Review

Point-of-Care Ultrasound in Pediatric Clinical Care

David J. McLario, DO, MS; Adam B. Sivitz, MD

IMPORTANCE Point-of-care (POC) ultrasound has been used by a variety of nonradiologist physicians. Recently, POC ultrasound use by pediatricians has received increased attention with the practice of both established and novel applications.

OBJECTIVES To review various uses of ultrasound by pediatricians, discuss challenges and potential pitfalls as pediatric physicians seek to use ultrasound in their practices, and consider various areas of research needs and opportunities.

EVIDENCE REVIEW Available English-language publications from 1970 through December 31, 2014.

FINDINGS Limited research supports the notion that many POC ultrasound applications practiced by nonradiologist pediatricians can assist in clinical decision making and procedural success. Future challenges include the need for institutions to train and credential large numbers of health care professionals in the use of pediatric POC ultrasound, as well as the necessity of diverse research efforts, including the establishment of pediatric-specific norms, consideration of optimal educational strategies, and inquiry intended to identify best practices for clinical effectiveness and efficiency.

CONCLUSIONS AND RELEVANCE Although considerable effort needs to be devoted to the continued development of pediatric POC ultrasound, there is potential for useful application in a variety of clinical and educational settings.

JAMA Pediatr. 2015;169(6):594-600. doi:10.1001/jamapediatrics.2015.22
Published online April 20, 2015.

Author Affiliations: Division of Emergency Medicine, Department of Pediatrics, University of Louisville School of Medicine, Louisville, Kentucky (McLario); Newark Beth Israel Medical Center, Children's Hospital of New Jersey, Newark (Sivitz); Department of Emergency Medicine, New Jersey Medical School, Rutgers University, Newark (Sivitz).

Corresponding Author: David J. McLario, DO, MS, Kosair Children's Hospital, 231 E Chestnut St, Louisville, KY 40202 (d0mcla01@louisville.edu).

Point-of-care (POC) ultrasound may be defined as medical sonography performed and interpreted at the patient's bedside for the purpose of informing diagnostic and/or resuscitation decisions and facilitating the safe and expeditious performance of procedures.[1] Diagnostic POC studies often address yes or no questions and therefore may be distinguished from the more comprehensive evaluations conducted by radiologists.

Just as the stethoscope revolutionized medicine nearly 200 years ago, advances in ultrasound now provide another opportunity for fundamental improvement of conventional medical practice.[2] Miniaturized and portable ultrasound systems now bring ultrasound to the patient and provide the opportunity for immediate assessment in previously inaccessible environments.

Ultrasound is ideal for children whose smaller size and accessible internal organs facilitate sound-wave penetration and image resolution. Moreover, the increased life span for potential radiation-induced malignant neoplasms has prompted wide-ranging advocacy for ultrasound as a preferred initial imaging modality for children, including those evaluated at the point of care.[3]

The advent of POC ultrasound has also generated considerable controversy.[4] Some believe this user-dependent technology is beyond the scope of busy physicians. Conversely, many health care professionals believe they are able to achieve competency in practiced applications without the breadth of responsibility assumed by radiologists.[5]

Pertinent information was obtained from available English-language publications from 1970 through December 31, 2014, using PubMed and other relevant databases. This article will review various ultrasound applications practiced by pediatricians. In addition, we will discuss challenges that lie ahead as POC ultrasound becomes increasingly popular among pediatricians and the families they serve. We will conclude by discussing various areas of research need and opportunity.

Current POC Ultrasound Applications

Resuscitation Ultrasound and Hydration Assessments

The focused assessment with sonography in trauma (FAST) examination is the progenitor of resuscitation ultrasound. It assesses for the presence of free fluid in the peritoneal cavity and evaluates the heart for contractility and pericardial effusion.[6] The extended FAST examination adds a limited lung assessment and has proved to be accurate in the assessment for possible posttraumatic pneumothorax.[7]

Although the FAST examination is well established in adult trauma patients, its utility in children is less definite owing to imperfect test sensitivity and the frequent use of nonoperative management for intra-abdominal injury.

A meta-analysis by Holmes et al[8] concluded that abdominal sonography was 80% (95% CI, 76%-84%) sensitive and 96% (95%

CI, 95%-97%) specific for the identification of intraperitoneal free fluid in children who sustained blunt trauma. In a subsequent study of 357 children with blunt abdominal trauma, Fox et al[9] demonstrated a sensitivity of 52% and specificity of 96% for the detection of clinically important intraperitoneal free fluid. Because of the relatively low sensitivity of the FAST examination, the absence of visible intraperitoneal free fluid, independent of additional patient information, cannot be assumed to provide compelling assurance against traumatic hemoperitoneum or hollow viscus injury.

