supine.(Gargani and Volpicelli 2014) The parietal pleura should be located for frame of reference and to evaluate for lung sliding, A-lines, and comet tails.(Lichtenstein 2014) Use of the M-mode will help evaluate lung sliding at the pleural line relative to superficial tissues (sea shore sign).(Lichtenstein 2014) Examination at the

PLAPS point posteriorly in the supine position will evaluate for pleural effusion.(Lichtenstein 2014) Convex and microconvex probes are generally used in most all purpose settings.(Gargani and Volpicelli 2014) They produce an intermediate frequency allowing for good resolution and visualization of the parietal pleura and associated lung signs such as comet tails and A-lines.(Gargani and Volpicelli 2014)

As an imaging modality, ultrasound has few known risks and is considered very safe to use. Unlike CT or conventional radiography, ultrasound does not utilize ionizing radiation, eliminating the risk of a significant radiation insult from even repeated exposures.(Fagenholz et al. 2012a) Ultrasound is versatile, allowing a single operator to examine a wide range of organ systems and parameters.(Fagenholz et al. 2012a) Ultrasound machines can be very expensive upfront; however, the daily operating expenses are relatively small. The unit is very portable and a large number of images can be acquired with no requirement for image processing or disposable parts; instead, all that is required is an ample supply of transducer gel.(Fagenholz et al. 2012a)

There are some disadvantages to portable ultrasound. Despite advances in durability, many ultrasound devices need special packaging for transport and may not function optimally in extreme environments.(Russell and Crawford 2013) The probe is the most fragile part of the machine due to the piezoelectric crystal array within, which cannot tolerate significant impact without performance degredation.(Russell and Crawford 2013) Battery life is limited, and other means of charging the device, such as solar powered arrays, have yet to be developed. Although basic sonography can be mastered in a short amount of time, there are some scanning technique principles that require specific training and skill.(Fagenholz et al. 2012b; Russell and Crawford 2013) Even so, it is not always necessary for the operators obtaining images to have a background in using ultrasound or the ability to diagnose the images they see, as some studies have demonstrated that minimally trained operators are capable of obtaining high-quality images that can be interpreted by remote, well-trained observers.(Otto et al. 2009) Those performing point-of-care ultrasound exams should be familiar with the equipment and have demonstrated proficiency in obtaining and recognizing sonographic signs from a wide variety of patients with different body habitus prior to field operations. Responding to an emergency in less than ideal conditions can be a chaotic event, and adequate training and familiarization with equipment is vital in maintaining a calm atmosphere as well as providing a systematic and accurate assessment.

Other factors limiting the utility of prehospital sonogram include the physical limitations of the equipment, such as weight, durability, start up time of hardware, visibility of the screen, and battery life. These features should be considered when choosing a particular ultrasound device. The use of ultrasound should never take precedence or replace standard clinical medicine and physical examination techniques. Airway, breathing, and circulation should be assessed first and foremost in any traumatic injury scenario. The use of ultrasound is adjunct and should not interrupt patient care.

This article focuses more on the use of ultrasound in recovery operations rather than on-orbit applications. It is worth noting that ultrasound use in microgravity conditions is in early stages of development. Ultrasound is currently the only imaging modality aboard the ISS and maximizing its diagnostic capabilities is important for continued monitoring of physiological changes and the capability to deal with potential trauma.(Wagner et al. 2014) Modified sonographic techniques will be required to account for the fluid and air dynamic changes that occur in microgravity.(Wagner et al. 2014) Studies using porcine models flown aboard NASA research aircraft performing parabolic flight to achieve 15-20 second intervals of microgravity have shown successful detection of pneumothorax, hemothorax, and hemoperitoneum.(Wagner et al. 2014) In microgravity a pneumothorax does not localize anteriorly as it does in an earthbound $+1G_z$ environment.(Wagner et al. 2014) Instead, air surrounds the collapsed lung, which floats centrally within the thoracic cavity.(Wagner et al. 2014) Examination needs to be conducted in anterior, lateral, and posterior positions for a full assessment.(Wagner et al. 2014) Fluid collections behave similarly and do not localize to dependent areas as they do on earth.(Wagner et al. 2014) Assessment of pleural fluid and abdominal fluid examinations such as the FAST exam should be conducted in a more generalized approach.(Wagner et al. 2014)

Ultrasound is proving to be a valuable tool in the examination of the pulmonary system, and sonographic image are comparable in many cases to more conventional imaging techniques. The portability of ultrasound equipment lends its use to a greater variety of working environments, making it an ideal piece of equipment to include in remote activities such as spaceflight-related field operations. Future research could include studies examining the efficacy of ultrasound in appropriate triage by first responders to various traumatic accidents. By examining whether ultrasound influenced the location of transfer or aided in stabilization and treatment in the field, we can better understand the role point-of-care ultrasound examination can play in aerospace operations.

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Vita

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