Safe and Effective Bedside Thoracentesis: A Review of the Evidence for Practicing Clinicians

Richard Schildhouse, MD[1,2*], Andrew Lai, MD, MPH[3], Jeffrey H. Barsuk, MD, MS[4], Michelle Mourad, MD[3], Vineet Chopra, MD, MSc[1,2]

[1]*Division of General Medicine, Department of Internal Medicine, University of Michigan School of Medicine, Ann Arbor, Michigan;* [2]*Division of General Medicine, VA Ann Arbor Healthcare System, Ann Arbor, Michigan;* [3]*Division of Hospital Medicine, Department of Medicine, University of California, San Francisco, San Francisco, California;* [4]*Department of Medicine, Northwestern University Feinberg School of Medicine, Chicago, Illinois.*

BACKGROUND: Physicians often care for patients with pleural effusion, a condition that requires thoracentesis for evaluation and treatment. We aim to identify the most recent advances related to safe and effective performance of thoracentesis.

METHODS: We performed a narrative review with a systematic search of the literature. Two authors independently reviewed search results and selected studies based on relevance to thoracentesis; disagreements were resolved by consensus. Articles were categorized as those related to the pre-, intra- and postprocedural aspects of thoracentesis.

RESULTS: Sixty relevant studies were identified and included. Pre-procedural topics included methods for physician training and maintenance of skills, such as simulation with direct observation. Additionally, pre-procedural topics included the finding that moderate coagulopathies (international normalized ratio less than 3 or a platelet count greater than 25,000/μL) and mechanical ventilation did not increase risk of postprocedural complications. Intraprocedurally, ultrasound use was associated with lower risk of pneumothorax, while pleural manometry can identify a nonexpanding lung and may help reduce risk of re-expansion pulmonary edema. Postprocedurally, studies indicate that routine chest X-ray is unwarranted, because bedside ultrasound can identify pneumothorax.

CONCLUSIONS: While the performance of thoracentesis is not without risk, clinicians can incorporate recent advances into practice to mitigate patient harm and improve effectiveness. *Journal of Hospital Medicine* 2017;12:266-276.

Pleural effusion can occur in myriad conditions including infection, heart failure, liver disease, and cancer.[1] Consequently, physicians from many disciplines routinely encounter both inpatients and outpatients with this diagnosis. Often, evaluation and treatment require thoracentesis to obtain fluid for analysis or symptom relief.

Although historically performed at the bedside without imaging guidance or intraprocedural monitoring, thoracentesis performed in this fashion carries considerable risk of complications. In fact, it has 1 of the highest rates of iatrogenic pneumothorax among bedside procedures.[2] However, recent advances in practice and adoption of newer technologies have helped to mitigate risks associated with this procedure. These advances are relevant because approximately 50% of thoracenteses are still performed at the bedside.[3] In this review, we aim to identify the most recent key practices that enhance the safety and the effectiveness of thoracentesis for practicing clinicians.

***Address for correspondence and reprint requests:** Richard J. Schildhouse, MD, VA Ann Arbor Healthcare System, Department of Internal Medicine (111), 2215 Fuller Road, Ann Arbor, MI 48105; Telephone: 734-222-8961; Fax: 734-913-0883; E-mail: rschildh@med.umich.edu

Additional Supporting Information may be found in the online version of this article.

Received: June 6, 2016; **Revised:** September 5, 2016; **Accepted:** September 18, 2016

2017 Society of Hospital Medicine DOI 10.12788/jhm.2716

METHODS

Information Sources and Search Strategy

With the assistance of a research librarian, we performed a systematic search of PubMed-indexed articles from January 1, 2000 to September 30, 2015. Articles were identified using search terms such as *thoracentesis*, *pleural effusion*, *safety*, *medical error*, *adverse event*, and *ultrasound* in combination with Boolean operators. Of note, as *thoracentesis* is indexed as a subgroup of *paracentesis* in PubMed, this term was also included to increase the sensitivity of the search. The full search strategy is available in the Appendix. Any references cited in this review outside of the date range of our search are provided only to give relevant background information or establish the origin of commonly performed practices.

Study Eligibility and Selection Criteria

Studies were included if they reported clinical aspects related to thoracentesis. We defined clinical aspects as those strategies that focused on operator training, procedural techniques, technology, management, or prevention of complications. Non-English language articles, animal studies, case reports, conference proceedings, and abstracts were excluded. As our intention was to focus on the contemporary advances related to thoracentesis performance, (eg, ultrasound [US]), our search was limited to studies published after the year 2000. Two authors, Drs. Schildhouse and Lai independently screened studies to determine inclusion, excluding studies with weak methodology, very small sample sizes, and those only tangentially related to our aim. Disagreements regarding study inclusion were resolved by consensus. Drs. Lai, Barsuk, and Mourad identified additional studies by hand review of reference lists and content experts (Figure 1).

Conceptual Framework

All selected articles were categorized by temporal relationship to thoracentesis as pre-, intra-, or postprocedure. Pre-procedural topics were those outcomes that had been identified and addressed before attempting thoracentesis, such as physician training or perceived risks of harm. Intraprocedural considerations included aspects such as use of bedside US, pleural manometry, and large-volume drainage. Finally, postprocedural factors were those related to evaluation after thoracentesis, such as follow-up imaging. This conceptual framework is outlined in Figure 2.

RESULTS

The PubMed search returned a total of 1170 manuscripts, of which 56 articles met inclusion criteria. Four additional articles were identified by experts and included in the study.[4-7] Therefore, 60 articles were identified and included in this review. Study designs included cohort studies, case control studies, systematic reviews, meta-analyses, narrative reviews, consensus guidelines, and randomized controlled trials. A summary of all included articles by topic can be found in the Table.

PRE-PROCEDURAL CONSIDERATIONS

Physician Training

Studies indicate that graduate medical education may not adequately prepare clinicians to perform thoracentesis.[8] In

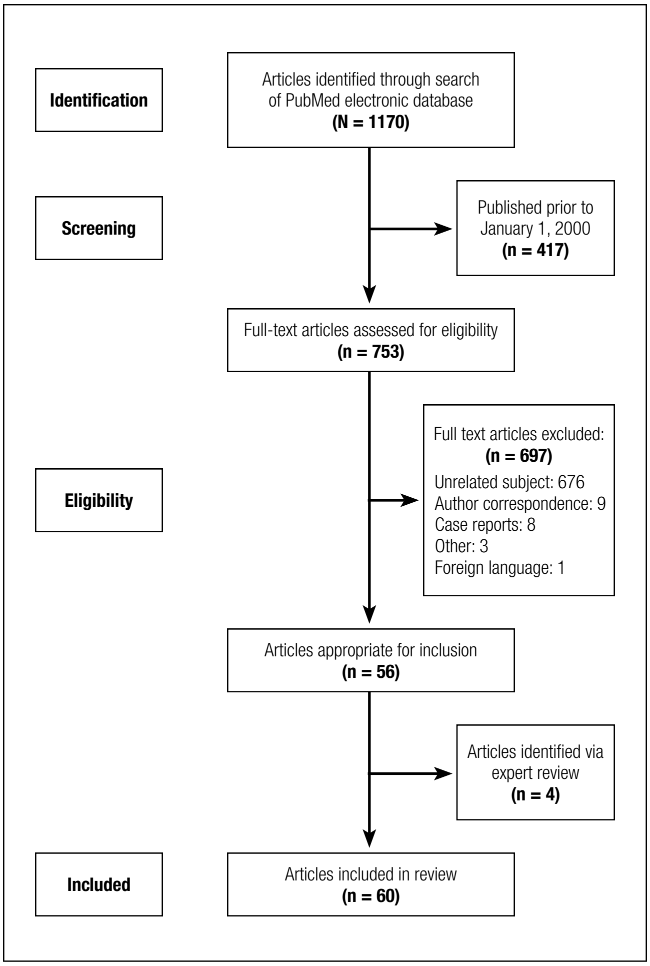

FIG. 1. Study eligibility and selection criteria.