The frequent use of nonoperative management for intra-abdominal injury is another issue that affects the usefulness of the FAST examination.[10,11] Many pediatric surgeons do not consider the presence of trauma-associated intraperitoneal free fluid to be an absolute indication for surgical laparotomy in otherwise stable and well-appearing patients; it is reported that more than 90% of children diagnosed with intra-abdominal injury are treated nonoperatively.[12] Despite these limitations, the FAST examination continues to be used to evaluate pediatric blunt torso trauma and may be most useful in children who are considered to be at low to moderate risk of intra-abdominal injury based on a multifaceted screening protocol.[13,14]

Several protocols provide systematic approaches to treating patients with undifferentiated cardiorespiratory compromise.[15] Pershad et al,[16] in a study of 31 children admitted to a pediatric intensive care unit, demonstrated good agreement between experienced independent pediatric echocardiographers and pediatric emergency physicians on sonographic measurements of left ventricular shortening fraction and inferior vena cava volume. The authors concluded that pediatric emergency physician sonographers with focused training who use the bedside limited echocardiography by the emergency physician (BLEEP) protocol were able to provide accurate estimates of left ventricular function and right ventricular filling.

The rapid ultrasound for shock and hypertension (RUSH) protocol addresses hemodynamic compromise via a conceptualization using "the pump," "the tank," and "the pipes."[17] Weingert et al[18] use a mnemonic, HIMAP, that instructs sonographic assessment of the heart, inferior vena cava, Morison pouch, aorta, and lungs in their RUSH protocol, which was developed in 2007. The ability of the complete RUSH protocol to identify or exclude various causes of shock in adults is unclear, with the available data taken from component studies. To date, test characteristics of the RUSH protocol have not been elucidated in pediatrics. When applied to children, the same inferior vena cava and heart assessments can be used, while the evaluation of the pipes for blood loss or obstruction to circulatory flow may search for pathologic features that are uncommon in adults.

Unique considerations in a pediatric-adapted RUSH protocol may involve POC ultrasound evaluation of the abdominal cavity in search of intraperitoneal free fluid resulting from a ruptured ectopic pregnancy.[19] Lung sonography may reveal evidence of increased capillary permeability or facilitate the diagnosis of spontaneous tension pneumothorax in patients with cystic fibrosis.[7,20] Transfontanelle ultrasound of the infant brain can detect the presence of unanticipated intraventricular hemorrhage.[21]

Determining hydration status is a frequent exercise in children. Clinical scores of dehydration have demonstrated suboptimal accuracy, while various studies attest to the promise of ultrasound assessments.[22] Original studies included static prerehydration and postrehydration measurements of capacitance vessel diameter, with sensitivities and specificities ranging from 86% to 93% and 56% to 59%, respectively.[23-26] More recent interest has focused on serial assessments of large-vessel collapse and expansion in response to provocative maneuvers, such as sniffing and lower-extremity elevation, respectively.[27] The potential for accurate identification of children in need of intensive treatment for dehydration holds considerable promise, particularly in resource-limited settings.

The opportunity provided by POC ultrasound for initial and serial assessments of preload, contractility, afterload, and possible volume loss carries significant potential for greater understanding and accuracy in pediatric resuscitation and will likely influence bedside decisions regarding the use of volume expansion, pressors, and inotropes.

At a Glance

- Point-of-care ultrasound use by pediatricians has received increased attention, with both established and novel applications being used.
- Current applications use resuscitation and hydration assessment, guided vascular access, evaluation of skin and soft-tissue infections, pulmonary assessment, and assessment of a variety of intra-abdominal conditions.
- Training and credentialing in point-of-care ultrasound is rapidly evolving.
- Other novel applications for ultrasound are fruitful areas for research.

Ultrasound-Guided Vascular Access

In response to the Institute of Medicine report, *To Err Is Human*,[28] the Agency for Healthcare Research and Quality advocated sonographic guidance for central venous access as 1 of 12 recommended practices for patient safety and error reduction. While central venous cannulation is not practiced by most pediatricians, establishing peripheral intravenous access in children is frequently a time-consuming, challenging, and frustrating process for all involved parties. In a prospective study of 50 children younger than 10 years, Doniger et al[29] realized improvements in overall success for establishment of intravenous access, less overall time, and fewer attempts and needle redirections when using ultrasound guidance vs the traditional technique. Costantino and colleagues[30] studied 60 patients for whom intravenous access had not been obtained following at least 3 attempts. The success rates for the ultrasound vs control groups were 97% and 33%, respectively, while the ultrasound group required less time to achieve successful cannulation and fewer percutaneous punctures.

Soft-Tissue Ultrasound

The incidence of skin and soft-tissue infection increased 3-fold between 1993 and 2005,[31] magnifying the repercussions that result from a health care professional's inability to distinguish an abscess from cellulitis, evidenced by the poor interrater reliability regarding clinical prediction of the need for a drainage procedure.[32]

Abscess visualization by ultrasound confirms the need for a drainage procedure and may decrease repeated visits, antibiotic use, and the duration of patient discomfort. Conversely, the visualization of cellulitis without abscess prevents an unnecessary incision and spares the time and patient discomfort resulting from procedural sedation and analgesia.

Prospective pediatric studies[33-35] have reported POC ultrasound to be 90% to 97% sensitive and 69% to 83% specific for distinguishing abscess from cellulitis compared with clinical suspicion, for which sensitivity and specificity were 75% to 78% and 66% to 80%, respectively.

