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

Meghan Kelly Herbst¹, Elizabeth Carter², Shirley Wu³, Christoph F Dietrich⁴, Beatrice Hoffmann⁵

¹Department of Emergency Medicine, University of Connecticut School of Medicine, Farmington CT, USA, ²Department of Emergency Medicine, Inova Alexandria Hospital, Alexandria VA, USA, ³Department of Emergency Medicine, Rhode Island Hospital, Brown University, Providence, RI, USA, ⁴Department of Medicine, Klinik Hirslanden, Bern, Switzerland, ⁵Department of Emergency Medicine, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston MA, USA

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 midepigastrium 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 postero-anterior 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

Received 15.05.2021 Accepted 21.07.2021

Med Ultrason

2022, Vol. 24, No 1, 7-13

Corresponding author: Beatrice Hoffmann

Beth Israel Deaconess Medical Center Boston,

Department of Emergency Medicine,

One Deaconess Road, Rosenberg 2,

Boston 02215, USA

E-mail: bhoffma2@bidmc.harvard.edu

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

Fig 1. Workflow of air injection and randomized scanning of cadavers.

Table I. Matrix of air injected for each cadaver per round of observation and area injected.

round 1	cadaver #	total mL	area	round 2	cadaver #	total mL	area	round 3	cadaver #	total mL	area
1	1	0	ME	16	1	0.5	ME	31	12	0.75	LLQ
2	13	0.25	LLQ	17	5	1	ME	32	11	0.25	LLQ
3	10	1	LLQ	18	13	4	LLQ	33	8	4	ME
4	4	0	ME	19	5	4	ME	34	8	10	ME
5	5	0.75	ME	20	14	0.75	LLQ	35	12	2	LLQ
6	14	0	LLQ	21	4	0.75	ME	36	11	1	LLQ
7	7	0.25	ME	22	1	1	ME	37	9	2	LLQ
8	15	0	LLQ	23	13	7	LLQ	38	6	1	ME
9	2	2	ME	24	15	1	LLQ	39	3	0.25	ME
10	14	0.5	LLQ	25	2	10	ME	40	3	0.75	ME
11	2	7	ME	26	10	4	LLQ	41	9	4	LLQ
12	15	0.5	LLQ	27	7	7	ME	42	6	4	ME
13	7	0.5	ME	28	11	0	LLQ	43	6	10	ME
14	10	2	LLQ	29	8	0	ME	44	3	2	ME
15	4	0.25	ME	30	12	0.25	LLQ	45	9	10	LLQ

ME = midepigastrium, LLQ = Left lower quadrant

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 with was combined with normal saline to total a volume of 12 mL. For example, if the assigned volume of air was 0.5 mL air, 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 in-

Fig 2. Normal peritoneal line (white thick arrow) over anterior liver (a). Typical ultrasonographic signs of pneumoperitoneum showing normal peritoneal line (white thick arrow) and the reverberation artifact caused by free air (thin arrows) below a free air collection (b).

Fig 3. Illustration of injection sites and transducer positioning for midepigastric (ME) and left lower quadrant (LLQ) injections of free air.

jections 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.

Fig 4. Progression of injection volume per cadaver. Each colored line represents one cadaver, and each point represents one encounter. The vertical axis represents the cumulative number of mLs injected, while the horizontal axis represents each round of injections.

Scanning

The two blinded expert sonographers (A and B) scanned each cadaver independently using a SonoSite Turbo (Bothell, WA) high a 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 ca-

Fig 5. Correctly diagnosed midepigastric (ME) and left lower quadrant (LLQ) injected free air.

Fig 6. Success rates of first, second and third observation for each mid-epigastric (ME) and left lower quadrant (LLQ) location free air injections after multiple scans on a single cadaver.

Fig 7. Overview of success rates of the 2 sonographers evaluating the mid-epigastrium (ME) or left lower quadrant (LLQ). Cadaver Number (#) shows injection side with injection volume in mL. Sonographer A and B are shown as a circle if making an incorrect diagnosis, and if correct as full dot.

davers). 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 midepigastrium 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 ≥ 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.

Acknowledgements: We would like to thank Dr. Richard Levitan and Mr. Ronn Wade from the University of Maryland, Baltimore Anatomical Services Division for permitting us to utilize their human cadavers and cadaver lab facilities. We would also like to thank Dr. Ilene Staff for her assistance with the statistical analysis of the data collected. Funding for this study was from the Hartford Hospital New Investigator Grant.