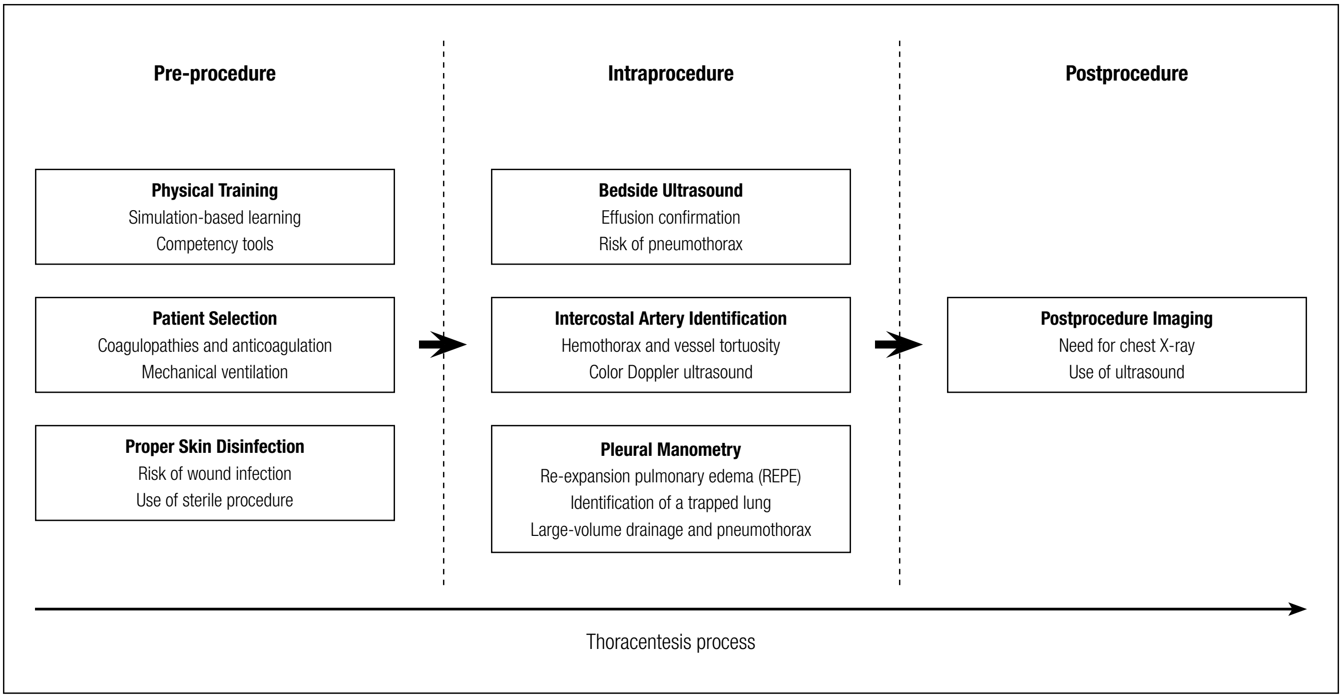

FIG. 2. Conceptual framework.

fact, residents have the least exposure and confidence in performing thoracentesis when compared to other bedside procedures.[9,10] In 1 survey, 69% of medical trainees desired more exposure to procedures, and 98% felt that procedural skills were important to master.[11] Not surprisingly, then, graduating internal medicine residents perform poorly when assessed on a thoracentesis simulator.[12]

Supplemental training outside of residency is useful to develop and maintain skills for thoracentesis, such as simulation with direct observation in a zero-risk environment. In 1 study, "simulation-based mastery learning" combined an educational video presentation with repeated, deliberate practice on a simulator until procedural competence was acquired, over two 2-hour sessions. In this study, 40 third-year medicine residents demonstrated a 71% improvement in clinical skills performance after course completion, with 93% achieving a passing score. The remaining 7% also achieved passing scores with extra practice time.[12] Others have built upon the concept of simulation-based training. For instance, 2 studies suggest that use of a simulation-based curriculum improved both thoracentesis knowledge and performance skills in a 3-hour session.[13,14] Similarly, 1 prospective study reported that a half-day thoracentesis workshop using simulation and 1:1 direct observation successfully lowered pneumothorax rates from 8.6% to 1.8% in a group of practicing clinicians. Notably, additional interventions including use of bedside US, limiting operators to a focused group, and standardization of equipment were also a part of this quality improvement initiative.[7] Although repetition is required to gain proficiency when using a simulator, performance and confidence appear to plateau with only 4 simulator trials. In medical students, improvements derived through simulator-based teaching were sustained when retested 6 months following training.[15]

An instrument to ensure competency is necessary, given variability in procedural experience among both new graduates and practicing physicians,. Our search did not identify any clinically validated tools that adequately assessed thoracentesis performance. However, some have been proposed[16] and 1 validated in a simulation environment.[12] Regarding the incorporation of US for effusion markup, 1 validated tool used an 11-domain assessment covering knowledge of US machine manipulation, recognition of images with common pleural effusion characteristics, and performance of thoracic US with puncture-site marking on a simulator. When used on 22 participants, scores with the tool could reliably differentiate between novice, intermediate, and advanced groups ($P < 0.0001$).[17]

Patient Selection

Coagulopathies and Anticoagulation. Historically, the accepted cutoff for performing thoracentesis is an international normalized ratio (INR) less than 1.5 and a platelet count greater than 50,000/µL. McVay et al.[18] first showed in 1991 that use of these cutoffs was associated with low rates of periprocedural bleeding, leading to endorsement in the British Thoracic Society (BTS) Pleural Disease Guideline 2010.[19] Other recommendations include the 2012 Society for Interventional Radiology guidelines that endorse correction of an INR greater than 2, or platelets less than 50,000/µL, based almost exclusively on expert opinion.[5]

However, data suggest that thoracentesis may be safely performed outside these parameters. For instance, a prospective study of approximately 9000 thoracenteses over 12 years found that patients with an INR of 1.5-2.9 or platelets of 20,000 - 49,000/µL experienced rates of bleeding complications similar to those with normal values.[20] Similarly, a 2014 review[21] found that the overall risk of hemorrhage during thoracentesis in the setting of moderate coagulopathy (defined as an INR of 1.5 - 3 or platelets of 25,000-50,000/µL), was not increased. In 1 retrospective study of more than 1000 procedures, no differences in hemorrhagic events were noted in patients with bleeding diatheses that received prophylactic fresh frozen plasma or platelets vs. those who did not.[22] Of note, included studies used a variety of criteria to define a hemorrhagic complication, which included: an isolated 2 g/dL or more decrement in hemoglobin, presence of bloody fluid on repeat tap with associated hemoglobin decrement, rapid re-accumulation of fluid with a hemoglobin decrement, or transfusion of 2 units or more of whole blood.

Whether it is safe to perform thoracentesis on patients taking antiplatelet therapy is less well understood. Although data are limited, a few small-scale studies[23,24] suggest that hemorrhagic complications following thoracentesis in patients receiving clopidogrel are comparable to the general population. We found no compelling data regarding the safety of thoracentesis in the setting of direct oral anticoagulants, heparin, low-molecular weight heparin, or intravenous direct thrombin inhibitors. Current practice is to generally avoid thoracentesis while these therapeutic anticoagulants are used.

Invasive mechanical ventilation. Pleural effusion is common in patients in the intensive care unit, including those requiring mechanical ventilation.[25] Thoracentesis in this population is clinically important: fluid analysis in 1 study was shown to aid the diagnosis in 45% of cases and changes in treatment in 33%.[26] However, clinicians may be reluctant to perform thoracentesis on patients who require mechanical ventilation, given the perception of a greater risk of pneumothorax from positive pressure ventilation.

Despite this concern, a 2011 meta-analysis including 19 studies and more than 1100 patients revealed rates of pneumothorax and hemothorax comparable to nonventilated patients.[25] Furthermore, a 2015 prospective study that examined thoracentesis in 1377 mechanically ventilated patients revealed no difference in complication rates as well.[20] Therefore, evidence suggests that performance of thoracentesis in mechanically ventilated patients is not contraindicated.

Skin Disinfection and Antisepsis Precautions

The 2010 BTS guidelines list empyema and wound infection as possible complications of thoracentesis.[19] However, no data regarding incidence are provided. Additionally, an alcohol-based skin cleanser (such as 2% chlorhexidine gluconate/70% isopropyl alcohol), along with sterile gloves, field, and dressing are suggested as precautionary measures.[19] In 1 single-center registry of 2489 thoracenteses performed using alcohol or iodine-based antiseptic and sterile drapes, no postprocedure infections were identified.[27] Of note, we did not find other studies (including case reports) that reported either incidence or rate of infectious complications such as wound infection and empyema. In an era of modern skin antiseptics that have effectively reduced complications such as catheter-related bloodstream infection,[28] the incidence of this event is thus likely to be low.