Musculoskeletal Ultrasound

Health care professionals who use ultrasound are able to rapidly visualize the cortical discontinuity of long bone fractures, facilitating diagnosis and early immobilization before conventional radiography.[36] Ultrasound also may be useful for rapid on-field evaluations where conventional radiography is not accessible.

In a study of nonangulated distal forearm injuries conducted by Chaar-Alvarez et al,[37] ultrasound demonstrated sensitivity and specificity of 96% and 93%, respectively, with less patient discomfort during the imaging procedure compared with conventional radiography. Ultrasound also has been used to guide reduction of simple fractures.[36,38] If additional studies support the safety and efficacy of this approach for selected fractures, C-arm–induced radiation exposure to children and staff could be reduced.

Pulmonary Ultrasound

Imperative to understanding pulmonary ultrasound is the notion that air scatters sound waves, rendering visualization of lung tissue difficult. The result is the consistent presence of characteristic default artifacts during ultrasound evaluation of healthy lungs. Conversely, many respiratory illnesses are characterized by the enhanced transmission of sound waves resulting from increased pulmonary fluid. When abnormal fluid accumulation is present in or around the lung, normal default artifacts may be altered or attenuated and a disease process can be inferred.[39,40]

In publications that report on adults in the intensive care unit,[41] various lung artifacts have been well described and their appearances organized into an algorithm to assist health care professionals. Differentiation of artifacts assists bedside identification of pneumothorax, pulmonary edema, effusion, and pneumonia. O'Connor et al[42] compared test characteristics of lung ultrasound and chest radiography using thoracic computed tomography as the reference standard. Eighty-four hemithoraces were evaluated by the 3 imaging techniques. The sensitivity, specificity, and diagnostic accuracy of chest radiography was 38%, 89%, and 49% for consolidation; 46%, 80%, and 69% for interstitial syndrome; 0%, 99%, and 89% for pneumothorax; and 65%, 81%, and 6% for pleural effusion. The corresponding values for lung ultrasound were 100%, 78%, and 95% for consolidation; 94%, 93%, and 94% for interstitial syndrome; 75%, 93%, and 92% for pneumothorax, and 100%, 100%, and 100% for pleural effusion. The authors concluded that, in their unselected intensive care unit population, lung ultrasound provided better diagnostic performance than chest radiography for the diagnosis of common pathologic conditions. Additional experience using pulmonary ultrasound in ambulatory patients is anticipated.

Shah et al,[43] in a prospective evaluation of children and young adults with suspicion of pneumonia, reported greater sensitivity for POC ultrasound vs chest radiography based on characteristic sonographic findings.

Intussusception

In children aged 3 months to 6 years, intussusception is the most common cause of intestinal obstruction.[44] The classic clinical triad of colicky abdominal pain, vomiting, and currant jelly stool occurs in less than 50% of cases.[45] Findings from the physical examination are often nonspecific, and radiographs may show no abnormalities.[46,47] Radiologist-performed sonography has emerged as the standard screening imaging modality for intussusception, with sensitivity greater than 98% and specificity of 88% to 100%.[47]

A recent prospective study of 82 patients with suspected intussusception by Riera et al[48] demonstrated a sensitivity of 85% and specificity of 97% with assessments performed by novice sonographers. The high specificity makes ultrasound attractive as a means to establish the diagnosis of intussusception, with the potential to expedite reduction.

Appendicitis

Acute appendicitis is the most common surgical emergency that occurs in children.[49,50] Computed tomographic evaluation provides sensitivity and specificity of more than 90%, while studies of radiology-performed ultrasound report similar specificity but lower sensitivity.[50] Many health care professionals advocate a staged imaging approach, using sonography as the initial modality with the option for computed tomography if findings from sonographic assessments are negative or indeterminate.[51]

Two recent prospective studies have focused specifically on pediatric emergency care professionals. Elikashvilli et al[52] evaluated 150 children for suspected appendicitis. Radiologists and pediatric emergency medicine sonographers achieved similar sensitivity (60.0% vs 62.5%) and specificity (94% vs 99%), respectively. A second study by Sivitz et al[53] used an anatomically based scanning protocol that improved appendix visualization relative to POC ultrasound studies insonating at the site of maximal tenderness. In the 264 POC ultrasound evaluations, sensitivity and specificity were 85% and 93%, respectively.

Perhaps most encouraging are data arising from subanalysis within the 2 abovementioned studies. Those with more than 25 sonographic assessments reported sensitivities of 80% to 88% and specificities of 98% to 99%, respectively, suggesting excellent predictive value for positive studies obtained by more experienced pediatric physician sonographers and emphasizing the importance of continuing practice and repetition.

Pyloric Stenosis

The most common surgical cause of nonbilious vomiting in infancy is hypertrophic pyloric stenosis.[54] Unfortunately, neither the palpable pathognomonic "olive," representing the hypertrophied pyloric muscle, nor the classically described hypochloremic hypokalemic metabolic acidosis are often present at the time of initial presentation.[55,56]

Since its introduction by Teele and Smith[57] in 1977, pyloric sonography has demonstrated accuracy near 100% and is presently considered the imaging standard. A prospective study reviewed pediatric emergency physician POC ultrasound findings in 60 patients with suspected hypertrophic pyloric stenosis.[58] All cases of hypertrophic pyloric stenosis were identified correctly, with measurements consistent with those obtained by co-investigators in radiology.

