Ultrasound Evaluation of the Magnitude of Pneumothorax: A New Concept

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Pneumothorax is commonly seen in trauma patients; the diagnosis is confirmed by radiography. The use of ultrasound where radiographic capabilities are absent, is being investigated by the National Aeronautics and Space Administration. We investigated the ability of ultrasound to assess the magnitude of pneumothorax in a porcine model. Sonography was performed on anesthetized pigs in both ground-based laboratory (n = 5) and microgravity conditions (0 × *g*) aboard the KC-135 aircraft during parabolic flight (n = 4). Aliquots of air (50–100 cm^3) were introduced into the chest to simulate pneumothorax. Results were videorecorded and digitized for later interpretation. Several distinct sonographic patterns of partial lung sliding were noted including the combination of a sliding zone with a still zone and a "segmented" sliding zone. These "partial lung sliding" patterns exclude massive pneumothorax manifested by a complete separation of the lung from the parietal pleura. In 0 × *g*, the sonographic picture is more diverse; one × *g* differences between posterior and anterior aspects are diminished. Modest pneumothorax can be inferred by the ultrasound sign of "partial lung sliding." This finding, which increases the negative predictive value of thoracic ultrasound, may be attributed to intermittent pleural contact, small air spaces, or alterations in pleural lubricant. Further studies of these phenomena are warranted.

PNEUMOTHORAX IS A COMMON clinical problem that may be spontaneous or iatrogenic or may follow chest trauma. The diagnosis of pneumothorax is suggested by the history and clinical examination; confirmation requires chest roentgenography. In settings where radiologic capabilities are not immediately available ultrasound may provide information that can aid in the diagnosis of pneumothorax. Numerous sonographic signs have been described that are associated with pneumothorax; however, prior investigators have suggested that ultrasound is inaccurate in the determination of the magnitude of the pneumothorax.

This study, using a controlled animal model, investigates the utility of thoracic ultrasound imaging to determine the extent of pneumothorax. We then examined the effects of weightlessness on these sonographic findings to ascertain the accuracy of ultrasound for the specialized application of determining the extent of pneumothorax during space flight.

Presented at the 43rd Annual Meeting, Midwest Surgical Association, Mackinac Island, Michigan, August 13–16, 2000.

This study was supported by NASA Contract NAS9-097005, National Aeronautics and Space Administration/Johnson Space Center.

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Methods

The procedures described herein conformed to the National Institutes of Health Guidelines for the Care of Laboratory Animals and were approved by the National Aeronautics and Space Administration (NASA) Johnson Space Center Institutional Review Board, the University of British Columbia, and University of Texas Medical Branch—Galveston Animal Care and Use Committees.

Initial ground studies were performed at the Animal Care Facility at the Jack Bell Animal Research Facility at the University of British Columbia (Vancouver, BC, Canada) to develop the model and verify the diagnostic accuracy of ultrasound in this porcine model. Adult female Yorkshire pigs (average weight 25 kg) were anesthetized with ketamine (10 mg/kg) and xylazine (2 mg/kg) and maintained with Pentobarbital. The animals were intubated and continuously ventilated with

an Impact Ventilator (Model 754) (Impact Instrumentation, West Caldwell, NJ) with a tidal volume of 600 to 750 cm^3 a positive end-expiratory pressure of 5 cm H_2O, and a rate of 12 to 16 per minute. Hair on the animals' chest and abdomen was removed with a depilatory agent and shaving. A Foley catheter was inserted into the bladder.

Baseline ultrasonic scans of both hemithoraces were performed with a high-definition ultrasound machine and a hand-held portable ultrasound device. Thoracic scans were done in a serial fashion in the anterior chest apex, the mid-lateral chest, and the posterior thoracic region. Continuous scanning was done for approximately 10 to 20 seconds in each area. When possible the scanning plane was aligned parallel to the long axis of the body to maximize the possible range of motion. The presence or absence of lung sliding (to-and-fro motion coincident with respiration at the visceral-parietal interface) was then determined. The images were digitally recorded for later data analysis.

Hardware

Two ultrasound imaging systems were investigated in this study. The first device was an HDI-5000 (ATL, Bothell, WA), which is similar to the unit that will be part of the Human Research Facility in the US Laboratory Module on the International Space Station. Images from this device were recorded and annotated for later analysis. The transducer used for this application was a broad-band 12-5-MHz linear probe. A second portable ultrasound device, the Sonosite 180 (Sonosite, Inc., Bothell, WA), which is a 5.4-lb battery-powered unit equipped with a 5-2-MHz broadband probe, was used.