Rereferences

- Langell JT, Mulvihill SJ. Gastrointestinal perforation and the acute abdomen. *Med Clin North Am* 2008;92:599-625.
- McCaig LF, Burt CW. National Hospital Ambulatory Medical Care Survey: 2002 emergency department summary. *Adv Data* 2004;(340):1-34.
- Court-Brown CM, McQueen MM, Patterson-Brown S, Nixon SJ. Emergency surgical care in Scotland. *Surgeon* 2007;5:72-75.
- Schietroma M, Cappelli S, Carlei F, Pescosolido A, Lygidakis NJ, Amicucci G. "Acute abdomen": early laparoscopy or active laparotomic-laparoscopic observation? *Hepato-gastroenterology* 2007;54:1137-1141.
- Ordonez CA, Puyana JC. Management of peritonitis in the critically ill patient. *Surg Clin North Am* 2006;86:1323-1349.
- Wittmann DH, Schein M, Condon RE. Management of secondary peritonitis. *Ann Surg* 1996;224:10-18.
- Feldman M, Friedman LS, Sleisenger MH. (Eds.). *Sleisenger and Fordtran's gastrointestinal and liver disease: Pathophysiology, diagnosis, management*. 7th ed. Philadelphia: WB Saunders, 2004.
- Stoker J, van Randen A, Lameris W, Boermeester MA. Imaging patients with acute abdominal pain. *Radiology* 2009;253:31-46.
- MacKersie AB, Lane MJ, Gerhardt RT, et al. Nontraumatic acute abdominal pain: unenhanced helical CT compared with three-view acute abdominal series. *Radiology* 2005;237:114-122.
- Butler J, Martin B. Towards evidence based emergency medicine: best BETs from the Manchester Royal Infirmary. Detection of pneumoperitoneum on erect chest radiograph. *Emerg Med J* 2002;19:46-47.
- Gupta H, Dupuy DE. Advances in imaging of the acute abdomen. *Surg Clin North Am* 1997;77:1245-1263.
- Billittier AJ, Abrams BJ, Brunetto A. Radiographic imaging modalities for the patient in the emergency department with abdominal complaints. *Emerg Med Clin North Am* 1996;14:789-850.
- Ahn SH, Mayo-Smith WW, Murphy BL, Reinert SE, Cronan JJ. Acute nontraumatic abdominal pain in adult patients: abdominal radiography compared with CT evaluation. *Radiology* 2002;225:159-164.
- Stapakis JC, Thickman D. Diagnosis of pneumoperitoneum: abdominal CT vs. upright chest film. *J Comput Assist Tomogr* 1992;16:713-716.
- Greene CS. Indications for plain abdominal radiography in the emergency department. *Ann Emerg Med* 1986;15:257-260.
- National Research Council. Health risks from exposure to low levels of ionizing radiation: BEIR VII phase 2. National Academies Press 2006. Available from: <http://www.nap.edu/catalog/11340.html>
- Preston DL, Ron E, Tokuoka S, et al. Solid cancer incidence in atomic bomb survivors: 1958-1998. *Radiat Res* 2007;168:1-64.
- Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet* 2012;380:499-505.
- Mathews JD, Forsythe AV, Brady Z, et al. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ* 2013;346:f2360.
- Lumbreras B, Donat L, Hernandez-Aguado I. Incidental findings in imaging diagnostic tests: a systematic review. *Br J Radiol* 2010;83:276-289.
- Thompson RJ, Wojcik SM, Grant WD, Ko PY. Incidental Findings on CT Scans in the Emergency Department. *Emerg Med Int* 2011;2011:624847.
- Medicare Payment Advisory Commission MPA. Report to the Congress: improving incentives in Medicare. Available from: http://www.medpac.gov/docs/default-source/reports/Jun09_EntireReport.pdf Accessed 2016.
- Seitz K, Reising KD. Ultrasound detection of free air in the abdominal cavity. *Ultraschall Med* 1982;3:4-6.
- Chang-Chien CS, Lin HH, Yen CL, Lee CM, Lin SM. Sonographic demonstration of free air in perforated peptic ulcers: comparison of sonography with radiography. *J Clin Ultrasound* 1989;17:95-100.
- Chen SC, Wang HP, Chen WJ, et al. Selective use of ultrasonography for the detection of pneumoperitoneum. *Acad Emerg Med* 2002;9:643-645.

26. Muradali D, Wilson S, Burns PN, Shapiro H, Hope-Simpson D. A specific sign of pneumoperitoneum on sonography: enhancement of the peritoneal stripe. *AJR Am J Roentgenol* 1999;173:1257-1262.
27. Butcher CH, Dooley RW, Levitov AB. Detection of subcutaneous and intramuscular air with sonography: a sensitive and specific modality. *J Ultrasound Med* 2011;30:791-795.
28. Moriwaki Y, Sugiyama M, Toyoda H, et al. Ultrasonography for the diagnosis of intraperitoneal free air in chest-abdominal-pelvic blunt trauma and critical acute abdominal pain. *Arch Surg* 2009;144:137-141.
29. Taylor MA, Merritt CH, Riddle PJ Jr, DeGennaro CJ, Barron KR. Diagnosis at gut point: rapid identification of pneumoperitoneum via point-of-care ultrasound. *Ultrasound J* 2020;12:52.
30. Nazerian P, Tozzetti C, Vanni S, et al. Accuracy of abdominal ultrasound for the diagnosis of pneumoperitoneum in patients with acute abdominal pain: a pilot study. *Crit Ultrasound J* 2015;7:15.
31. Hoffmann B, Nürnberg D, Westergaard MC. Focus on abnormal air: diagnostic ultrasonography for the acute abdomen. *Eur J Emerg Med* 2012;19:284-291.
32. Lee DH, Lim JH, Ko YT, Yoon Y. Sonographic detection of pneumoperitoneum in patients with acute abdomen. *AJR Am J Roentgenol* 1990;154:107-109.
33. Karahan OI, Kurt A, Baykara M, Coskun A. Detectability of intraperitoneal free air by ultrasonography. *Tani Girisim Radyol* 2003;9:60-62.