Ocular Ultrasound

The aqueous and vitreous humors of the eye serve as excellent acoustic media for sonographic evaluation of the optic nerve, providing an alternative assessment to traditional fundoscopy. Ultrasound has been used successfully by nonophthalmologist health care professionals in patients with suspected retinal detachment, while optic nerve measurements have been used in the evaluation of suspected ventriculoperitoneal shunt malfunction and high-altitude cerebral edema.[59-62] Bäuerle and Nedelmann[63] measured the optic nerve void diameter in 25 patients with suspected idiopathic intracranial hypertension who underwent lumbar puncture. Patients with an idiopathic intracranial hypertension diagnosis based on lumbar puncture measurements of increased intracranial pressure had statistically significantly higher optic nerve void diameter measurements than patients without idiopathic intracranial hypertension.

Future Challenges

Point-of-care ultrasound is an example of a disruptive innovation, whereby a novel technique or strategy transforms the status quo by introducing unprecedented simplicity, convenience, accessibility, and/or affordability.[64] It is incumbent on us, as professionals who provide care for children, to continue a collegial dialogue regarding the many yet-to-be-resolved questions that have arisen subsequent to the advent of POC ultrasound.

Training and Credentialing

Can physicians learn ultrasound? The attainment of competence in ultrasound is no small task, necessitating skills in both image acquisition and interpretation. The development of specialty-specific expertise by cardiologists, obstetricians, anesthesiologists, intensivists, and others endorses the notion that nonradiologist physicians can master ultrasound in a circumscribed discipline. Meanwhile, the collateral achievement of broad competence in POC ultrasound by emergency medicine physicians supports its potential for nonspecialist pediatricians.

Two routes to physician competency and credentialing in clinical ultrasound are common in emergency medicine. The first involves obtaining core sonographic skills during emergency medicine residency or pediatric emergency medicine fellowship training via a combination of dedicated ultrasound rotations, supervised clinical use, and a didactic curriculum. Vieira et al[65] provided a consensus guideline for pediatric emergency medicine fellow POC ultrasound training that included unique pediatric-specific curriculum content. Many graduates opt to advance their POC ultrasound training beyond their emergency medicine training. There are currently 98 emergency ultrasound fellowships, including a small number of pediatric-specific emergency ultrasound programs.[66]

Many institutions that credential physicians in clinical ultrasound use American College of Emergency Physicians guidelines.[67] The physician is initially credentialed in basic applications following the performance of 25 to 50 quality-reviewed ultrasounds per application, while for procedural credentialing, 5 to 10 quality-reviewed interventions are recommended per application. In environments of lower patient acuity that provide fewer opportunities for procedures, simulator repetitions may supplement live patient encounters. Maintenance of credentialing requires both documented ultrasound use and ultrasound-related education.

For physicians outside residency or fellowship training, practice-based pathways that recognize clinical repetition are often acceptable for institutional credentialing. This type of credentialing pathway may follow participation in a formal course that combines didactic and hands-on instruction. Both practice- and training-based credentialing pathways should encourage an initial minimum number of training scans per indication, with access to expert sonographers for assessment of competence in image acquisition and interpretation. Longitudinal quality assurance using periodic image review should occur once initial competency has been achieved.

Another question pertains to when ultrasound learning is best accomplished. Many believe ultrasound should be introduced at the beginning of medical school while others contend that training is optimal at the onset of undergraduate clinical rotations. Bahner et al,[68] in a 2012 survey of 134 US medical school curriculum administrators, inquired about the state of undergraduate ultrasound education. Only 62% of respondents reported integration of ultrasound into the undergraduate medical education curriculum; it was most often introduced during the third year. Despite respondent consensus affirming its importance, the authors concluded that the integration of ultrasound education in US medical schools was highly variable and suggested the implementation of national standards to guide implementation. Studies comparing the performance of students involved in differing ultrasound curricula will be informative.

Discussions of the timing of ultrasound education should not bypass the training of practicing physicians. Clinical use of POC ultrasound will be compromised if senior physicians are unable to confidently interpret ultrasound images obtained by the physicians-in-training they are charged to supervise. Special strategies for older, late-adopting, and technologically nonintuitive physicians must be developed.

Even if learnable, is POC ultrasound in the best interest of our patients? While there is reasonable consensus regarding the utility of POC ultrasound for procedural guidance and real-time assistance in patient resuscitation, discussion of appropriate diagnostic POC ultrasound applications will necessarily include the difficulty of the application relative to physician competency, the risk of misdiagnosis, specialist availability, and time considerations. For example, the sonographic differentiation of abscess and cellulitis is a relatively simple skill, while neither condition confers immediate risk of significant morbidity or mortality. In contradistinction, the sonographic evaluation of ovarian torsion is challenging and pertains to the patient's future fertility, with health care professionals frequently opting for radiology consultation.[69] The effect of POC ultrasound on patient flow is of considerable importance. While many ultrasound studies performed at the point of care have the potential to shorten patient length of stay, more complicated studies have the potential to decrease patient flow. Interdisciplinary dialogue regarding the scope of pediatric POC ultrasound will continue and will likely reflect unique institutional and community characteristics. A list of basic and advanced pediatric POC ultrasound applications is provided in the Box.

