Feasibility of pneumoperitoneum diagnosis using point-of-care ultrasound: a pilot study using a fresh cadaver model

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Abstract

Aims: To assess the accuracy of point-of-care ultrasound (PoCUS) in the hands of two trained and blinded emergency physicians (EPs) in detecting very small amounts of free intraperitoneal air injected intra-abdominally, using a fresh human cadaver model. Material and methods: Fifteen cadavers were injected on 3 occasions with predefined quantities of free intraperitoneal air ranging from 0-10 mL. Seven cadavers were injected in the mid-epigastrium (ME), while 8 were injected in the left lower quadrant (LLQ). Each cadaver was scanned after each of the 3 injections by 2 trained and blinded EPs, resulting in 45 scans per sonographer. Scans were performed using previously validated and standardized techniques. All scans were recorded, time-stamped and labeled. For each scan the sonographers indicated “yes” or “no” to whether pneumoperitoneum was detected. A chi square analysis was performed to determine the sensitivity and specificity of PoCUS utilized by each sonographer of pneumoperitoneum based on the location and volume of air injected. Results: Free air (0.25-10 mL) injected into the ME was successfully diagnosed in 36/42 instances (86% sensitivity), but only detected in 10/36 instances when injected into the LLQ (28% sensitivity). Both EPs detected all air injections of ≥2 mL into the ME. Conclusion: Detection of free air originating from the midepigastric region may become a future PoCUS indication for adequately trained EPs.

Keywords: point-of-care ultrasound; emergency medicine; pneumoperitoneum; cadaver

Introduction

The acute abdomen, a sudden severe abdominal pain of unclear etiology that is less than 24 hours in duration, accounts for more than 7 million United States Emergency Department (ED) visits annually and up to 40% of emergency surgical admissions [1]. Gastrointestinal perforation with pneumoperitoneum is often considered in the differential diagnosis for the acute abdomen [2-4]. Morbidity and mortality from secondary peritonitis remains high (30-50%) despite advances in medical and surgical therapies [5]. Rapid diagnosis and management in the ED is therefore essential to reduce complications associated with gastrointestinal perforation [5-7].

While the initial conventional imaging approach in the ED to detect pneumoperitoneum is upright posteroanterior chest or left lateral decubitus radiography, it is known to be insufficiently sensitive for small to moderate amounts of free air and may miss the diagnosis and delay management [8-14]. X-rays also expose patients to small doses of ionizing radiation and should be avoided when possible in children and women of reproductive age [15]. Computed tomography (CT) is highly accurate for even small amounts of free intraabdominal air and is considered gold standard imaging for this diagnosis, however, it
is associated with even higher exposure to ionizing radiation and higher health care costs [14,16-22]. Critically ill and hemodynamically unstable patients may especially benefit from a portable imaging modality, such as point-of-care ultrasound (PoCUS) performed by trained emergency physicians (EPs), to expedite diagnosis and management prior to definitive imaging.

Prior investigations by non-EP imaging experts have shown that ultrasound (US) can detect small quantities of intraperitoneal air. As early as 1982, Seitz and Reising reported in a proof of concept study that the accuracy of US is compatible with conventional chest x-ray imaging, the gold standard imaging test in 1982 for free air. These highly trained experts detected as little as 1 mL of free intraperitoneal air with 100% accuracy [23]. In their large-scale follow up study of about 4,000 consecutive patients presenting to a single ED with non-traumatic acute abdominal pain, the same authors demonstrated 90% sensitivity and 100% specificity of US for pneumoperitoneum [23]. Smaller subsequent studies performed by highly trained physicians further supported these initial findings, including in blunt trauma and non-trauma patients. All showed high accuracy and superior sensitivity when compared to plain radiography [24-28]. However, given the trend of increasing use of PoCUS in emergency medicine education, there is little knowledge about whether EPs who train in PoCUS can reliably identify pneumoperitoneum [29,30]. It would additionally be of interest to learn if a cadaver model with induced pneumoperitoneum can serve as a reliable teaching model for emergency physicians learning to diagnose pneumoperitoneum with PoCUS.

If EPs trained in PoCUS can accurately detect free intraperitoneal air, especially small amounts of free intraperitoneal air, management of critically ill patients with perforated viscous and free air could potentially be expedited.

We conducted a pilot study to determine if two PoCUS trained EPs could reliably detect small amounts of intraabdominal free air. We chose a fresh human cadaver model for feasibility reasons to assure a prospective blinded study design and to reliably determine the exact amount of free air present in the intraabdominal cavity.