INTRAPROCEDURAL CONSIDERATIONS

Use of Bedside Ultrasound

Portable US has particular advantages for evaluation of pleural effusion vs other imaging modalities. Compared with computerized tomography (CT), bedside US offers similar performance but is less costly, avoids both radiation exposure and need for patient transportation, and provides results instantaneously.[29,30] Compared to chest x-ray (CXR), US is more sensitive at detecting the presence, volume, and characteristics of pleural fluid[30,31] and can be up to 100% sensitive for effusions greater than 100 mL.[29] Furthermore, whereas CXR typically requires 200 mL of fluid to be present for detection of an effusion, US can reliably detect as little as 20 mL of fluid.[29] When US was used to confirm thoracentesis puncture sites in a study involving 30 physicians of varying experience and 67 consecutive patients, 15% of sites found by clinical exam were inaccurate (less than 10 mm fluid present), 10% were at high risk for organ puncture, and a suitable fluid pocket was found 54% of times when exam could not.[4]

A 2010 meta-analysis of 24 studies and 6605 thoracenteses estimated the overall rate of pneumothorax at 6%; however, procedures performed with US guidance were associated with a 70% reduced risk of this event (odds ratio, 0.30; 95% confidence interval, 0.20 - 0.70).[32] In a 2014 randomized control trial of 160 patients that compared thoracentesis with US guidance for site marking vs no US use, 10 pneumothoraces occurred in the control group vs 1 in the US group (12.5% vs 1.25%, $P = 0.009$).[33] Similarly, another retrospective review of 445 consecutive patients with malignant effusions revealed a pneumothorax rate of 0.97% using US in real time during needle insertion compared to 8.89% for unguided thoracenteses ($P < 0.0001$).[34] Several other studies using US guidance for either site markup or in real time reported similar pneumothorax rates, ranging from 1.1% - 4.8%.[35-37] However, it is unclear if real-time US specifically provides an additive effect vs site marking alone, as no studies directly comparing the 2 methods were found.

Benefits of US also include a higher rate of procedural success, with 1 study demonstrating a 99% success rate when using US vs. 90% without ($P = 0.030$).[33] A larger volume of fluid removed has been observed with US use as well, and methods have been described using fluid-pocket depth to guide puncture site localization and maximize drainage.[38] Finally, US use for thoracentesis has been associated with lower costs and length of stay.[39,40]

Intercostal Artery Localization

Although rare (incidence, 0.18%-2%[20,21,39]), the occurrence of hemothorax following thoracentesis is potentially catastrophic. This serious complication is often caused by laceration of the intercostal artery (ICA) or 1 of its branches during needle insertion.[41]

While risk of injury is theoretically reduced by needle insertion superior to the rib, studies using cadaver dissection and 3D angiography show significant tortuosity of the ICA.[6,41-43] The degree of tortuosity is increased within 6 cm of the midline, in more cephalad rib spaces, and in the elderly (older than 60 years).[41-43] Furthermore, 1 cadaveric study also demonstrated the presence of arterial collaterals branching off the ICA at multiple intercostal spaces, ranging between 8 cm and 11 cm from the midline.[41] This anatomic variability may explain why some have observed low complication and hemothorax rates with an extreme lateral approach.[35] Bedside US with color flow Doppler imaging has been used to identify the ICA, with 88% sensitivity compared to CT imaging while adding little to exam time.[44,45] Of note, a 37% drop in the rate of hemothorax was observed in 1 study with routine US guidance alone.[39]

Pleural Pressure Monitoring and Large-Volume Thoracentesis

While normal intrapleural pressures are approximately -5 to -10 cm H_2O,[46] the presence of a pleural effusion creates a complex interaction between fluid, compressed lung, and chest wall that can increase these pressures.[47] During drainage of an effusion, pleural pressures may rapidly drop, provoking re-expansion pulmonary edema (REPE). While rare (0 -1%), clinically-diagnosed REPE is a serious complication that can lead to rapid respiratory failure and death.[20,48] REPE is postulated to be caused by increased capillary permeability resulting from inflammation, driven by rapid re-inflation of the lung when exposed to highly negative intrapleural pressures.[47,49]

Measurement of intrapleural pressure using a water manometer during thoracentesis may minimize REPE by terminating fluid drainage when intrapleural pressure begins to drop rapidly.[50,51] A cutoff of -20 cm H_2O has been cited repeatedly as safe since being suggested by Light in 1980, but this is based on animal models.[50,52] In 1 prospective study of 185 thoracenteses in which manometry was performed, 15% of patients had intrapleural pressure drop to less than -20 cm H_2O (at which point the procedure was terminated) but suffered no REPE.[50]

Manometry is valuable in the identification of an unexpandable or trapped lung when pleural pressures drop rapidly with only minimal fluid volume removal.[47,53] Other findings

Continued on page 273

TABLE. Summary of Studies in Review, Organized by Topic

Topic	Author (Year)	Study Design	Participants (n)	Study Description or Intervention	Results and Authors' Conclusions
Physician training	Grover S, et al (2009)[8]	Cohort survey	188 IM residents	Assess resident knowledge of 3 core medical procedures; 32-item multiple choice test developed and given to students, residents, and clinicians	The instrument was reliable ($\alpha = 0.79$); resident median score was 53%; overall knowledge of procedures was poor
	Promes S, et al (2009)[9]	Cohort survey	256 1st y IM residents at 3 training sites	Self-reported survey to evaluate attitudes, competency, and exposure to common medical procedures in medical school	New medical interns report having the least experience and confidence with thoracentesis of all procedures
	Huang G, et al (2006)[10]	Prospective cohort	106 IM residents	Residents logged procedures performed, answering questions evaluating their comfort with 9 aspects of 4 medical procedures	Many residents are uncomfortable performing bedside procedures, especially when unsupervised (37%); thoracentesis associated with less comfort (OR, 0.40; CI, 0.20-0.80)
	Lagan J, et al (2015)[11]	Online survey	156 medical trainees	Online survey given to trainees regarding attitudes and experience related to medicine procedures	Majority of trainees felt procedures were important and wanted more exposure; trainees did not feel competent in independent US use; thoracentesis confidence positively correlated with exposure ($P <$ 0.003).
	Wayne D, et al (2008)[12]	Pretest-posttest design with no control	40 3rd y IM residents	Baseline knowledge and skills assessment followed by video instruction and deliberate practice on thoracentesis simulator until competence attained	Simulation with deliberate practice led to a 71% improvement in clinical skills exam, with 100% reaching the mastery standard; amount of practice time required was a negative predictor of posttest performance
	Lenchus J (2010)[13]	Case cohort before and after	56 residents and 4 medical students	Procedural instruction curriculum (including thoracentesis) and pilot developed consisting of instruction with videos, simulation, and deliberate practice; knowledge, and skills assessed before and after	Standardized course resulted in significantly increased knowledge scores for all procedures ($P < 0.001$), along with increased technical skills rated on first patient performance ($P < 0.001$)
	Lenchus J, et al (2011)[14]	Case cohort before and after	85 IM residents	Residents completed 4 wk multimodal procedure course including simulation; assessed with a knowledge and skills test before and after	All participants demonstrated an improvement in medical knowledge and technical skills ($P < 0.05$); a blended, standardized procedure curriculum has potential to address shortcomings of traditional training
	Duncan D, et al (2009)[7]	Prospective cohort	244 procedures	Institution of a training system to reduce pneumothorax rate including focused group of operators, ultrasound, and standardization of methods and equipment	Institution of improvement program with simulation and US reduced rates of pneumothorax from 8.6% to 1.1% ($P = 0.0034$); effect sustained for 2 y
	Jiang G, et al (2011)[15]	Case cohort before and after	52 medical students	Students performed repeated trials on a thoracentesis simulator, and performance was recorded	Performance score, time, and confidence were maximized after trial number 4 ($P < 0.05$); effect persisted at 6 mo on retest and 12 mo on first live patient
	Berg D, et al (2013)[16]	NA	8 physician experts	Checklist developed to aid in the standardization of thoracentesis training and competence evaluation	Developed a 23-point checklist with a high level of agreement between experts ($\alpha = 0.94$); requires implementation for validation in simulation and clinical environment
	Salamonsen M, et al (2013)[17]	NA	22 trainees	11-domain, 100-point scoring tool developed to gauge thoracic US competence; used to score participant performance on simulator	The tool reliably predicted experience level (novice, intermediate, expert) regarding thoracic US use and effusion markup ($P < 0.0001$); can be used to document adequacy of US training
Coagulopathies and anticoagulation	Havelock T, et al (2010)[19]	Consensus guidelines	NA	Literature review and expert opinion regarding the preparation, technique, and complications related to bedside thoracentesis	Thoracentesis can be safely performed in most patients with INR <1.5 and platelets >50,000/µL, US guidance is recommended; routine postprocedure chest X-ray (CXR) not indicated unless concern for complication
	Patel I, et al (2012)[5]	Consensus guidelines	NA	Literature review and expert opinion used to determine best practices related to the hematologic management of patients undergoing percutaneous interventions	Thoracentesis is a low-risk bleeding procedure; recommend performance if INR <2.0 and platelets >50,000/µL; benefit of prophylactic transfusion unclear and risk/benefit should be weighed by physician
	Ault M, et al 2015)[20]	Prospective cohort	9320 thoracenteses	To evaluate specific demographic and clinical factors that have been associated with complications of thoracentesis	Low rate of complications with experienced operator; no increase in risk with moderate coagulopathy ($P = 0.97$ INR category, $P = 0.55$ platelet category); risk factors for complications included >1 needle pass ($P = 0.002$) and >1.5L fluid removed ($P = 0.0001$)
	Puchalski J (2014)[21]	Literature review	8 studies, 2600 procedures	Review of the literature regarding the risk of bleeding complications after thoracentesis in patients with baseline coagulopathy and the practice of prophylactic reversal	Thoracentesis appears to be safe to perform despite significant coagulation abnormalities (INR <3, platelets >25,000/µL); prophylactic reversal of coagulation abnormalities not beneficial
	Hibbert R, et al (2013)[22]	Retrospective chart review	1009 procedures	Chart review of US-guided thoracenteses done with INR >1.6 or platelets <50,000/µL; patients separated by whether or not coagulopathy corrected prior with blood products	Despite the presence of coagulopathy, the risk of hemorrhagic complication is very low (0.40%; CI 0.15%-1.02%); prophylactic transfusion of blood products did not alter this risk
	Zalt M, et al (2012)[23]	Prospective cohort	30 patients, 45 thoracenteses	US-guided thoracentesis performed in patients on clopidogrel with symptomatic effusion, assessed for bleeding complications postprocedure	No clinically significant bleeding complications observed; unnecessary to hold clopidogrel before US-guided thoracentesis for symptomatic effusion as bleeding risk is low; larger studies required to confirm results
	Mahmood K, et al (2014)[24]	Prospective cohort with control group	75 patients	25 patients underwent US-guided percutaneous pleural intervention without cessation of clopidogrel; bleeding rates compared with control group	1 patient on clopidogrel developed a hemothorax requiring transfusion (overall rate, 4%); clinically significant bleeding risk is low and comparable to control group ($P = 0.15$)