Confusion regarding what POC ultrasound is—and is not—also warrants mention. Parents may communicate to the effect of, "We already had an ultrasound at the hospital last week and it was fine." In the event of a need for follow-up consultative study, a health care professional's presumption that a full sonographic evaluation has been accomplished carries significant risk of diagnostic delay or omis-

Box. Pediatric Point-of-Care Ultrasound Applications

Basic

1. Basic echocardiography
2. Volume and/or hydration assessment
3. Peripheral vascular access
4. Soft-tissue examination (abscess and/or cellulitis)
5. Bladder volume measurement
6. Musculoskeletal examination (long bone fractures)
7. Intrauterine pregnancy identification

Advanced

1. Resuscitation (eg, extended focused assessment with sonography in trauma, rapid ultrasound for shock and hypertension)
2. Foreign body detection and removal
3. Nerve blocks
4. Pulmonary applications
5. Central vascular access
6. Ocular applications
7. Abdomen (constipation, hydronephrosis, hepatobiliary system, and spleen)

sion. Information regarding the limited scope of POC diagnostic examinations should be included in the medical record, discussed with the family, and explicated in the discharge instructions.

Interdisciplinary Dialogue

Perhaps the greatest distinction between radiologists and physicians who use ultrasound occurs in response to diverging strategies used for diagnostic studies.[4] Radiologists have customarily performed comprehensive assessments of anatomic areas and have assumed responsibility for all possible pathologic features within predetermined anatomic boundaries. Point-of-care ultrasound takes a focused approach: is an abscess noted? Is intraperitoneal free fluid visible following trauma? Is there an intrauterine pregnancy? The use of a binary approach to diagnostic ultrasound is understandable given the time constraints endemic to the nonradiologist physician's practice environment.

In many instances, focused diagnostic POC ultrasound studies provide information that guides physicians to request the most appropriate consultative ultrasound study, expediting patient flow and workplace efficiency. When clinical findings warrant high suspicion for a disease but findings from a focused examination show no abnormalities, collaboration with colleagues in radiology may facilitate the investigation of alternative diagnoses.

Discussions with consultants and admitting teams are frequently augmented by findings from POC ultrasound. In children who appear seriously ill or unstable, bedside evaluation may inform the treatment of those who cannot safely leave the clinical care area. Point-of-care ultrasound findings may also prompt activation of resources while health care professionals await additional radiologic imaging.

Reimbursement Issues

In fee-for-service models, credentialed physicians are reimbursed for the professional component of the ultrasound examination under Current Procedural Terminology coding guidelines.[70] Current Procedural Terminology modifiers exist to differentiate focused examinations from comprehensive examinations and for the designation of repeated evaluations.

Physician reimbursement for ultrasound necessitates documentation of the indication for the study, an archived representative image, and its interpretation by a credentialed physician sonographer.[70] Consultation with informative technology specialists is recommended.

Research

Just as pediatric patients are not little adults, pediatric POC ultrasound is not simply a miniaturized version of the clinical ultrasound that has been provided to adults. Pediatric-specific POC ultrasound research will be of paramount importance going forward.

The acquisition of repetition and competence in pediatric ultrasound-guided procedures will likely increase the use of anatomic ultrasound phantoms and interact with developing simulation curricula. Tolerance of procedural skill acquisition on patients will likely decrease in view of increasingly available alternative-learning strategies. Assessments of rapidity and durability of skill acquisition will be eagerly anticipated. Along these lines, best practices for credentialing and quality assurance programs will require delineation.

Strategies and benefits of communication between physicians and radiologists using the shared language of ultrasound will likely be studied in collegial pediatric medical communities. In certain situations, the nonradiologist physician sonographer's role may emphasize image acquisition before consultation with radiologists or other specialists using images that are available on accessible image-archiving systems. Institutions that are able to achieve and codify interdisciplinary collaboration on behalf of their patients will have considerable opportunity to instruct others.

One of the most exciting aspects of pediatric POC ultrasound is the opportunity for the creative development of novel applications. The already astonishing variety of innovations will require study and refinement at different sites, in unique populations, and with physician sonographers of varying experience and training. The pursuit of normative pediatric-specific anatomic and physiologic characteristics will be a natural result of this ongoing development.

Conclusions

Point-of-care ultrasound is an exciting innovation. Miniaturization of increasingly durable units, dramatic improvements in image quality, archiving systems, instruction in the early stages of medical training, institutional credentialing programs, and an expanding array of educational resources will likely provide the infrastructure necessary for health care professionals' competence in practiced applications. Many pediatric specialists will achieve considerable competence and creative development in their systems of expertise, while common diagnostic applications will be adopted by increasing numbers of nonspecialist pediatric health care professionals. Point-of-care ultrasound offers extraordinary opportunity but portends caution and responsibility as it appears poised to change the practice of pediatric medicine.