Material and methods

Preparation of cadavers

Fifteen fresh human cadavers donated to the Anatomy Institute were utilized for this prospective randomized study, which took place at the University of Maryland, Baltimore, Anatomical Services Division cadaver lab. The Institutional Review Board reviewed this research study and deemed this study exempt as per current federal guidelines.

In preparation of scanning, all cadavers were positioned in reverse Trendelenburg at 30 degrees for ten minutes and pre-scanned by two trained separate EPs, to rule out the presence of any artifacts or irregularities at the peritoneal area including sonographic artifacts consistent with pneumoperitoneum. All participating emergency physicians had prior extensive US experience in PoCUS including pneumoperitoneum diagnosis.

The two coordinators injected 15 fresh human cadavers with various predefined quantities of free intraperitoneal air, ranging from 0-10 mL. Each cadaver was injected 3 times throughout the study and scanned three times. The injection/scanning order was based upon a pre-designed randomized order and matrix (Table I, fig 1). Figure 2 illustrates a positive and negative US finding for free intraperitoneal air. The matrix specified the quantity of air to be injected, the location of injection and the order of the cadavers to be scanned. A cadaver was randomized to either the mid-epigastric (ME) injection (1 cm cephalad to the umbilicus) or left lower quadrant (LLQ) abdominal injection, which was performed exactly equidistant between umbilicus and left anterior superior iliac spine (ASIS). Once a cadaver was randomized to a specific injection site, all three injections for this cadaver were administered at the same anatomical location and resulted in cumulative amounts of free air.

Of the 15 cadavers, eight were injected x3 in the midepigastric area, seven x3 into the left lower quadrant as described above. This created 45 different scanning scenarios: 24 for cadavers with ME free air and 21 for LLQ free air (fig 3). As each cadaver was scanned by both sonographer A and B, this resulted in a total of 48 encounters for ME cadavers and 42 observations in LLQ.
injected cadavers. Several of the initial injections were sham injections with 0 mL of free air.

For each of the three rounds or observations, injections of air in increments of 0, 0.25, 0.5, 0.75, 1, 2, 4, 7 or 10 mL were performed. The assigned volume of air was combined with normal saline to total a volume of 12 mL. For example, if the assigned volume of air was 0.5 mL, 11.5 mL normal saline was added to the syringe so that the total volume of air and normal saline to be injected was 12 mL. For the sites assigned zero mL of air, a total of 12 mL of normal saline was injected. All injections were performed under ultrasound guidance. The skin was punctured with a 25-gauge needle in both the ME and LLQ regions of all cadavers regardless of the location of injection for blinding purposes. As noted above, injections were repeated x2 for each of the 15 cadavers to introduce 45 (15x3) combinations of scanning scenarios for each sonographer (fig 4). Cadavers were stationed in several rooms, covered with sheets and towels, and wheeled to different locations randomly to preserve sonographer blinding. All cadaver anatomy was concealed with the exception of the abdomen.
Scanning

The two blinded expert sonographers (A and B) scanned each cadaver independently using a SonoSite Turbo (Bothell, WA) high frequency linear probe (L38) positioned sagittally with the indicator directed cephalad in three locations: the right upper quadrant (RUQ), the ME and the left upper quadrant (LUQ). Scans were performed via previously validated and standardized techniques to detect typical signs of pneumoperitoneum. The ME and LLQ were chosen as injection sites as these are common sites of perforated viscous that can produce air visible throughout the abdomen and detectable at perforation site, right upper quadrant and mid-abdomen [23,31-33]. All scans were recorded, time-stamped and labeled. For each scan, the sonographers indicated “yes” or “no” to whether pneumoperitoneum was detected.

Statistical analysis

A chi square analysis was performed to determine the sensitivity and specificity of PoCUS utilized by each sonographer to detect accuracy and various quantities of pneumoperitoneum based on location of air injected. An unweighted Cohen’s Kappa value was calculated to measure interrater agreement.

Results

The sonographers were considerably more effective at correctly diagnosing and documenting air that had been injected (0.25-10 mL) into the ME region than in instances where air had been injected into the LLQ region (p<0.001 by Chi-square analysis). Air (0.25-10 mL) injected into ME was successfully diagnosed and documented with 86% sensitivity in 36 of 42 encounters. Pneumoperitoneum was not detected and/or documented in 26 of 36 instances when injected into LLQ (28% sensitivity in 18 separate injections, fig 5-7). Notably, the sonographers correctly diagnosed and documented all 10 separate air injections of ≥2 mL into the ME (6 cadavers) but were not successful to diagnose comparable air injections of ≥2 mL into the LLQ in 13 of 16 trials (4 cadavers).
The disparity in success rates for diagnosing and documenting air injections into the two locations is further illustrated by the number of instances in which the sonographers had correctly diagnosed and documented air at a lower volume of injection, only to fail to diagnose or document a higher volume of air injected into the same location in the same cadaver (once with injections in ME, versus eight separate instances (four for each sonographer) with injections into the LLQ).