Pneumothorax Model

Baseline scans of both hemithoraces were performed before instrumentation to determine the presence or absence of lung sliding or comet tail artifacts in all three thoracic portals. A 16-F Cordis introducer was then inserted in the apex of the right chest through a small stab incision. Care was taken to avoid introduction of air or lung injury during insertion; the thoracic scans were repeated before instillation of air into the chest. Aliquots of air were then serially introduced into the chest through the catheter followed by thoracic ultrasound examinations in the anterior, lateral, and posterior portals. Gradually increasing thoracic inflation volumes were used starting at 10 cm^3 and concluding with a total inflation volume of 1000 cm^3 of air. A chest tube was then inserted and connected to a Heimlich valve, and the intrathoracic pressure was increased by the addition of positive end-expiratory pressure and sigh ventilation. The thoracic ultrasound examinations were then repeated before conclusion of the protocol. Each animal was euthanized and necropsies were performed to verify catheter and chest tube placement and examine the lungs for evidence of iatrogenic injury.

Microgravity Investigations

The microgravity phase of the study was done in conjunction with the University of Texas Medical Branch (UTMB) in Galveston, TX and the NASA/Johnson Space Center in Houston, TX. The animals were prepared at an offsite animal facility (UTMB-Galveston) before transport to Ellington Field for the flight. The zero gravity ($0 \times g$) studies were performed onboard NASA KC-135 research aircraft during parabolic flight profiles. Each parabola consisted of two phases lasting approximately 2 minutes: 30 to 40 seconds of $1.8 \times g$ followed by approximately 15 to 20 seconds of transition followed by 20 to 25 seconds of $0 \times g$ flight followed by another transition period. The animal, life support, monitoring equipment, and ultrasound equipment were secured in the aircraft floor before takeoff.

Baseline ultrasound evaluations were completed during level flight ($1 \times g$) and during parabolic flight ($0 \times g$) before instrumentation. The insufflation catheter was then inserted and the air insufflations were done as previously outlined during the initial zero-gravity transition to allow adequate time for air equilibration and ultrasound evaluation during the period of zero gravity.

Results

Lung sliding was readily apparent in all lung fields before instrumentation in all of the animals. Image quality was excellent with the HDI 5000 ultrasound machine with comet tail artifacts noted in a number of the animals. The Sonosite 180 ultrasound device produced image quality of lesser resolution; however, lung sliding was also evident on the smaller built-in screen. When the Sonosite 180 was connected to an external 15-inch monitor through its output channel excellent image quality was noted.

There was no evidence of pneumothorax after insertion of the insufflation catheter; lung sliding was unchanged in all animals. After insufflation of 150 cm^3 of air into the insufflation catheter an area of delineation of lung sliding/not sliding was identified in the anterior thoracic portal (Table 1). This finding of "partial lung sliding" consisted of visualization of lung sliding in a portion of the scanning window with adjacent absence of sliding noted in the same window. It is presumed that this occurs when the transducer is placed over an area where the visceral and parietal pleura are separated in the scanning window.

TABLE 1. *Lung Sliding (S) or Partial Sliding (P/S) Was Determined during Real-Time Scanning in the Anterior, Lateral, and Posterior Thoracic Portals under Normal Gravity (One × g) Conditions*

	Anterior	Lateral	Posterior
Baseline	S (4/4)	S (4/4)	S (4/4)
Postcatheter	S (4/4)	S (4/4)	S (4/4)
50 cm^3	S (4/4)	S (4/4)	S (4/4)
150 cm^3	P/S (2/4)	P/S (1/4)	S (4/4)
250 cm^3	P/S (3/4)	P/S (1/4)	P/S (1/4)
Post-chest tube	S (4/4)	S (4/4)	S (4/4)

Numerical data reflect the number of animals with the described ultrasound finding. Baseline scans were performed before instrumentation (baseline) and after insufflation of air (postcatheter); the post-chest tube readings were done after evacuation of the chest and with ventilatory assistance.

As insufflation volumes increased there was a progressive loss of movement of lung sliding from the anterior window, to the lateral thorax, and finally to the posterior window. As the loss of lung sliding progressed through the chest there was a contiguous absence of lung sliding in the anterior and lateral thorax and finally the entire chest. Higher insufflation volumes did not affect the thoracic ultrasound visualization. After placement of the chest tube and evacuation of air from the thorax lung sliding reappeared in all thoracic portals.

Thoracic ultrasound visualization in the NASA Microgravity Research Facility was not different from the ground controls during level flight or after instrumentation with continued visualization of lung sliding. Partial lung sliding was variably seen during microgravity (Table 2). Additionally there was no anterior-to-posterior progression of lung sliding noted during microgravity; all of the visualized thoracic portals appeared to be of equivalent sensitivity. During 2 × *g* pullout, however, lung sliding often returned in the posterior thorax presumably from the gravitational displacement of the lung posteriorly. Lung sliding returned in all visualization portals after chest tube insertion and re-expansion of the lung.

