Point-of-Care Ultrasound Utility and Potential for High Altitude Crew Recovery Missions

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INTRODUCTION: Flights to high altitude can lead to exposure and unique pathology not seen in normal commercial aviation.

METHODS: This paper assesses the potential for point-of-care ultrasound to aid in management and disposition of injured crewmembers from a high altitude incident. This was accomplished through a systematic literature review regarding current diagnostic and therapeutic uses of ultrasound for injuries expected in high altitude free fall and parachuting.

RESULTS: While current research supports its utility in diagnostics, therapeutic procedures, and triage decisions, little research has been done regarding its utility in high altitude specific pathology, but its potential has been demonstrated.

DISCUSSION: An algorithm was created for use in high altitude missions, in the event of an emergency descent and traumatic landing for an unconscious and hypotensive pilot, to rule out most life threatening causes. Each endpoint includes disposition, allowing concise decision-making.

KEYWORDS: aviation, space, ultrasonography, pre-hospital.

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Flights to high altitude can potentially expose crewmembers to unique pathologies that are not seen in normal commercial aviation. The most likely life-threatening medical risks during these flights include a combination of trauma, injury from rapid spin in freefall (e.g., intracranial hemorrhage) and anoxia, pulmonary barotrauma, ebullism, and decompression illness from a suit depressurization.[11] Prior high altitude jumps have resulted in multiple injuries and fatalities, including Pyotr Dolgov (1962), who suffered hypoxia and ebullism when his helmet cracked at 93,970 ft (28,642 m), and Nick Piantanida (1966), who sustained severe anoxic encephalopathy when his facemask depressurized at 57,000 ft (17,374 m).[27,68,69] As the high-altitude flight, high-altitude jump, and space tourism markets grow, the potential to encounter one or more of these conditions also grows. Imagine a spacecraft with passengers that experiences a depressurization event with a nontraumatic landing, a pilot in a hypobaric chamber who has a suit failure, a spacecraft malfunction that causes the crew to bail out without viable spacesuits, or an unconscious high-altitude pilot who lands on a rocky terrain and sustains unknown damage. Each of these scenarios can include a combination of rapid depressurization, rapid spin, or traumatic injuries.

Currently, many spaceports and high-altitude jump locations are far removed from high-population cities in order to minimize the risk to the community and maximize the ability to reach the crew quickly if they are downed unexpectedly.[45] Depending on the condition, the destination for definitive care could include a lengthy transfer, which highlights the need for portable technology that can be used in an algorithmic fashion in order to make rapid management decisions and perform extended stabilization.[11] Ultrasound is an ideal technology due to its ease of use, affordability, and miniaturization. It is becoming increasingly used both in the field and in-hospital to aid in assessment, diagnosis, and, if needed, intervention guidance.[14,35,67]

The purpose of this paper is to assess the potential for point-of-care ultrasound (POCUS) used by field personnel, including physicians, EMS, or private medical crew, and create an algorithm to streamline the management and disposition of downed crewmembers from high-altitude incidents involving both low atmospheric exposure and trauma. We performed a

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systematic literature review regarding current diagnostic and therapeutic uses of ultrasound for injuries expected in these missions. The StratEx Space Dive mission on October 24, 2014, consisted of a single pilot ascent to over 135,890 ft (41,419 m), free falling over 123,000 ft (37,490 m), and landing using a parachute similar to those used in tandem sport jumping [with multiple prior test jumps at 56,857 and 105,678 ft (17,330 and 32,211 m)]. We used this mission as a model to create and integrate the algorithm; however, both the results and algorithm are applicable to a variety of high-altitude flights, including both orbital and suborbital with more than one crewmember and/or passengers.

METHODS

A systematic review was conducted on currently available information and published literature regarding the utility of ultrasound as a rapid diagnostic or treatment modality in prehospital environments. Databases used were the Texas Medical Center Online Library, PubMed, the Cochrane Library, Scopus, the Federal Aviation Administration, and the National Transport Safety Board. Search terms used included "emergency ultrasound," "ultrasound decompression sickness," "ultrasound atelectasis," "emergency ultrasound procedures," "ultrasound ebullism," and "emergency ultrasound trauma." The initial search yielded 29,856 papers between the 3 search engines, with some repeats (see **Fig. 1**).