There was no obvious benefit of performing multiple scans on a single cadaver, as success rates when air had been injected were comparable after the 1st, 2nd and 3rd injections in both the ME (90, 88 and 81% respectively) and the LLQ (50, 14 and 29% respectively). Sonographer B more frequently provided a correct diagnosis and documentation of air injected into the ME (95 vs. 76%) or the LLQ (39 vs. 17%), but also more frequently generated false positive diagnoses (3 vs. 1).

Interobserver agreement between Sonographer A and B for all 45 exams was moderate (Cohen’s unweighted Kappa = 0.486, 95% CI [0.260, 0.711]) with agreement in 33 of the 45 observations (73%). Agreement improved and was good for the 18 exams with 2 mL or more of free air injected. Numbers of observed agreements were 15/18 (83.33%) of the observations and Kappa = 0.649 (standard error of kappa = 0.173; 95% CI [0.310, 0.989]). When looking only at cadavers where air was injected into the ME, the sensitivity and specificity of PoCUS performed by sonographer A for pneumoperitoneum were 76.1% (95% CI [52.4, 90.9]) and 100% (95% CI [31, 100]), respectively; Sonographer B PoCUS sensitivity and specificity were 90.4% (95% CI [68.1, 98.3] and 33.3% (95% CI [1.8, 87.4], respectively.

**Discussion**

We found in our pilot study that two PoCUS trained EPs detected small amounts of free air ≥ 2 mL with 100% accuracy when injected into the mid-epigastrium in a human cadaver model. While prior studies and case reports suggest that US can be a critical tool in the identification of free air [23] and has been shown to identify small amounts of free air by specialized imaging experts [24], this is the first study showing that EPs trained in PoCUS can reliably perform PoCUS to detect very small pneumoperitoneum on a cadaver model. Importantly, this may translate into detecting small pneumoperitoneum on patients with undifferentiated abdominal pain or hypotension, which can help inform next steps and management in the acute care setting.

If validated in a clinical setting, PoCUS would be a safe, quick and potentially sensitive option for detecting pneumoperitoneum, when performed by trained physicians. In very young patients and populations at highest risk from radiation exposure, PoCUS may even obviate the need for CT imaging.

The study also shows a potential training module for EPs that would allow fresh frozen cadavers for pneumoperitoneum training models.

Our study has several limitations. Fresh cadavers are different than living human beings, which impact the external validity of this study. In live humans, there are many ongoing dynamic processes, that likely promote movement of pneumoperitoneum to the least dependent region possible. For example, bowel peristalsis, diaphragmatic movements, movements of the abdominal and back musculature and ambulation all may contribute to free air movement to the RUQ or least dependent region of the peritoneal space.

In our cadaver model, factors that may have prevented air from moving to the least dependent region of the peritoneal space could include not allowing the air enough time to travel to the least dependent regions after positioning the cadavers in reverse Trendelenburg positions, lack of bowel peristalsis and abdominal muscle tone. These barriers to air migration may have especially skewed results of pneumoperitoneum detected from the LLQ injection cadavers.

While not a common occurrence, bowel can interpose itself between the peritoneal line and the liver, creating a sonographic appearance similar to that of free air. In this situation, the presence of peristalsis may help differentiate free air from air within the bowel in a living patient. Because peristalsis does not occur in our cadaver model, air within the bowel may appear to be just beneath the peritoneal line, contributing to the false positive findings.
Despite the creation of 45 blinded encounters, this was a small study limited by the number of cadavers available and needs to be repeated on a larger scale, ideally on live patients.

In conclusion, this study demonstrated that two trained emergency physicians detected small amounts of free air $\geq 2$ mL reliably when injected into the ME in this human cadaver model. PoCUS appeared feasible for detecting small amounts of pneumoperitoneum in this model with this approach, and, if clinically validated, could expedite the diagnosis and management of patients suspected of having pneumoperitoneum in the acute care setting.

A future prospective study looking at PoCUS detection of pneumoperitoneum among live human beings would be needed to improve external validity and provide clinical value.

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