Continued on page 271

TABLE. Summary of Studies in Review, Organized by Topic (continued)

Topic	Author (Year)	Study Design	Participants (n)	Study Description or Intervention	Results and Authors' Conclusions
Invasive mechanical ventilation	Goligher E, et al (2011)[25]	Systematic review and meta-analysis	19 studies, 1124 thoracenteses	Review of studies relevant to the utility and safety of draining pleural effusions in patients on mechanical ventilation	Rates of pneumothorax (3.4%; CI, 1.7-6.5%) and hemothorax (1.6%; CI, 0.8-3.3%) were low; drainage of pleural effusions in mechanically ventilated patients is safe and appears to improve oxygenation
	Fartoukh M, et al (2002)[26]	Prospective cohort	113 patients, 68 on mechanical ventilation	MICU patients with effusion underwent thoracentesis; clinicians queried on both pre- and post-tap diagnosis	8.4% of MICU patients had an effusion; thoracentesis aided treatment in 56% of cases and altered the final diagnosis in 45% of cases; pneumothorax noted in 6 patients (7%)
Skin disinfection and antisepsis precautions	Cervini P, et al (2010)[27]	Retrospective chart review	2489 thoracenteses	Chart review of patients who underwent US-guided thoracentesis to evaluate for infectious complications and determine infection rate	US-guided thoracentesis confers an extremely low risk of infectious complication when aseptic technique is used; no infections were observed
Use of bedside ultrasound	Soni N, et al (2015)[29]	Literature review	NA	Review of the literature related to the use of point-of-care US to evaluate and mange pleural effusions	Regarding pleural effusion characterization US performs similarly to CT and is more sensitive than CXR; US guidance reduces thoracentesis complications and increases success rates
	Feller-Kopman D (2006)[30]	Literature review	NA	Review of the basic techniques of bedside US related to evaluation of pleural disease and performance of thoracentesis	US guidance improves patient outcomes by reducing the risk of complication, and is especially helpful in the setting of small effusions and mechanical ventilation
	Shojaee S and Argento A (2014)[31]	Literature review	NA	Literature reviewed pertaining to basic US physiology, common thoracic exam findings, and utility related to pleural access	Bedside US during thoracentesis is recommended because it provides immediate results, improved site selection, fewer complications, and high accuracy even when done by trainees
	Diacon A, et al (2003)[4]	Prospective comparative	67 consecutive patients	To assess the value of thoracentesis puncture sites identified by clinical examination alone; clinician-proposed locations were evaluated for accuracy against thoracic US	US found that 15% of clinician exam-proposed puncture sites to be inaccurate (<10 mm fluid depth) with 10% of sites overlying solid organs; US able to identify accurate pocket in 54% of cases where exam could not; US increases procedure yield and potentially reduces complications
	Gordon C, et al (2010)[32]	Systematic review and meta-analysis	24 studies, 6605 thoracenteses	Literature reviewed to determine the baseline rate of pneumothorax related to thoracentesis and identify influencing factors	Overall calculated risk of pneumothorax was 6% (95% CI, 4.6%-7.8%); US guidance associated with lower risk (OR, 0.3; CI, 0.2-0.7); factors increasing this risk were therapeutic indication (OR, 2.6; CI, 1.8-3.8) and periprocedural symptoms (OR, 26.6; CI, 2.7-262.5)
	Perazzo A, et al (2014)[33]	Randomized control trial	160 patients	Patients randomized to thoracentesis with or without US use prior to identifying fluid pocket; measured rate of procedure success, fluid yield, and pneumothorax	Use of US prior to thoracentesis resulted in a significantly lower rate of pneumothorax (1.25% vs 12.5%, $P = 0.009$), higher procedure success (99% vs 90%, $P = 0.03$) and higher fluid yield ($P > 0.014$)
	Cavanna L, et al (2014)[34]	Retrospective chart review	445 patients with malignant pleural effusions	Chart review of patients status post-thoracentesis with or without real-time US guidance; procedure success, yield, and complication rates compared	US guidance used in 310 (69%) thoracenteses; use of real-time US guidance during thoracentesis for malignant effusions resulted in drastically lower pneumothorax rates (0.89% vs 8.89%, $P = 0.0001$)
	Soldati G, et al (2013)[35]	Prospective cohort	106 patients, 131 procedures	Evaluate efficacy and safety of thoracentesis or pigtail catheter placement in the supine or lateral recumbent position under real-time US guidance	97% of all procedures successful; pneumothorax rate was 1.4% with no bleeding complications observed; pleural procedures in the supine or lateral recumbent positions are safe, comfortable, and conducive to real-time US guidance
	Pihlajamaa K, et al (2004)[36]	Retrospective chart review	212 patients, 264 thoracenteses	Chart review performed to determine the incidence of pneumothorax and contributing variables after US-guided thoracentesis	Post-thoracentesis pneumothorax rates were low (4.2%) with no increase in risk in mechanical ventilation or based on operator experience; recommend against routine CXR postprocedure
	Barnes T, et al (2005)[37]	Retrospective chart review	450 thoracenteses	Charts reviewed of all thoracenteses performed over 1-year period, assessing for use of US and relation to pneumothorax rates	Use of US prior to thoracentesis resulted in a significantly lower rate of pneumothorax (4.9% vs 10.3%, $P < 0.05$); recommend US use be considered in all patients
	Hooper C, et al (2015)[3]	Retrospective review	1252 thoracenteses	British Thoracic Society pleural procedures audit of 90 hospitals over a 2-mo period outlining complication rates, consent rates, and use of bedside US	Rates of pneumothorax (1.3%) and hemothorax (1.1%) are low; use of US guidance is rising since 2010 (69% vs 52%); 50% of thoracenteses are still performed at bedside
	Zanforlin A, et al (2013)[38]	Prospective cohort	45 thoracenteses	Assessment of safety and efficacy of thoracentesis performed over the area of effusion with maximum depth between lung and diaphragm as identified on bedside US ("V-point")	The "V point" is an easy-to-identify US landmark that provides a safe area for needle puncture; no pneumothoraces observed; measurement of maximum pocket depth provides a rough estimation of effusion volume
	Patel P, et al (2012)[39]	Retrospective chart review	19,339 thoracenteses	Premier hospital database queried for thoracenteses performed over 1-y period; cost analysis performed to determine if use of US led to a change in outcomes and cost	US guidance was used in 46% of thoracenteses; associated with a decrease in pneumothorax of 16.3% (OR, 0.837; CI, 0.73-0.96, $P = 0.014$) and hemothorax by 38.7% (OR, 0.613; CI, 0.36-1.04; $P = 0.071$); US use was associated with a lower cost of hospitalization ($P < 0.0001$) and shorter length of stay ($P < 0.0001$)
	Mercaldi C and Lanes S (2013)[40]	Retrospective chart review	61,261 thoracenteses	Claims data reviewed over 2-y period on thoracenteses with analysis of US use, pneumothorax, length of stay, and hospitalization cost	Use of US during thoracentesis resulted in a reduction in pneumothorax by 19% (OR, 0.81; CI, 0.74-0.90); pneumothorax occurrence found to increase hospital cost by $2801 ($P < 0.001$) and length of stay by 1.5 days ($P > 0.001$)
	Celik B, et al (2009)[2]	Retrospective chart review	12,010 invasive procedures	Records of patients treated for iatrogenic pneumothorax reviewed to determine causal procedure, location, service, treatment required, and consequences	164 cases of iatrogenic pneumothorax were identified (1.36%); highest risk procedures included central venous catheter insertion (43.8% of cases) and thoracentesis (20.1% of cases); 56.7% of procedures causing pneumothorax were performed under emergency conditions