Of note, "ultrasound ebullism" yielded no results in any search engine. Inclusion criteria included publication within the last 5 yr, availability in English, and humans being the primary species of interest. Exclusion criteria included repeat papers and discussion of topics specific to neonates, children, or pregnancy. The abstracts of the remaining papers were scanned to include only those in which the results or conclusions focused on the use of ultrasound to make diagnostic or management decisions regarding the pathology of interest (fractures, abdominal trauma, pneumothorax, etc.). This resulted in just over 250 papers, which were reviewed in their entirety and discarded if determined to lack specific applicability to crew recovery, including those that dealt primarily with chronic disease states. Some references were extracted from the bibliographies of these papers if deemed to be unique, historically important, or required additional verification for accuracy. Literature used included in vivo studies, Cochrane reviews, technical reports, books chapters, and review articles.

RESULTS

An ultrasound transducer uses piezoelectric crystals to convert electricity to sound waves. These penetrate and reflect off tissues, depending on the tissues' character, and the echoes are interpreted by the machine to create a two-dimensional (2-D) image of the underlying structures. High-frequency probes (linear probes) create high resolution images, but cannot penetrate deep, while low-frequency probes (curvilinear or phased array probes) penetrate deeper, but are lower resolution.[55] Along with this 2-D (or B) mode, M mode allows us to monitor movement of tissue along a single ultrasound beam throughout time. Color flow mode allows us to determine direction and velocity of flow (i.e., blood vessels), and power Doppler represents flow velocity.[55] In an ultrasound image, 'echoic' is used to describe how bright or reflective the tissue is (usually using the liver as a reference). An anechoic structure is black (fluid or blood), a hypoechoic structure is dark gray (fat), and a hyperechoic structure is bright white (bone).[55]

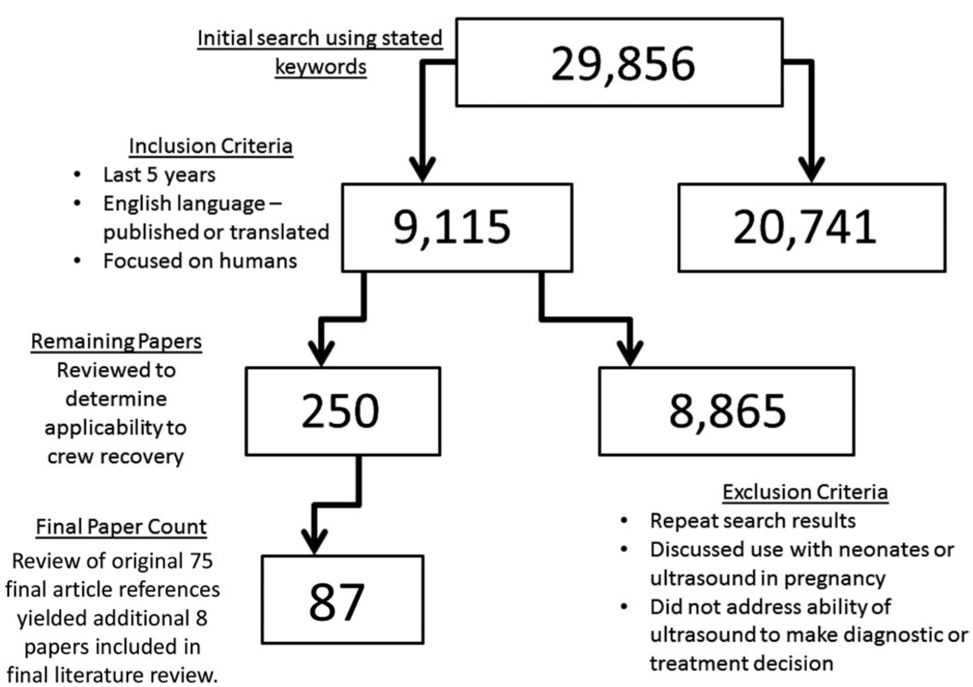

Fig. 1. Breakdown of literature review method. Inclusion and exclusion criteria were used initially to narrow the number of papers.