TABLE 2. *Results from Thoracic Ultrasound Performed during Parabolic Flight on the NASA KC-135 Microgravity Research Facility under Microgravity (O × g) Conditions*

	Anterior	Lateral	Posterior
Baseline	S (4/4)	S (4/4)	S (4/4)
Postcatheter	S (4/4)	S (4/4)	S (4/4)
50 cm^3	S (2/4)	S (3/4)	S (3/4)
150 cm^3	S (1/4)	S (1/4)	S (1/4)
250 cm^3	S (1/4)	S (0/4)	S (1/4)
Post-chest tube	S (4/4)	S (4/4)	S (4/4)

The ultrasonographic findings were recorded during the microgravity portions of the flight. Numerical data reflect the number of animals with the described ultrasound finding. S, lung sliding.

The insufflation catheters were all noted to lie in the anterior chest cavity at autopsy examination. There was no evidence of iatrogenic lung injury; however, a small amount of blood was seen in some of the animals presumably resulting from chest tube placement or additional instrumentation that followed the reported portion of this protocol.

Discussion

Pneumothorax frequently results from penetrating chest trauma, blunt chest injury, or barotrauma; occurs spontaneously; or occurs as a complication after therapeutic or diagnostic chest procedures. The diagnosis of pneumothorax is made on the basis of the history, clinical signs, and characteristic physical findings and is confirmed with chest radiography or occasionally CT. Although a small or moderate pneumothorax is generally not life threatening a delay in diagnosis and treatment may result in respiratory and circulatory collapse. Furthermore, a high index of suspicion of pneumothorax and inability to obtain a radiograph often mandates definitive care or movement of the patient to an environment where additional diagnostic capabilities are available. In remote locations this can present significant logistic challenges.

Ultrasound has proven diagnostic accuracy in numerous applications involving the abdomen and extremities; however, the use of ultrasound in the thorax has been hindered by the high acoustic impedance of air. Recently ultrasound has been suggested to be a useful modality in the evaluation of pneumothorax in patients after ultrasound-guided lung biopsy,[1] in ventilated medical intensive care unit patients,[2] and more recently in patients with penetrating chest trauma.[3]

The first reported use of ultrasound to diagnosis pneumothorax occurred in a veterinary journal. A pneumothorax in a horse was diagnosed after thoracic scanning identified the normal respiratory motion of the lung against a static air artifact.[4] Ultrasonic evaluation of the lung has been suggested to be paradoxical, because the diagnosis rests on the absence of findings normally seen in the chest such as pleural sliding or motion at the lung-chest wall interface. Scanning is performed between ribs that are easily identified as a dense acoustic shadow. The lung-chest wall interface or pleural line moves with a to-and-fro sliding motion synchronized with respiration.[3] Ultrasonographic signs associated with pneumothorax have been reported and include the absence of normal lung sliding and lack of comet tail artifacts, which are acoustic highlighting resulting from localized irregularities in the subpleural parencyma.[5–8]

The sensitivity of ultrasound in the diagnosis of pneumothorax appears to be comparable with that of

chest radiography. The presence of lung sliding or comet tail signs reliably excludes pneumothorax; however, prior investigators have not been able to correlate ultrasound findings with the extent of pneumothorax. Sistrom et al.[1] blindly compared taped thoracic ultrasound examinations of patients with variable-sized pneumothoraces and found limited correlation. The diagnostic sensitivity of ultrasound in this series was less than that of comparable reports, suggesting that the accuracy of the examination is reduced when images are stored for later review on tape. Furthermore the absence of a trained operator at the primary investigation to allow repeat scanning or interpretation of subtle findings may affect the sensitivity of the examination.

In this report partial lung sliding was initially evident at very low insufflation volumes that would correlate with a clinically and possibly radiographically silent pneumothorax. This finding has been recently reported in two patients who had a small pneumothorax detected on CT with a normal chest radiograph.[9] Although the complete absence of lung sliding is a reliable indicator of the presence of pneumothorax the addition of the partial lung sliding sign may improve the diagnostic sensitivity of the examination in the detection of small pneumothoraces.

Thoracic ultrasound appears to be a useful test in the microgravity environment with some interesting differences from terrestrial applications. Lung sliding is readily apparent in zero-gravity in normal lungs and is reliably absent in animals with pneumothorax. Thoracic ultrasound appears to be more sensitive in a zero-gravity environment possibly because of more uniform distribution of the interpleural air in the absence of gravity. Furthermore all areas of the thorax were equally sensitive as the lung assumes a central perihilar position during pneumothorax in zero gravity. This finding was confirmed in this investigation by visualization of the thoracic cavity by thoracoscopy as a secondary objective of this study (data not shown).