Continued on page 272

TABLE. Summary of Studies in Review, Organized by Topic (continued)

Topic	Author (Year)	Study Design	Participants (n)	Study Description or Intervention	Results and Authors' Conclusions
Intercostal artery localization	Shurtleff E and Olinger A (2012)[41]	Observational cohort	29 cadavers	Identify the course and tortuosity of the posterior intercostal coronary artery (ICA) and its collaterals in elderly cadavers using dissection	The ICA is unshielded and most tortuous in its course near the posterior midline, also demonstrating collaterals within the first 120 mm; age >60 was associated with higher rates of tortuosity; recommend tall pleural procedures be performed ≥120 mm from midline
	Helm E, et al (2013)[42]	Retrospective review	47 patients, 298 arteries	Thoracic CT angiograms reformatted and analyzed to describe the course and variability in the ICAs and the factors that may influence them	The ICA is often exposed in the IC space within the first 6 cm lateral to the spine; artery course is more variable when age >60 (coefficient 0.91, $P < 0.001$) and more cephalad rib spaces (coefficient -2.60, $P < 0.001$); recommend all procedures be performed lateral to 6 cm from the spine
	Yoneyama H, et al (2010)[43]	Observational cohort	33 patients	3D CT angiography was performed in elderly patients to identify the ICA with calculation of the "percent safe space" to quantify vulnerability of laceration during thoracentesis	The ICA "percent safe space" was significantly higher at the lateral position versus medial position (79.8% vs 61.2%; $P < 0.0001$); ICA tortuosity increased with age, but correlation was low ($P = 0.0378$; r = -0.3631)
	Salamonsen M, et al (2012)[44]	Prospective cohort	22 patients	Describe a method to visualize the ICA prior to thoracentesis using US, and calculate its location relative to the overlying rib to identify a "vulnerable" vessel	US was able to identify the ICA in 74 of 88 positions examined; the ICA was noted to be most central within the IC space near the spine and migrated to lie under the rib more laterally; ICA location is variable and may be vulnerable even with a lateral approach
	Salamonsen M, et al (2013)[45]	Prospective cohort	50 patients	Physicians evaluate the reliability of bedside US to identify the ICA in patients prior to planned CT thoracic angiography as gold standard	The sensitivity and specificity of portable US compared to CT was 0.86 (0.18-0.91) and 0.30 (0.13-0.54) respectively; bedside US with color flow Doppler is a reliable method for detection of a vulnerable IC artery; exam added 42 seconds to the procedure time
	Wraight W, et al (2005)[6]	Observational cohort	38 cadavers, 62 rib blocks	Rib blocks dissected to identify the neurovascular bundle and measure its relation to the inferior rib border and attempt to describe a "safe zone" for drain insertion	The "safe zone" in the IC space is narrower than thought, and is approximately 50%-70% of the way down an interspace to avoid the variably positioned IC neurovascular bundle and collaterals
Pleural pressure monitoring and large-volume thoracentesis	Huggins J and Doelken P (2006)[47]	Literature review	NA	This review discusses pleural mechanics and pleural manometry including its role in re-expansion pulmonary edema (REPE) and diagnosing of a nonexpandable lung	Pleural pressure can be helpful in diagnosing pleural pathologies and may improve safely by avoiding REPE performing thoracentesis
	Echevarria C, et al (2008)[48]	Systematic review	13 studies	Literature review performed to determine the prevalence of REPE after thoracentesis and associated risk factors	The incidence of REPE is 0%-1%; patients who have a lung collapsed >7 days, >3 L fluid drained, or are young appear to be at higher risk for this complication
	Sue R, et al (2004)[49]	Retrospective	7 patients on mechanical ventilation	To investigate if clinical REPE is due to increased permeability of the alveolar capillary barrier through analysis of pulmonary edema fluid and plasma	The average edema to plasma-fluid protein ratio was 0.58, which supports increased alveolar permeability and a hydrostatic mechanism as the cause of REPE
	Feller-Kopman D, et al (2007)[50]	Prospective cohort	185 thoracenteses	Patients undergoing thoracentesis with >1 L removed had volume drained, pleural pressure, elastance, and presence of symptoms recorded; parameters compared with those who developed REPE	1 patient developed REPE (0.5%); both clinical and radiographic REPE are rare and independent of volume removed, elastance, and pleural pressure; no need to stop drainage at 1 L if pleural pressure is > -20 cm H_2O or symptoms absent
	Villena V, et al (2000)[51]	Prospective cohort	61 patients	During therapeutic thoracentesis, pleural pressures were measured to determine if they could predict the amount of fluid that could be safely removed or effusion etiology	Measuring intrapleural pressure can allow large amounts of fluid to be safely removed and reinforce a diagnosis of trapped lung; neither initial pressure nor pleural elastance after the first 500 mL removed were predictive of fluid removed
	Doelken P, et al (2004)[52]	Prospective cohort	40 patients	To compare the agreement between an electronic transducer and water manometer in measuring pleural pressures during thoracentesis	Pleural manometry during lar-volume thoracentesis can prevent the development of excessively negative pleural pressures; a simple water manometer correlated well with an electronic transducer (r = 0.97; $P < 0.001$)
	Feller-Kopman D (2007)[53]	Literature review	NA	This review summarizes the relevant data for the use of US and manometry, and their use during therapeutic thoracentesis	The data regarding pleural US are sound enough to suggest its use should become standard of care; further research is required to define the role of formal manometry
	Boshuizen R, et al (2013)[54]	Prospective cohort	30 patients, 34 procedures	Manometry used to explore the relationship between pleural pressure and a nonexpanded lung in patients with malignant effusions; compared with imaging to check lung expansion	4 patients were identified as having a nonexpanding lung; total drop in pleural pressure ($P = 0.009$), difference in pleural pressure with respiration ($P = 0.007$), and pleural elastance ($P = 0.002$) were all significantly associated with a nonexpanding lung
	Pannu J, et al (2014)[55]	Retrospective chart review	214 patients	Chart review of thoracenteses performed with and without manometry to assess for a correlation between intrapleural pressure and patient discomfort	The use of manometry did not reliably predict the change in chest pain ($P = 0.12$) or dyspnea ($P = 0.24$) during thoracentesis; similar results found in large-volume thoracentesis group
	Feller-Kopman D, et al (2006)[56]	Prospective cohort	169 patients	Serial manometry performed during therapeutic thoracentesis to explore the correlation between intrapleural pressure changes and symptom onset	Symptoms developed in 17% of patients; chest discomfort was significantly associated with large drops in pleural pressure ($P = 0.001$), but opening pressure and total volume removed were not
	Abunasser J. and Brown R (2010)[57]	Retrospective chart review	237 patients, 300 thoracenteses	Charts reviewed of thoracenteses performed to assess the risk of large-volume drainage (>1 L) without manometry	137 thoracenteses performed were large volume; no statistically significant difference in the risk of pneumothorax, hypotension, or bleeding