Diagnostic Ultrasound

Ultrasound has proven useful in the assessment of various cardiovascular pathologies. In Advanced Trauma Life Support, two cardiac injuries not to be missed in the primary and secondary survey include cardiac tamponade and blunt cardiac injury.[3] These are especially concerning given the potential for blunt trauma during the parachute landing phase and the amenability to field intervention. An acute pericardial effusion as small as 50 mL can result in tamponade and is first visualized as a hypoechoic layer posterior to the heart (**Table I**).[43,59] Tamponade occurs when the fluid accumulation in the pericardial sac increases pressure enough to overcome the diastolic pressure of the right atrium and/or ventricle, preventing proper filling.[59,89] In POCUS, right ventricular collapse during diastole is most relied upon for detecting tamponade, with a sensitivity and specificity of 48–100% and 72–100%, respectively.[29,59] Collapse of the right atrium has also been used, with a sensitivity of 50% in early tamponade and up to 100% in late tamponade, but a poorer specificity of 33–100%.[29,59] Visualization of a plethoric inferior vena cava (IVC) can also support a diagnosis of tamponade.[59] The focused cardiac ultrasound (FOCUS) exam is a comprehensive cardiac assessment looking at pericardial effusion, relative chamber size, global cardiac function, and volume status (via left ventricle size, ventricular function, or IVC size and change with respiration).[43] Trials show decreased morbidity and mortality through incorporation of the FOCUS exam into blunt and penetrating trauma injuries, respectively.[43] Several recent studies have investigated the use of ultrasound to determine the utility in continuing CPR in instances of cardiac arrest. Field survival rate for cardiac arrest is less than 5% and absence of cardiac kinetic activity on ultrasound suggests a 1–2% probability of return of spontaneous circulation.[12] More stringent criteria, such as no flickering of ventricle walls and no valve motion, result in lower false negative rates.[12,13,72] Positive cardiac contractility did not show much prognostic significance, as return of spontaneous circulation occurred only 50% of the time.[12]

Due to prior fatalities during high altitude flights, decompression and associated pulmonary barotrauma (including pneumothorax, pulmonary contusion, and massive hemothorax) are of great concern.[15] Ultrasound can be used to look for pleural sliding, which would be absent in a pneumothorax.[49,76,87] Anterior lung ultrasound was found to be superior in detecting pneumothoraxes compared to supine chest radiography, having a higher sensitivity, between 59–80%, and comparable specificity, between 89–99%, for detecting a pneumothorax (Table I).[32,34] False negatives are rare and occur mostly in small, clinically insignificant pneumothoraces.[4] The presence of a lung point (transition point on ultrasound between features of normal lung and features of a pneumothorax) has a reported specificity of 100% (although controversy exists over this finding).[41,62,76]

The views of the right and left upper abdominal quadrants can capture pleural effusions and hemothoraces, seen as anechoic or hypoechoic signal above the diaphragm, and visualization of the spine through the fluid (the "spine sign").[62] Lung movement in the fluid during inspiration and expiration can also be visualized.[14,87] Hand held ultrasound is superior to chest radiography for detecting clinically significant pleural effusions, having similar sensitivity (91% versus 74%) and higher specificity (100% versus 31%).[47,74,83] Ultrasound also has comparable diagnostic performance to computed tomography in detecting atelectasis.[14,76] The presence of irregularities at the pleural margin, which appear similar to shredded tissue (the 'shred sign'), is the most common ultrasound finding in atelectasis.[1,87] Other evidence of atelectasis can be seen as the presence of heart activity in the tissue (normally prevented by pleural movement), 'lung hepatization' (collapsed lung tissue has the same echogenicity as the liver), shift of the mediastinum toward the atelectic lung, and hemidiaphragm elevation or standstill.[14,76,87] Overall, lung ultrasound has a sensitivity

Table I. Summary of the Diagnostic Capabilities of Ultrasound in Relation to Field Management of an Injured Crewmember or Passenger from a High-Altitude Mission.

PATHOLOGY	ULTRASOUND FINDING	SENSITIVITY	SPECIFICITY	COMMENTS
Pericardial effusion	Hypoechoic layer posterior to heart	–	–	
Cardiac tamponade	RV Collapse	48–100%	72–100%	Most used for tamponade
	RA Collapse	Early: 50% Late: 100%	33–100%	
	Plethoric IVC	–	–	
Pulmonary edema	B-lines	94%	92%	Outperforms CXR
Pneumothorax	Pleural sliding	59–80%	89–99%	Outperforms supine CXR
	Lung point	–	100%	Controversial finding
Pleural effusion/ hemothorax	Hypoechoic area above diaphragm	91%	100%	Outperforms CXR
	Spine sign	–	–	
Atelectasis	Lung pulse	Low	–	Overall comparable to CT
	Lung hepatization, shred sign, heart shifted toward atelectasis, hemidiaphragm elevation	Overall for signs of atelectasis: Sensitivity: 90–93%; Specificity: 89–100%		
Pulmonary contusion	Similar to atelectasis	–	–	Air artifact differentiates from atelectasis
DCI	Bubble score	–	Low	Low diagnostic value
Acute diaphragmatic rupture	Inability to visualize spleen	Moderate	Low	Little value due to lack of field intervention
	Diaphragm elevation, subphrenic effusion	–	Low	
Hemoperitonium	FAST Exam	60–85%	96–98%	Outperforms physical exam and hemodynamic measurements
Extremity fracture	Direct visualization	90–95%	86–97%	Less accurate if near joints