ARTICLE INFORMATION

Accepted for Publication: January 5, 2015.

Published Online: April 20, 2015. doi:10.1001/jamapediatrics.2015.22.

Author Contributions: Dr McLario had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.
Study concept and design: All authors.
Acquisition, analysis, or interpretation of data: All authors.
Drafting of the manuscript: All authors.
Critical revision of the manuscript for important intellectual content: All authors.
Administrative, technical, or material support: All authors.
Study supervision: All authors.

Conflict of Interest Disclosures: None reported.

REFERENCES

1. Moore CL, Copel JA. Point-of-care ultrasonography. *N Engl J Med*. 2011;364(8):749-757.

2. Laennec RTH. *A Treatise on the Diseases of the Chest and on Mediate Auscultation.* 3rd rev ed. Forbes J, trans. London, England: Thomas & George Underwood; 1829.

3. Minton KK, Abuhamad A. 2012 Ultrasound First Forum proceedings. *J Ultrasound Med*. 2013;32(4):555-566.

4. Goodman TR, Scoutt LM, Brink JA. A survey of emergency physician-performed ultrasound: implications for academic radiology departments. *J Am Coll Radiol*. 2011;8(9):631-634.

5. Kendall JL, Hoffenberg SR, Smith RS. History of emergency and critical care ultrasound: the evolution of a new imaging paradigm. *Crit Care Med*. 2007;35(5)(suppl):S126-S130.

6. Rozycki GS, Ballard RB, Feliciano DV, Schmidt JA, Pennington SD. Surgeon-performed ultrasound for the assessment of truncal injuries: lessons learned from 1540 patients. *Ann Surg*. 1998;228(4):557-567.

7. Blaivas M, Lyon M, Duggal S. A prospective comparison of supine chest radiography and bedside ultrasound for the diagnosis of traumatic pneumothorax. *Acad Emerg Med*. 2005;12(9):844-849.

8. Holmes JF, Gladman A, Chang CH. Performance of abdominal ultrasonography in pediatric blunt trauma patients: a meta-analysis. *J Pediatr Surg*. 2007;42(9):1588-1594.

9. Fox JC, Boysen M, Gharahbaghian L, et al. Test characteristics of focused assessment of sonography for trauma for clinically significant abdominal free fluid in pediatric blunt abdominal trauma. *Acad Emerg Med*. 2011;18(5):477-482.

10. Taylor GA, Sivit CJ. Posttraumatic peritoneal fluid: is it a reliable indicator of intraabdominal injury in children? *J Pediatr Surg*. 1995;30:1644-1648.

11. Taylor GA, Sivit CJ. Computed tomography imaging of abdominal trauma in children. *Semin Pediatr Surg*. 1992;1(4):253-259.

12. Soudack M, Epelman M, Maor R, et al. Experience with focused abdominal sonography for trauma (FAST) in 313 pediatric patients. *J Clin Ultrasound*. 2004;32(2):53-61.

13. Menaker J, Blumberg S, Wisner DH, et al; Intra-abdominal Injury Study Group of the Pediatric Emergency Care Applied Research Network (PECARN). Use of the focused assessment with sonography for trauma (FAST) examination and its impact on abdominal computed tomography use in hemodynamically stable children with blunt torso trauma. *J Trauma Acute Care Surg*. 2014;77(3):427-432.

14. Retzlaff T, Hirsch W, Till H, Rolle U. Is sonography reliable for the diagnosis of pediatric blunt abdominal trauma? *J Pediatr Surg*. 2010;45(5):912-915.

15. Seif D, Perera P, Mailhot T, Riley D, Mandavia D. Bedside ultrasound in resuscitation and the rapid ultrasound in shock protocol. *Crit Care Res Pract*. 2012;2012:503254.

16. Pershad J, Myers S, Plouman C, et al. Bedside limited echocardiography by the emergency physician is accurate during evaluation of the critically ill patient. *Pediatrics*. 2004;114(6):e667-e671.

17. Perera P, Mailhot T, Riley D, Mandavia D. The RUSH exam: Rapid Ultrasound in SHock in the evaluation of the critically ill. *Emerg Med Clin North Am*. 2010;28(1):29-56, vii.

18. Weingert SD, Duque D, Nelson B. Rapid ultrasound for shock and hypotension (RUSH-HIMAP). EMedHome website. http://emedhome.com/. Accessed December 28, 2014.

19. Stein JC, Wang R, Adler N, et al. Emergency physician ultrasonography for evaluating patients at risk for ectopic pregnancy: a meta-analysis. *Ann Emerg Med*. 2010;56(6):674-683.

20. Lichtenstein DA. Pneumothorax and introduction of ultrasound signs in the lung. In: Lichtenstein DA, ed. *General Ultrasound in the Critically Ill.* New York, NY: Springer; 2004:105-114.