Continued on page 273

TABLE. Summary of Studies in Review, Organized by Topic (continued)

Topic	Author (Year)	Study Design	Participants (n)	Study Description or Intervention	Results and Authors' Conclusions
	Mynarek G, et al (2004)[58]	Retrospective chart review	711 procedures in 371 patients	Chart review performed of patients who underwent US-guided thoracentesis to assess type and frequency of complications and associated risk factors	US-guided thoracentesis is a safe procedure with a 2.8% rate of pneumothorax; no association with the amount of fluid removed (*P* = 0.096); authors recommend against postprocedure CXR in the absence of symptoms
	Josephson T, et al (2009)[59]	Prospective cohort	471 patients, 735 thoracenteses	US-guided therapeutic thoracenteses performed and effusions drained with no upper limit and without manometry; stratified by amount of fluid removed and pneumothorax rates analyzed	A steep increase in pneumothorax rate noted when > 1.8 L fluid (OR, 3.8; CI 1.28-11.2) and >2.3 L fluid (OR, 5.7; CI, 1.30-24.7) removed; amount of fluid removed also associated with higher risk for chest tube placement (*P* < 0.0001)
	Heidecker J, et al (2006)[60]	Retrospective chart review	367 patients	Charts reviewed of US-guided thoracenteses performed with goal of explaining mechanism of pneumothoraces that occurred	Authors propose that the majority of pneumothoraces observed were found to be related to unexpanded lung as opposed to direct trauma or entranced air, and cannot be avoided with manometry
Postprocedure imaging	Jones P, et al (2003)[62]	Prospective cohort	605 patients, 941 thoracenteses	Thoracenteses performed in the radiology department under US guidance were analyzed to determine the incidence of complications	The complication rates of pneumothorax (2.5%), hemothorax (0.2%), and REPE (0.5%) were low for US-guided thoracenteses performed by interventional radiologists; these rates are less than the reported rates for nonguided thoracentesis
	Petersen W, et al (2000)[63]	Prospective cohort	199 patients, 251 thoracenteses	Physicians given questionnaire postprocedure rating their concern for complication with CXR obtained at doctor discretion; rate of pneumothorax	Pneumothorax rate was 2.7% when there was no concern for complication vs 30% when complication suspected; only procedural risk factor associated with pneumothorax was aspiration of air; recommend no CXR obtained unless clinical suspicion for complication suspected
	Sachdeva A, et al (2014)[64]	Literature review	NA	Review of relevant literature pertaining to US exam techniques, thoracentesis, and an US-based procedure service	Bedside US has utility throughout the pre-, intra-, and postprocedure process. It is a viable option for use to detect postprocedure pneumothorax and is more sensitive than CXR
	Shostak E, et al (2013)[65]	Prospective cohort	185 patients	Bedside US exam performed on patients prior to and after pleural procedures to detect pneumothorax	8 pneumothoraces identified by CXR, 7 of which were seen on bedside US; sensitivity was 88% and specificity 97%; bedside US is a valuable tool to detect pneumothorax when a good quality scan is obtained

NOTE: Abbreviations: CI, confidence interval; CT, computed tomography; CXR, chest x-ray; ICA, intercostal artery; IM, internal medicine; INR, international normalized ratio; MICU, medical intensive care unit; OR, odds ratio; REPE, re-expansion pulmonary edema; US, ultrasound.

Continued from page 269

correlated with an unexpandable lung include a negative opening pressure[47] and large fluctuations in pressure during the respiratory cycle.[54]

While development of symptoms (eg, chest pain, cough, or dyspnea) is often used as a surrogate, the correlation between intrapleural pressure and patient symptoms is inconsistent and not a reliable proxy.[55] One study found that 22% of patients with chest pain during thoracentesis had intrapleural pressures lower than -20 cm H_2O compared with 8.6% of asymptomatic patients,[56] but it is unclear if the association is causal.

Thoracentesis is often performed for symptomatic relief and removal of large fluid volume. However, it remains common to halt fluid removal after 1.5 L, a threshold endorsed by BTS.[19] While some investigators have suggested that removal of 2 L or more of pleural fluid does not compromise safety,[57,58] a 4- to 5-fold rise in the risk of pneumothorax was noted in 2 studies.[20,59] when more than 1.5 L of fluid was removed. The majority of these may be related to pneumothorax *ex vacuo*, a condition in which fluid is drained from the chest, but the lung is unable to expand and fill the space (eg, "trapped lung"), resulting in a persistent pneumothorax. This condition generally does not require treatment.[60] When manometry is employed at 200-mL intervals with termination at an intrapleural pressure of less than 20 mm H_2O, drainage of 3 L or more has been reported with low rates of pneumothorax and very low rates of REPE.[50,51] However, whether this is cause and effect is unknown because REPE is rare, and more work is needed to determine the role of manometry for its prevention.

POSTPROCEDURAL CONSIDERATIONS

Postprocedure Imaging

Performing an upright CXR following thoracentesis is a practice that remains routinely done by many practitioners to monitor for complications. Such imaging was also endorsed by the American Thoracic Society guidelines.[61] However, more recent data question the utility of this practice. Multiple studies have confirmed that post-thoracentesis CXR is unnecessary unless clinical suspicion for pneumothorax or REPE is present.[36,58,62,63] The BTS guidelines also advocate this approach.[19] Interestingly, a potentially more effective way to screen for postprocedure complications is through bedside US, which has been shown to be more sensitive than CXR in detecting pneumothorax.[64] In 1 study of 185 patients, bedside US demonstrated a sensitivity of 88% and a specificity of 97% for diagnosing pneumothorax in patients with adequate quality scans, with positive and negative likelihood ratios of 55 and 0.17, respectively.[65]

DISCUSSION

Thoracentesis remains a core procedural skill for hospitalists, critical care physicians, and emergency physicians. It is the foundational component when investigating and treating pleural effusions. When the most current training, techniques, and technology are used, data suggest this procedure is safe to perform at the bedside. Our review highlights these strategies and evaluates which aspects might be most applicable to clinical practice.

Our findings have several implications for those who perform this procedure. First, appropriate training is central to procedural safety, and both simulation and direct observation by procedural experts have been shown by multiple investigators to improve knowledge and skill. This training should integrate the use of US in performing a focused thoracic exam.

Second, recommendations regarding coagulopathy and a "safe cutoff" of an INR less than 1.5 or platelets greater than 50,000/µL had limited evidentiary support. Rather, multiple studies suggest no difference in bleeding risk following thoracentesis with an INR as high as 3.0 and platelets greater than 25,000/µL. Furthermore, prophylactic transfusion with fresh frozen plasma or platelets before thoracentesis did not alter bleeding risk and exposes patients to transfusion complications. Thus, routine use of this practice can no longer be recommended. Third, further research is needed to understand the bleeding risk for patients on antiplatelet medications, heparin products, and also direct oral anticoagulants, given the growing popularity in their use and the potential consequences of even temporary cessation. Regarding patients on mechanical ventilation, thoracentesis demonstrated no difference in complication rates vs. the general population, and its performance in this population is encouraged when clinically indicated.