RV: right ventricle; RA: right atrium; IVC: inferior vena cava; CXR: chest X-ray; CT: computed tomography; FAST: focused assessment with sonography in trauma.

and specificity of 90–93% and 89–100%, respectively, for complete atelectasis.[1,76] Lung contusion can mimic atelectasis, but is differentiated by the presence of air artifacts within the tissue (absent in atelectasis).[46,49,87]

Ebullism is a trauma specific to exposure above Armstrong's line (~63,000 ft/19,202 m), when water spontaneously evolves from liquid to gas in tissues due to the vapor pressure of water falling below body temperature. This can cause massive swelling and vascular damage in the lungs, causing over-inflated alveoli to burst.[53] No case reports or studies on ultrasound findings in ebullism were identified; however, in a case with concern for ebullism, an ultrasound showing evidence of new atelectasis, pneumothorax, hemothorax, or flash pulmonary edema could lend support to a decision to intervene.[41,53] These findings can also be seen in pulmonary barotrauma; however, field management would be similar for both.[13,72] Decompression illness (DCI) is seen in exposure to low environmental pressure, where evolved nitrogen gas bubbles form and manifest as cough, dyspnea, neurological symptoms, pulmonary edema, cardiac collapse or death.[10,81] Cardiac Doppler ultrasound has been used to monitor venous gas emboli as a marker of decompression stress.[21] A high load of left ventricular nitrogen bubbles can suggest potential for cerebral gas emboli resulting from a right to left shunt of the bubbles, which enter arterial circulation via either intracardiac defects, pulmonary shunts, or passage through the pulmonary microcirculation.[5] Monitoring bubbles in the anterior chamber of the eye or retina is also possible, but technically more difficult.[16,85] A double-blind, prospective clinical trial was conducted using simulated dives to determine if cardiac Doppler bubble detection correlated with clinical diagnosis of diving/hyperbaric DCI. Bubble scores were only slightly higher in DCI and, as other studies have since concluded, appeared to have limited diagnostic value.[8,48,52] Transcranial Doppler ultrasonography has been used to monitor cerebral embolization of bubbles from pulmonary barotrauma in a hospital setting, but is not practical in a field setting given its lack of a proven relationship to symptomatology and the exam's moderate time requirement.[57,80]

Acute diaphragmatic rupture is possible in severe trauma. Clinical manifestations are variable, but can present as significant respiratory distress, requiring mechanical ventilation and urgent surgical repair.[28] Ultrasound is mainly used to rule out rupture, but impaired visualization of the spleen or heart (due to overlying, herniated bowel), poor movement of the diaphragm, and a subphrenic effusion can support the diagnosis.[14,28]

Should fire be involved, smoke inhalation can lead to endotracheal and endobronchial injury that can result in respiratory distress. A case report from Kameda and Fujita demonstrated thickening of the anterior tracheal wall on ultrasound following smoke inhalational imaging.[38] This could allow responders to anticipate the need for increased monitoring of the airway and breathing of these patients. Further studies are needed to confirm this ultrasound finding before its practical implementation in field use.

Ultrasound can also be used in flight or immediately on landing to evaluate a patient with severe shortness of breath who may have acute decompensation of pre-existing cardiovascular or pulmonary disease (as occurs on commercial airlines and should be expected to occur on commercial spacecraft).[25,64,66] For instance, ultrasound can help differentiate congestive heart failure from asthma or other pathologies and help determine the need for immediate interventions, such as nitroglycerin or albuterol, to improve their clinical standing en route to the hospital.[59,83,86] Ultrasound has an overall sensitivity of 94.1% and specificity of 92.4% for acute pulmonary edema, outperforming chest radiography in both areas.[2]