21. Huisman TA. Intracranial hemorrhage: ultrasound, CT and MRI findings. *Eur Radiol*. 2005;15(3):434-440.

22. Steiner MJ, DeWalt DA, Byerley JS. Is this child dehydrated? *JAMA*. 2004;291(22):2746-2754.

23. Krause I, Birk E, Davidovits M, et al. Inferior vena cava diameter: a useful method for estimation of fluid status in children on haemodialysis. *Nephrol Dial Transplant*. 2001;16(6):1203-1206.

24. Kosiak W, Swieton D, Piskunowicz M. Sonographic inferior vena cava/aorta diameter index, a new approach to the body fluid status assessment in children and young adults in emergency ultrasound—preliminary study. *Am J Emerg Med*. 2008;26(3):320-325.

25. Chen L, Kim Y, Santucci KA. Use of ultrasound measurement of the inferior vena cava diameter as an objective tool in the assessment of children with clinical dehydration. *Acad Emerg Med*. 2007;14(10):841-845.

26. Chen L, Hsiao A, Langhan M, Riera A, Santucci KA. Use of bedside ultrasound to assess degree of dehydration in children with gastroenteritis. *Acad Emerg Med*. 2010;17(10):1042-1047.

27. Levine AC, Shah SP, Umulisa I, et al. Ultrasound assessment of severe dehydration in children with diarrhea and vomiting. *Acad Emerg Med*. 2010;17(10):1035-1041.

28. Kohn LT, Corrigan JM, Donaldson MS; Institute of Medicine. *To Err Is Human: Building a Safer Health System.* Washington, DC: National Academy Press; 2000.

29. Doniger SJ, Ishimine P, Fox JC, Kanegaye JT. Randomized controlled trial of ultrasound-guided peripheral intravenous catheter placement versus traditional techniques in difficult-access pediatric patients. *Pediatr Emerg Care*. 2009;25(3):154-159.

30. Costantino TG, Parikh AK, Satz WA, Fojtik JP. Ultrasonography-guided peripheral intravenous access versus traditional approaches in patients with difficult intravenous access. *Ann Emerg Med*. 2005;46(5):456-461.

31. Pallin DJ, Egan DJ, Pelletier AJ, Espinola JA, Hooper DC, Camargo CA Jr. Increased US emergency department visits for skin and soft tissue infections, and changes in antibiotic choices, during the emergence of community-associated methicillin-resistant *Staphylococcus aureus*. *Ann Emerg Med*. 2008;51(3):291-298.

32. Marin JR, Bilker W, Lautenbach E, Alpern ER. Reliability of clinical examinations for pediatric skin and soft-tissue infections. *Pediatrics*. 2010;126(5):925-930.

33. Sivitz AB, Lam SH, Ramirez-Schrempp D, Valente JH, Nagdev AD. Effect of bedside ultrasound on management of pediatric soft-tissue infection. *J Emerg Med*. 2010;39(5):637-643.

34. Iverson K, Haritos D, Thomas R, Kannikeswaran N. The effect of bedside ultrasound on diagnosis and management of soft tissue infections in a pediatric ED. *Am J Emerg Med*. 2012;30(8):1347-1351.

35. Marin JR, Dean AJ, Bilker WB, Panebianco NL, Brown NJ, Alpern ER. Emergency ultrasound-assisted examination of skin and soft tissue infections in the pediatric emergency department. *Acad Emerg Med*. 2013;20(6):545-553.

36. Chen L, Kim Y, Moore CL. Diagnosis and guided reduction of forearm fractures in children using bedside ultrasound. *Pediatr Emerg Care*. 2007;23(8):528-531.

37. Chaar-Alvarez FM, Warkentine F, Cross K, Herr S, Paul RI. Bedside ultrasound diagnosis of nonangulated distal forearm fractures in the pediatric emergency department. *Pediatr Emerg Care*. 2011;27(11):1027-1032.

38. Chinnock B, Khaletskiy A, Kuo K, Hendey GW. Ultrasound-guided reduction of distal radius fractures. *J Emerg Med*. 2011;40(3):308-312.

39. Coley BD. Pediatric chest ultrasound. *Radiol Clin North Am*. 2005;43(2):405-418.

40. Caiulo VA, Gargani L, Caiulo S, et al. Lung ultrasound characteristics of community-acquired pneumonia in hospitalized children. *Pediatr Pulmonol*. 2013;48(3):280-287.

41. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. *Chest*. 2008;134(1):117-125.

42. O'Connor M, Isitt CE, Vizcaychipi MP. Comment on Xirouchaki et al: impact of lung ultrasound on clinical decision making in critically ill patients. *Intensive Care Med*. 2014;40(7):1061-1062.

43. Shah VP, Tunik MG, Tsung JW. Prospective evaluation of point-of-care ultrasonography for the diagnosis of pneumonia in children and young adults. *JAMA Pediatr*. 2013;167(2):119-125.

44. Wyllie R. Ileus, adhesions, intussusception, and closed-loop obstructions. In: Kliegman R, Nelson WE, eds. *Nelson Textbook of Pediatrics*. 18th ed. Philadelphia, PA: Saunders; 2007:lii, 3147.

45. Daneman A, Navarro O. Intussusception, part 1: a review of diagnostic approaches. *Pediatr Radiol*. 2003;33(2):79-85.