Intraprocedural considerations include the use of bedside US. Due to multiple benefits including effusion characterization, puncture site localization, and significantly lower rates of pneumothorax, the standard of care should be to perform thoracentesis with US guidance. Both use of US to mark an effusion immediately prior to puncture or in real time during needle insertion demonstrated benefit; however, it is unclear if 1 method is superior because no direct comparison studies were found. Further work is needed to investigate this potential.

Our review suggests that the location and course of the ICA is variable, especially near the midline, in the elderly, and in higher intercostal spaces, leaving it vulnerable to laceration. We recommend physicians only attempt thoracentesis at least 6 cm lateral to the midline due to ICA tortuosity and, ideally, 12 cm lateral, to avoid the presence of collaterals. Although only 2 small-scale studies were found pertaining to the use of US in identifying the ICA, we encourage physicians to consider learning how to screen for its presence as a part of their routine thoracic US exam in the area underlying the planned puncture site.

Manometry is beneficial because it can diagnose a nonexpandable lung and allows for pleural pressure monitoring.[52,53] A simple U-shaped manometer can be constructed from intravenous tubing included in most thoracentesis kits, which adds little to overall procedure time. While low rates of REPE have been observed when terminating thoracentesis if pressures drop below -20 cm H_2O or chest pain develops, neither measure appears to have reliable predictive value, limiting clinical utility. Further work is required to determine if a "safe pressure cutoff" exists. In general, we recommend the use of manometry when a nonexpandable (trapped) lung is suspected, because large drops in intrapleural pressure, a negative opening pressure, and respiratory variation can help confirm the diagnosis and avoid pneumothorax *ex vacuo* or unnecessary procedures in the future. As this condition appears to be more common in the setting of larger effusions, use of manometry when large-volume thoracenteses are planned is also reasonable.

Postprocedurally, routine imaging after thoracentesis is not recommended unless there is objective concern for complication. When indicated, bedside US is better positioned for this role compared with CXR, because it is more sensitive in detecting pneumothorax, provides instantaneous results, and avoids radiation exposure.

Our review has limitations. First, we searched only for articles between defined time periods, restricted our search to a single database, and excluded non-English articles. This has the potential to introduce selection bias, as nonprimary articles that fall within our time restrictions may cite older studies that are outside our search range. To minimize this effect, we performed a critical review of all included studies, especially nonprimary articles. Second, despite the focus of our search strategy to identify any articles related to patient safety and adverse events, we cannot guarantee that all relevant articles for any particular complication or risk factor were captured given the lack of more specific search terms. Third, although we performed a systematic search of the literature, we did not perform a formal systematic review or formally grade included studies. As the goal of our review was to categorize and operationalize clinical aspects, this approach was necessary, and we acknowledge that the quality of studies is variable. Lastly, we aimed to generate clinical recommendations for physicians performing thoracentesis at the bedside; others reviewing this literature may find or emphasize different aspects relevant to practice outside this setting.

In conclusion, evaluation and treatment of pleural effusions with bedside thoracentesis is an important skill for physicians of many disciplines. The evidence presented in this review will help inform the process and ensure patient safety. Physicians should consider incorporating these recommendations into their practice.

Acknowledgments

The authors thank Whitney Townsend, MLIS, health sciences informationist, for assistance with serial literature searches.

Disclosure: Nothing to report.

References

1. Kasper DL. *Harrison's Principles of Internal Medicine*. 19th ed. New York, NY: McGraw Hill Education; 2015.
2. Celik B, Sahin E, Nadir A, Kaptanoglu M. Iatrogenic pneumothorax: etiology, incidence and risk factors. *Thorac Cardiovasc Surg*. 2009;57(5):286-290.
3. Hooper CE, Welham SA, Maskell NA, Soc BT. Pleural procedures and patient

safety: a national BTS audit of practice. *Thorax*. 2015;70(2):189-191.