The FAST (focused assessment with sonography for trauma) exam is a quick assessment of a trauma patient for evidence of fluid in the abdominal, pericardial, or pelvic cavity. The required views are subxiphoid cardiac, right and left upper abdominal quadrant, and suprapelvic views.[18,36,83] Extended-FAST (E-FAST), also used in trauma, includes all FAST views in addition to a bilateral anterior lung ultrasound. Prehospital ultrasound provides highly reliable detection of hemoperitoneum and hemopericardium (96–98% specificity, 99% accuracy), which is substantially better than both physical exam (57% accuracy) and hemodynamic measurements.[18,36,83] Prehospital implementation of FAST has resulted in decreased mortality and morbidity by allowing early initiation of life support interventions, determination of the best admitting hospital, facilitation of early surgical care, and increased diagnostic accuracy of an injury.[36] However, portable ultrasound is only 60–85% sensitive in detecting abdominal effusions and less sensitive in detecting suprapubic effusions.[18,83] Recommended practice is to use only a positive FAST for triage decisions.[78] Serial FAST examinations can be performed en route to detect any evolving or occult effusion and improve sensitivity.

Impact forces can produce direct trauma, causing fractures of the extremities and vertebrae and short bone crushing.[24] History and physical exam are not accurate in determining the presence of a fracture in trauma.[37] Bedside ultrasound performed by emergency physicians can reliably rule out extremity and clavicular fractures (sensitivity of 90–95%, specificity of 86–97%) in individuals with history of trauma in varying anatomical locations, but is less accurate if the fracture occurs close to a joint.[37] A positive examination has a wide range of positive likelihood ratios, so it cannot reliably rule in a fracture.[37] Ruling out a fracture may help to avoid time spent for immobilization, allowing responders to focus attention elsewhere.

Procedural Ultrasound

Stabilization of airway, breathing, and circulation are first priority to emergency responders. Up to 55% of endobronchial intubations are missed by auscultation and cardiac arrest patients can lack sufficient circulation to the lungs to expel enough carbon dioxide for accurate capnography.[75] Ultrasound can be used to verify the correct placement of the ET tube indirectly or directly.[20,75,83] The indirect method uses the transducer placed at the midclavicular line to view bilateral pleural sliding following intubation (limited in the setting of a unilateral pneumothorax).[75,83] The direct method uses the transducer placed above the suprasternal notch to monitor for a single air artifact as the tube passes (signaling tracheal intubation), or a double air artifact signaling esophageal intubation (since air would be in both the trachea and esophagus in this instance). This direct method has 100% specificity in noncardiac arrest patients, 75% specificity in cardiac arrest patients, and an overall sensitivity of 98.9% (**Table II**).[19] This method is limited if the esophagus lies directly behind the trachea, as the tracheal shadow obscures visualization of the esophagus.[20] Ultrasound improves verification time by 7 s compared to capnography, but is similar in timing to auscultation.[61] If ET tube placement fails, ultrasound can guide marking of the cricothyroid membrane for subsequent cricothyroidotomy or be used in real time to observe scalpel penetration of the membrane.[26,51]

Decompensation in the setting of pneumothorax requires urgent treatment with needle decompression.[9,88] Ultrasound allows targeted placement of a needle by identifying the best site, angle, and depth of needle insertion to maximize output and avoid organ puncture or intercostal vessel damage.[49,71,79] In a comparison study, it improved puncture site selection in over 50% of patients and decreased needle injury to visceral pleura by 10%.[70]

Similarly, ultrasound can be used to verify chest tube placement.[4,82] Extrathoracic placement is estimated to occur between 0.5–2.6%.[73] Ultrasound has a sensitivity of 83–100% and specificity of 83–100% for differentiating extrathoracic and intrathoracic placement of a chest tube (Table II).[73] The chest tube (seen as a hyperechoic arc) should disappear as it enters the pleural space, but in extrathoracic placement can be seen in its entirety.[73] Ultrasound guidance lowers the rate of iatrogenic pneumothorax from 4–30% to 1.3–6.7%, helps avoid intercostal vessels, helps identify iatrogenic pneumothorax and re-expansion pulmonary edema, and can be used to estimate the size of a pleural effusion.[49,70,71] A maximum distance between the visceral and parietal pleura of >5 cm at the posterior axillary line with the patient supine can indicate the presence of an effusion greater than 500 mL with a specificity of 90% and sensitivity of 100%.[18,65,87] Though limited by population size, a previous study found significant improvement in oxygen saturation to F_IO_2 ratio in patients with over 500 mL drained from their pleural cavity (so this finding can help determine the utility of an immediate intervention).[4]