The absence of immediate chest roentgenography complicates the diagnosis of pneumothorax and can significantly impact treatment and outcome. This is of particular importance in rural settings, in military conflicts, and in aerospace medicine where radiologic capabilities are absent. Injured patients with a possible pneumothorax in remote areas may receive thoracostomy tube placement without definitive diagnosis before transport to a treatment center. Astronauts aboard the International Space Station are at risk for pneumothorax from hypobaric exposure during space walks and potential blunt injury. Power and weight restrictions prohibit the use of X-ray imaging aboard the International Space Station. The use of ultrasound may be of potential benefit for the diagnosis of pneumothorax in these settings and others facilitating appropriate treatment before emergency transfer.

Thoracic ultrasound appears to be a promising technique for the exclusion of pneumothorax in patients in whom chest radiography is delayed or impossible. Familiarity gained by performance of thoracic ultrasound concomitant with abdominal evaluation in trauma patients has led to the ability to detect an apical pneumothorax with the identification of a partial lung sliding sign. Theoretically recognition of the partial lung sliding sign may be used to diagnose partial or loculated pneumothoraces that may not be identified by the strict application of complete absence of lung sliding as the only criterion for diagnosis of pneumothorax. Verification of the usefulness of thoracic ultrasound requires randomized evaluation in trauma centers that should be explored during routine Focused Abdominal Sonography for Trauma (FAST) analysis.

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DISCUSSION

DR. R. STEPHEN SMITH (Wichita, KS): It would appear from your paper that a relatively large pneumothorax had to be present, in the range of 150 to 250 cm^3, in a fairly small swine model before the technique was reliable. Could you then surmise that this will lead to missed small pneu-

mothoraces when used in the clinical setting? In the clinical setting many patients with traumatic pneumothorax present with subcutaneous air in the affected hemithorax, and as we all know subcutaneous air usually makes ultrasound imaging of deeper structures difficult if not impossible. How will this problem affect the utilization of this technique in the clinical setting?

Relatively high-frequency broadband transducers were used in your study. This was possible because of the small animals involved. These transducers provide very good resolution but poor penetration due to ultrasound attenuation. Will the use of lower-frequency transducers such as a 3.5-MHz transducer that is usually used in the evaluation of an adult trauma patient lessen the accuracy of this technique?

Your group at Detroit Receiving has extensive experience with the FAST exam in the trauma setting. Can you compare the difficulty of the FAST exam with this exam? Is this more difficult to do than the FAST? Is there a learning curve that you went through before you could pick up this sliding lung sign and partial sliding sign?

I guess a bigger question, as far as NASA is concerned, is: Can you actually train astronauts with limited experience to do this study?

I think the authors have offered us yet another method for making a diagnosis of pneumothorax, and I do think this will have clinical implications, not only in our trauma centers but in space as well.

Based on your initial experience with the technique would you recommend that this becomes a standard component of the FAST exam? And finally do you think we will ever become proficient enough to eliminate routine chest X-ray from the evaluation of our trauma patients?

DR. ANDREW W. KIRKPATRICK: This technique can definitely diagnose small pneumothoraces. I think it will miss some, and we are all still learning about it.

We have picked up small pneumothoraces that weren't seen on chest X-ray but were discovered later on a CT scan obtained for some other reason. One of those cases can actually be downloaded from the Web. We have posted it there at www.vghtraumaresearch.com.

There is no question that subcutaneous emphysema will prevent getting images of anything deeper. No test works in all situations. This is supported by the Sunnybrook experience with undeterminate FAST exam which also reported that sonography is not useful when there is subcutaneous emphysema, although this was uncommon.

In terms of the transducer frequency you will see images with the 3.5-MHz transducer. There is no question though that the 7.5-MHz transducer gives a better image, and it is easier with the linear transducer to get it between the ribs. So if you have the opportunity to use the higher-frequency transducer that is definitely what we would recommend.

The learning curve for diagnosing a complete pneumothorax is steep. For small pneumothoraces I think that the jury is out, and I think we really need to do the clinical studies in human patients before changing the standard FAST examination. But maybe in a year or two we will come back and say, yes, this should be part of the FAST exam and we should have both the 3.5- and 7.5-MHz transducers available.

Training astronauts to do this is quite feasible with remote direction. That is where you might discuss telemedicine or telesonography. This may be feasible from a low earth's orbit. For anything further, you may get into inordinate time delays.

Finally, I don't think it will replace chest X-ray. It is a complementary technique. I think its value is in its portability. However, you get so much more additional information from a chest X-ray.

DR. GERARD V. ARANHA (Maywood, IL): Does NASA prescreen its astronauts for pulmonary blebs or hyperinflated lungs?

DR. KIRKPATRICK: No, not at present, although pneuothoraces are a real risk up there, partially because of some of the hyperbaric changes with decompression procedures required for space walks.