46. Roskind CG, Ruzal-Shapiro CB, Dowd EK, Dayan PS. Test characteristics of the 3-view abdominal radiograph series in the diagnosis of intussusception. *Pediatr Emerg Care*. 2007;23(11):785-789.

47. Applegate KE. Intussusception in children: evidence-based diagnosis and treatment. *Pediatr Radiol*. 2009;39(suppl 2):S140-S143.

48. Riera A, Hsiao AL, Langhan ML, Goodman TR, Chen L. Diagnosis of intussusception by physician novice sonographers in the emergency department. *Ann Emerg Med*. 2012;60(3):264-268.

49. Hall MJ, DeFrances CJ, Williams SN, Golosinskiy A, Schwartzman A. National hospital discharge survey: 2007 summary. *Natl Health Stat Report*. 2010;(29):1-20.

50. Bachur RG, Hennelly K, Callahan MJ, Monuteaux MC. Advanced radiologic imaging for pediatric appendicitis, 2005-2009: trends and outcomes. *J Pediatr*. 2012;160(6):1034-1038.

51. Garcia Peña BM, Cook EF, Mandl KD. Selective imaging strategies for the diagnosis of appendicitis in children. *Pediatrics*. 2004;113(1, pt 1):24-28.

52. Elikashvili I, Tay ET, Tsung JW. The effect of point-of-care ultrasonography on emergency department length of stay and computed tomography utilization in children with suspected appendicitis. *Acad Emerg Med*. 2014;21(2):163-170.

53. Sivitz AB, Cohen SG, Tejani C. Evaluation of acute appendicitis by pediatric emergency physician sonography. *Ann Emerg Med*. 2014;64(4):358-364.e4.

54. Hunter AK, Liascouras CA. Hypertrophic pyloric stenosis. In: Kliegman R, Nelson WE, eds. *Nelson Textbook of Pediatrics*. 19th ed. Philadelphia, PA: Elsevier/Saunders; 2011:1274.

55. Chen EA, Luks FI, Gilchrist BF, Wesselhoeft CW Jr, DeLuca FG. Pyloric stenosis in the age of ultrasonography: fading skills, better patients? *J Pediatr Surg*. 1996;31(6):829-830.

56. Hernanz-Schulman M, Sells LL, Ambrosino MM, Heller RM, Stein SM, Neblett WW III. Hypertrophic pyloric stenosis in the infant without a palpable olive: accuracy of sonographic diagnosis. *Radiology*. 1994;193(3):771-776.

57. Teele RL, Smith EH. Ultrasound in the diagnosis of idiopathic hypertrophic pyloric stenosis. *N Engl J Med*. 1977;296(20):1149-1150.

58. Sivitz AB, Tejani C, Cohen SG. Evaluation of hypertrophic pyloric stenosis by pediatric emergency physician sonography. *Acad Emerg Med*. 2013;20(7):646-651.

59. Elia J, Borger R. Diagnosis of retinal detachment in the ED with ultrasonography. *J Emerg Med*. 2009;37(4):415-416.

60. Winter K, Baker T. Images in emergency medicine: retinal detachment. *Ann Emerg Med*. 2007;50(1):89-95.

61. Blaivas M, Theodoro D, Sierzenski PR. A study of bedside ocular ultrasonography in the emergency department. *Acad Emerg Med*. 2002;9(8):791-799.

62. Keyes LE, Paterson R, Boatright D, Browne V, Leadbetter G, Hackett P. Optic nerve sheath diameter and acute mountain sickness. *Wilderness Environ Med*. 2013;24(2):105-111.

63. Bäuerle J, Nedelmann M. Sonographic assessment of the optic nerve sheath in idiopathic intracranial hypertension. *J Neurol*. 2011;258(11):2014-2019.

64. Christensen CM. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston, MA: Harvard Business Preview; 1997.

65. Vieira RL, Hsu D, Nagler J, Chen L, Gallagher R, Levy JA; American Academy of Pediatrics. Pediatric emergency medicine fellow training in ultrasound: consensus educational guidelines. *Acad Emerg Med*. 2013;20(3):300-306.

66. Society for Clinical Ultrasound Fellowships. EUS fellowship programs. Emergency Ultrasound website. http://www.eusfellowships.com. Accessed December 30, 2014.

67. American College of Emergency Physicians. Emergency ultrasound guidelines—2008. http://www.acep.org/Clinical---Practice-Management/Ultrasound/. Accessed December 1, 2014.

68. Bahner DP, Goldman E, Way D, Royall NA, Liu YT. The state of ultrasound education in U.S. medical schools: results of a national survey. *Acad Med*. 2014;89(12):1681-1686.

69. Servaes S, Zurakowski D, Laufer MR, Feins N, Chow JS. Sonographic findings of ovarian torsion in children. *Pediatr Radiol*. 2007;37(5):446-451.

70. Resnick J, Hoffenberg S, Tayal V, Dickman E; American College of Emergency Physicians. Emergency medicine section: ultrasound coding and reimbursement document 2009. http://www.acep.org/workarea/DownloadAsset.aspx?id=33280. Accessed December 1, 2014.