Ultrasound-guided pericardiocentesis allows localization of maximum fluid accumulation and optimal approach to spare other structures.[79] Ultrasound guidance changed the classical subxiphoid approach to an apical approach in over 80% of patients due to fluid collection visualization.[59,79] Confirmation of catheter placement can be accomplished by visualizing injected agitated saline (acts as contrast agent) using ultrasound.[59]

Ultrasound is commonly used in-hospital for guiding peripheral and central intravenous (IV) line placement.[6,22,77] In patients with difficult IV access (obese, young, IV drug abuser, etc.), ultrasound guided peripheral IV placement is consistently twice as fast and decreases the number of punctures performed by two, but has variable success rates (80–90%).[7,22,35] Emergency physicians and residents with greater ultrasound experience showed a greater difference (>60% increase) in success rates between ultrasound guided vs. landmark based than did novice EMTs with no ultrasound background.[7,22,40] The use of ultrasound for central line placement has resulted in the reduction of placement failure by 64%, complications by 78%, and the need for multiple attempts by 40%.[76]

Point-of-care ultrasound has seen increasing use in both emergency medicine and spaceflight applications and was recently reviewed for applications in the aerospace medicine field.[83] A brief training period has proven adequate to allow prehospital providers the ability to accurately assess trauma patients for internal injury and relay their findings to the hospital for expedited care upon arrival.[30,84] Cases of life-saving diagnosis and treatment using prehospital ultrasound have been recorded and European Guidelines on resuscitation were updated in 2010 to recognize the potential role of ultrasound in Advanced Cardiac Life Support.[17,50,56] Feasibility of prehospital use in aeromedical evacuation has been demonstrated.[33,39,63] A few protocols have been established using ultrasound to help systematically investigate the cause of undifferentiated hypotension in both trauma (FAST, E-FAST) and medical (FOCUS,

Table II. Summary of the Procedural Capabilities of Ultrasound in Relation to Field Management of an Injured Crewmember or Passenger from a High-Altitude Mission.

	ULTRASOUND FINDING OR METHOD	COMMENTS
Determine CPR continuation	No cardiac kinetic activity	1–2% probability of ROSC
	No ventricle flickering or valve motion	Lower false negative rate
Verify ET tube placement	Direct method	Sensitivity: Noncardiac arrest: 100%
		Cardiac arrest: 75%
		Specificity: 98.9%
Pericardiocentesis	Agitated saline injection	Verification postprocedure
	Direct needle visualization	Improves puncture site in > 80% of patients
Verification of chest tube placement	Direct visualization	Sensitivity: 83–100%
		Specificity: 83–100%
		Lowers rate of iatrogenic PTX
Needle thoracostomy	Direct visualization	Improves puncture site in >50% of patients
Cricothyroidotomy	Visualize cricothyroid membrane	Guide marking or dissection of cricothyroid membrane
Peripheral IV placement	Direct visualization	Decreases time to completion and number of punctures
Central IV placement	Direct visualization	Reduces placement failure, complications, and number of attempts

CPR: cardiopulmonary resuscitation; ROSC: return of spontaneous circulation; ET: endotracheal; PTX: pneumothorax; IV: intravenous.

Rapid Ultrasound for Shock and Hypotension) patients. For example, the Rapid Ultrasound for Shock and Hypotension exam includes IVC measurements (evaluate volume status), cardiac exam [assess for tamponade, right ventricle failure (sign of pulmonary embolism), left ventricle contractility], and abdominal/pelvic views to look for free fluid.[60] Given the significant and varied risks involved with high-altitude flight or jump accidents, it is critical when creating a diagnostic algorithm to balance the benefits of field ultrasound with the risk of delaying critical treatments for a severely injured pilot.

DISCUSSION

As demonstrated, ultrasound has proven efficacy in diagnosing multiple life-threatening conditions that should be anticipated in high-altitude flight and jump accidents (**Table III**), including cardiac tamponade, pneumothorax, massive hemothorax, pulmonary contusion, solid organ injury with intraperitoneal hemorrhage, and long bone fracture. Other conditions, such as ebullism, DCI, and inhalational injury, do not yet have solid evidence showing ultrasound's efficacy, but show great potential for its future use with additional research. Ultrasound has also helped reduce complications and improve success rates of many procedures, including cricothyroidotomy, needle thoracostomy, chest tube placement, and peripheral and central IV placement. With proven utility in the field and continually decreasing size and cost, ultrasound is a phenomenal tool to help increase confidence in diagnoses and guide intervention for a variety of life-threatening conditions in cases where field stabilization is required and long transport time is anticipated.[30,31,54]

Again, using the StratEx Space Dive as a model for high-altitude missions, the worst case scenario envisioned included high-altitude exposure complicated by landing trauma, in which case the need for stabilization and rapid transport were paramount. A rapid ultrasound algorithm was created (**Fig. 2**) using the information gathered on its diagnostic and therapeutic capabilities to sequentially evaluate for most life-threatening and intervenable issues, provide interventions, and send information ahead to a receiving center. The algorithm was designed for an unconscious, hypotensive crewmember (presumably the most unstable); however, it could be applied to any crew following high-altitude exposure or landing trauma to investigate for occult or evolving processes.