4. Diacon AH, Brutsche MH, Soler M. Accuracy of pleural puncture sites: a prospective comparison of clinical examination with ultrasound. *Chest*. 2003;123(2): 436-441.
5. Patel IJ, Davidson JC, Nikolic B, et al. Consensus guidelines for periprocedural management of coagulation status and hemostasis risk in percutaneous image-guided interventions. *J Vasc Interv Radiol*. 2012;23(6):727-736.
6. Wraight WM, Tweedie DJ, Parkin IG. Neurovascular anatomy and variation in the fourth, fifth, and sixth intercostal spaces in the mid-axillary line: a cadaveric study in respect of chest drain insertion. *Clin Anat*. 2005;18(5):346-349.
7. Duncan DR, Morgenthaler TI, Ryu JH, Daniels CE. Reducing iatrogenic risk in thoracentesis: establishing best practice via experiential training in a zero-risk environment. *Chest*. 2009;135(5):1315-1320.
8. Grover S, Currier PF, Elinoff JM, Mouchantaf KJ, Katz JT, McMahon GT. Development of a test to evaluate residents' knowledge of medical procedures. *J Hosp Med*. 2009;4(7):430-432.
9. Promes SB, Chudgar SM, Grochowski CO, et al. Gaps in procedural experience and competency in medical school graduates. *Acad Emerg Med*. 2009;16 Suppl 2:S58-62.
10. Huang GC, Smith CC, Gordon CE, et al. Beyond the comfort zone: residents assess their comfort performing inpatient medical procedures. *Am J Med*. 2006;119(1):71 e17-24.
11. Lagan J, Cutts L, Zaidi S, Benton I, Rylance J. Are we failing our trainees in providing opportunities to attain procedural confidence? *Br J Hosp Med (Lond)*. 2015;76(2):105-108.
12. Wayne DB, Barsuk JH, O'Leary KJ, Fudala MJ, McGaghie WC. Mastery learning of thoracentesis skills by internal medicine residents using simulation technology and deliberate practice. *J Hosp Med*. 2008;3(1):48-54.
13. Lenchus JD. End of the "see one, do one, teach one" era: the next generation of invasive bedside procedural instruction. *J Am Osteopath Assoc*. 2010;110(6): 340-346.
14. Lenchus J, Issenberg SB, Murphy D, et al. A blended approach to invasive bedside procedural instruction. *Med Teach*. 2011;33(2):116-123.
15. Jiang G, Chen H, Wang S, et al. Learning curves and long-term outcome of simulation-based thoracentesis training for medical students. *BMC Med Educ*. 2011;11:39.
16. Berg D, Berg K, Riesenberg LA, et al. The development of a validated checklist for thoracentesis: preliminary results. *Am J Med Qual*. 2013;28(3):220-226.
17. Salamonsen M, McGrath D, Steiler G, Ware R, Colt H, Fielding D. A new instrument to assess physician skill at thoracic ultrasound, including pleural effusion markup. *Chest*. 2013;144(3):930-934.
18. McVay PA, Toy PT. Lack of increased bleeding after paracentesis and thoracentesis in patients with mild coagulation abnormalities. *Transfusion*. 1991;31(2): 164-171.
19. Havelock T, Teoh R, Laws D, Gleeson F, Group BTSPDG. Pleural procedures and thoracic ultrasound: British Thoracic Society Pleural Disease Guideline 2010. *Thorax*. 2010;65 Suppl 2:ii61-76.
20. Ault MJ, Rosen BT, Scher J, Feinglass J, Barsuk JH. Thoracentesis outcomes: a 12-year experience. *Thorax*. 2015;70(2):127-132.
21. Puchalski J. Thoracentesis and the risks for bleeding: a new era. *Curr Opin Pulm Med*. 2014;20(4):377-384.
22. Hibbert RM, Atwell TD, Lekah A, et al. Safety of ultrasound-guided thoracentesis in patients with abnormal preprocedural coagulation parameters. *Chest*. 2013;144(2):456-463.
23. Zalt MB, Bechara RI, Parks C, Berkowitz DM. Effect of routine clopidogrel use on bleeding complications after ultrasound-guided thoracentesis. *J Bronchology Interv Pulmonol*. 2012;19(4):284-287.
24. Mahmood K, Shofer SL, Moser BK, Argento AC, Smathers EC, Wahidi MM. Hemorrhagic complications of thoracentesis and small-bore chest tube placement in patients taking clopidogrel. *Ann Am Thorac Soc*. 2014;11(1):73-79.
25. Goligher EC, Leis JA, Fowler RA, Pinto R, Adhikari NK, Ferguson ND. Utility and safety of draining pleural effusions in mechanically ventilated patients: a systematic review and meta-analysis. *Crit Care*. 2011;15(1):R46.
26. Fartoukh M, Azoulay E, Galliot R, et al. Clinically documented pleural effusions in medical ICU patients: how useful is routine thoracentesis? *Chest*. 2002;121(1):178-184.
27. Cervini P, Hesley GK, Thompson RL, Sampathkumar P, Knudsen JM. Incidence of infectious complications after an ultrasound-guided intervention. *AJR Am J Roentgenol*. 2010;195(4):846-850.
28. Mimoz O, Chopra V, Timsit JF. What's new in catheter-related infection: skin cleansing and skin antisepsis. *Intensive Care Med*. 2016;42(11):1784-1786.
29. Soni NJ, Franco R, Velez MI, et al. Ultrasound in the diagnosis and management of pleural effusions. *J Hosp Med*. 2015;10(12):811-816.
30. Feller-Kopman D. Ultrasound-guided thoracentesis. *Chest*. 2006;129(6): 1709-1714.
31. Shojaee S, Argento AC. Ultrasound-guided pleural access. *Semin Respir Crit Care Med*. 2014;35(6):693-705.
32. Gordon CE, Feller-Kopman D, Balk EM, Smetana GW. Pneumothorax following thoracentesis: a systematic review and meta-analysis. *Arch Intern Med*. 2010;170(4):332-339.
33. Perazzo A, Gatto P, Barlascini C, Ferrari-Bravo M, Nicolini A. Can ultrasound guidance reduce the risk of pneumothorax following thoracentesis? *J Bras Pneumol*. 2014;40(1):6-12.
34. Cavanna L, Mordenti P, Berte R, et al. Ultrasound guidance reduces pneumothorax rate and improves safety of thoracentesis in malignant pleural effusion: report on 445 consecutive patients with advanced cancer. *World J Surg Oncol*. 2014;12:139.
35. Soldati G, Smargiassi A, Inchingolo R, Sher S, Valente S, Corbo GM. Ultrasound-guided pleural puncture in supine or recumbent lateral position - feasibility study. *Multidiscip Respir Med*. 2013;8(1):18.
36. Pihlajamaa K, Bode MK, Puumalainen T, Lehtimaki A, Marjelund S, Tikkakoski T. Pneumothorax and the value of chest radiography after ultrasound-guided thoracocentesis. *Acta Radiol*. 2004;45(8):828-832.
37. Barnes TW, Morgenthaler TI, Olson EJ, Hesley GK, Decker PA, Ryu JH. Sonographically guided thoracentesis and rate of pneumothorax. *J Clin Ultrasound*. 2005;33(9):442-446.
38. Zanforlin A, Gavelli G, Oboldi D, Galletti S. Ultrasound-guided thoracenthesis: the V-point as a site for optimal drainage positioning. *Eur Rev Med Pharmacol Sci*. 2013;17(1):25-28.
39. Patel PA, Ernst FR, Gunnarsson CL. Ultrasonography guidance reduces complications and costs associated with thoracentesis procedures. *J Clin Ultrasound*. 2012;40(3):135-141.
40. Mercaldi CJ, Lanes SF. Ultrasound guidance decreases complications and improves the cost of care among patients undergoing thoracentesis and paracentesis. *Chest*. 2013;143(2):532-538.
41. Shurtleff E, Olinger A. Posterior intercostal artery tortuosity and collateral branch points: a cadaveric study. *Folia Morphol (Warsz)*. 2012;71(4):245-251.
42. Helm EJ, Rahman NM, Talakoub O, Fox DL, Gleeson FV. Course and variation of the intercostal artery by CT scan. *Chest*. 2013;143(3):634-639.
43. Yoneyama H, Arahata M, Temaru R, Ishizaka S, Minami S. Evaluation of the risk of intercostal artery laceration during thoracentesis in elderly patients by using 3D-CT angiography. *Intern Med*. 2010;49(4):289-292.
44. Salamonsen M, Ellis S, Paul E, Steinke K, Fielding D. Thoracic ultrasound demonstrates variable location of the intercostal artery. *Respiration*. 2012;83(4):323-329.
45. Salamonsen M, Dobeli K, McGrath D, et al. Physician-performed ultrasound can accurately screen for a vulnerable intercostal artery prior to chest drainage procedures. *Respirology*. 2013;18(6):942-947.
46. Grippi MA. *Fishman's pulmonary diseases and disorders*. 5th ed. New York, NY: McGraw-Hill Education; 2015.
47. Huggins JT, Doelken P. Pleural manometry. *Clin Chest Med*. 2006;27(2):229-240.
48. Echevarria C, Twomey D, Dunning J, Chanda B. Does re-expansion pulmonary oedema exist? *Interact Cardiovasc Thorac Surg*. 2008;7(3):485-489.
49. Sue RD, Matthay MA, Ware LB. Hydrostatic mechanisms may contribute to the pathogenesis of human re-expansion pulmonary edema. *Intensive Care Med*. 2004;30(10):1921-1926.
50. Feller-Kopman D, Berkowitz D, Boiselle P, Ernst A. Large-volume thoracentesis and the risk of reexpansion pulmonary edema. *Ann Thorac Surg*. 2007;84(5): 1656-1661.
51. Villena V, Lopez-Encuentra A, Pozo F, De-Pablo A, Martin-Escribano P. Measurement of pleural pressure during therapeutic thoracentesis. *Am J Respir Crit Care Med*. 2000;162(4 Pt 1):1534-1538.
52. Doelken P, Huggins JT, Pastis NJ, Sahn SA. Pleural manometry: technique and clinical implications. *Chest*. 2004;126(6):1764-1769.
53. Feller-Kopman D. Therapeutic thoracentesis: the role of ultrasound and pleural manometry. *Curr Opin Pulm Med*. 2007;13(4):312-318.
54. Boshuizen RC, Sinaasappel M, Vincent AD, Goldfinger V, Farag S, van den Heuvel MM. Pleural pressure swing and lung expansion after malignant pleural effusion drainage: the benefits of high-temporal resolution pleural manometry. *J Bronchology Interv Pulmonol*. 2013;20(3):200-205.
55. Pannu J, DePew ZS, Mullon JJ, Daniels CE, Hagen CE, Maldonado F. Impact of pleural manometry on the development of chest discomfort during thoracentesis: a symptom-based study. *J Bronchology Interv Pulmonol*. 2014;21(4):306-313.
56. Feller-Kopman D, Walkey A, Berkowitz D, Ernst A. The relationship of pleural pressure to symptom development during therapeutic thoracentesis. *Chest*. 2006;129(6):1556-1560.
57. Abunasser J, Brown R. Safety of large-volume thoracentesis. *Conn Med*. 2010;74(1):23-26.
58. Mynarek G, Brabrand K, Jakobsen JA, Kolbenstvedt A. Complications following ultrasound-guided thoracocentesis. *Acta Radiol*. 2004;45(5):519-522.
59. Josephson T, Nordenskjold CA, Larsson J, Rosenberg LU, Kaijser M. Amount

drained at ultrasound-guided thoracentesis and risk of pneumothorax. *Acta Radiol*. 2009;50(1):42-47.

60. Heidecker J, Huggins JT, Sahn SA, Doelken P. Pathophysiology of pneumothorax following ultrasound-guided thoracentesis. *Chest*. 2006;130(4):1173-1184.
61. Sokolowski JW Jr, Burgher LW, Jones FL Jr, Patterson JR, Selecky PA. Guidelines for thoracentesis and needle biopsy of the pleura. This position paper of the American Thoracic Society was adopted by the ATS Board of Directors, June 1988. *Am Rev Respir Dis*. 1989;140(1):257-258.
62. Jones PW, Moyers JP, Rogers JT, Rodriguez RM, Lee YC, Light RW. Ultrasound-guided thoracentesis: is it a safer method? *Chest*. 2003;123(2):418-423.
63. Petersen WG, Zimmerman R. Limited utility of chest radiograph after thoracentesis. *Chest*. 2000;117(4):1038-1042.
64. Sachdeva A, Shepherd RW, Lee HJ. Thoracentesis and thoracic ultrasound: state of the art in 2013. *Clin Chest Med*. 2013;34(1):1-9.
65. Shostak E, Brylka D, Krepp J, Pua B, Sanders A. Bedside sonography for detection of postprocedure pneumothorax. *J Ultrasound Med*. 2013;32(6):1003-1009.