Specific to high-altitude jumps is the crew's extraction from the space suit, which is laborious and can delay management, but must be accomplished prior to interventions to prevent equipment becoming dislodged during extraction. Airway, breathing, and circulation management (pursuant to Advanced Trauma Life Support protocols) are then implemented and transport called. Ultrasound is considered an adjunct to field or transport stabilization, performed after this primary assessment. In the case of hypotension, IV access and blood products are initiated prior to or in parallel with ultrasound screening.

The risk of potential exposure to high altitude [>62,992 ft (19,200 m) altitude] and the possibility of ebullism is analyzed after initial considerations. Exposure to vacuum for several minutes is survivable with aggressive medical therapy.[42] If ebullism is likely, or it cannot be ruled out in the face of rapid decompensation, providers would proceed to the ebullism protocol previously described in support of the Red Bull Stratos freefall program,[53] which includes high-frequency percussive ventilation. Unfortunately, there is insufficient data with ultrasound in either DCI or ebullism to claim any diagnostic capability, an area that could be better informed from future research. Of note, if bubbles are seen on the cardiac echo in a normotensive, altered crewmember, they could specifically be transported to a hospital containing a hyperbaric facility at the expense of a longer transport time (not advised in a hypotensive crewmember) for potential DCI treatment following evaluation for other potential injuries.

Potential thoracic injuries (massive hemothorax, pneumothorax, and cardiac tamponade) are investigated next using the ultrasound E-FAST exam. If identified, intervention can occur with or without ultrasound guidance or evaluation as needed. Of the abdominal injuries related to trauma (Table III), solid organ damage is most likely to be inferred by ultrasound via visualization of intra-abdominal free fluid. Findings (such as free fluid or rupture of the diaphragm) are unlikely to drive field intervention, but early notice to a trauma center can facilitate

Table III. Pathologies of Concern for Recovery Teams Involved in Rescue of Injured Crew from Missions with Potential High Altitude Exposure, Free Fall Injury, and/or Landing Trauma.[2]

THORACIC TRAUMA	ABDOMINAL TRAUMA	HIGH ALTITUDE EXPOSURE	FREE FALL INJURY
Airway obstruction	Diaphragm injury	Pulmonary ebullism	Rapid spin injury
Tension pneumothorax	Spleen or liver injury	Ebullism	Pelvic fracture
Open pneumothorax	Pancreatic injury	DCI	Long bone fracture
Flail chest/rib fractures	Genitourinary injury	Hypothermia	Vertebral fracture
Pulmonary contusion	Hollow viscous injury	Hypoxia/anoxia	Spinal cord injury
Massive hemothorax		Neurological DCI	Blunt head injury
Tracheobronchial tree injury		CAGE	Sternal fracture
Cardiac tamponade			Clavicular fracture
Blunt cardiac injury			
Traumatic aortic disruption			
Blunt esophageal rupture			

DCI: decompression illness; CAGE: cerebral arterial gas embolism.

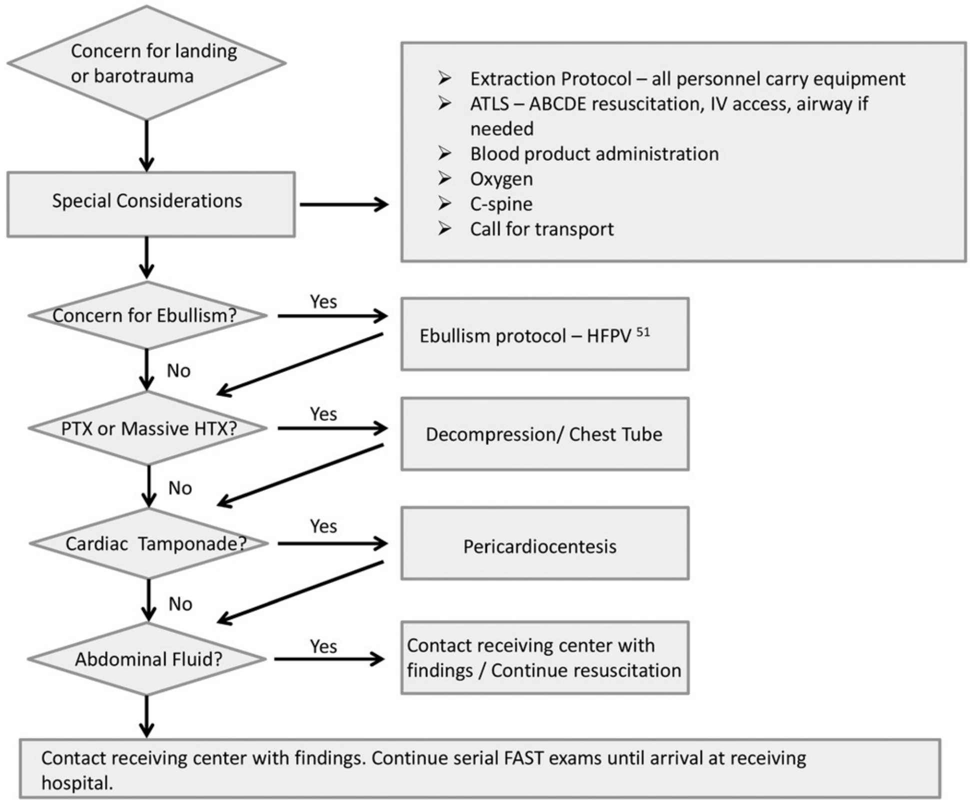

Fig. 2. Ultrasound algorithm designed for use in StratEx for a downed, hypotensive crewmember with concern for landing or barotrauma. ATLS: Advanced Trauma Life Support; ABCDE: Airway Breathing Circulation Disability Exposure; PTX: pneumothorax; HTX: hemothorax; HFPV: high-frequency percussive ventilation.

the marshaling of resources and early operative intervention on arrival at the trauma center. The E-FAST exam can be completed in a serial fashion during transport to keep the receiving hospital informed of status changes. Long bone fracture should be investigated in light of continued decompensation, with traction splint application to realign the bones if there is evidence of gross deformity or hematoma formation. This algorithm can allow optimal use of the 'Golden Hour' (the time window following trauma with highest likelihood of prompt treatment preventing death) in the case of extended suit extraction and long transport time to definitive care.[23]

Trauma, neurological DCI, and rapid negative spin injury can all result in significant neurological impairment.[8] If the etiology is unclear, the difficulty in clinically separating symptoms of neurological DCI from traumatic damage to the brain or spinal cord suggests that the first triage point should always be a Level 1 Trauma Center before proceeding to a hyperbaric chamber. Ultrasound can identify pneumothorax as a contraindication to immediate hyperbaric treatment or air evacuation in an unpressurized aircraft. A presumably barotrauma-associated pneumothorax should also raise suspicion for cerebral arterial gas emboli causing neurological DCI. NASA has developed an in-suit Doppler ultrasound for use in their Extravehicular Mobility Unit space suit to assess for decompression stress, but this is not yet commercially available technology.[44] Toe-to-head acceleration resulting from rapid spin during freefall can result in focal/global neurological impairment and ocular or cerebral hemorrhage, but is unlikely to produce hypotension and has no well-described ultrasound findings. Therefore, it is excluded from this algorithm, though assessment for this injury in the normotensive patient with neurological deficits should be prioritized.[58]

In conclusion, the StratEx Space Dive program marks a turning point in prehospital emergency medical needs. Prior to Red Bull Stratos and StratEx, the only high-altitude missions that required medical personnel were NASA and military programs with government and contract medical crews who came with significant resources. The burgeoning field of commercial spaceflight and high-altitude forays require emergency medical specialists who are familiar with injuries specific to these missions and familiar with field diagnosis and management using portable, affordable, and time efficient equipment. The inclusion of portable ultrasound with highly skilled and trained providers in the field has the potential to improve survivability of these high-risk activities at low cost. The algorithm created is versatile and has the potential to be modified and applied to a variety of circumstances that can include sole exposure to low pressures and no trauma (suit failure in hypobaric chamber or high-altitude spacecraft depressurization), or trauma with no exposure to low pressures. These conclusions represent the authors' opinion based on the research performed and reported here.

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