Lung Ultrasound for the Diagnosis of Pneumonia in Children: A Meta-analysis

María A. Pereda, MD; Miguel A. Chavez, MD; Catherine C. Hooper-Miele, MD; Robert H. Gilman, MD, DTMH; Mark C. Steinhoff, MD; Laura E. Ellington, MD; Margaret Gross, MA, MLS; Carrie Price, MLS; James M. Tielsch, PhD; William Checkley, MD, PhD

BACKGROUND AND OBJECTIVE: Pneumonia is the leading cause of death of children. Diagnostic tools include chest radiography, but guidelines do not currently recommend the use of lung ultrasound (LUS) as a diagnostic method. We conducted a meta-analysis to summarize evidence on the diagnostic accuracy of LUS for childhood pneumonia.

METHODS: We performed a systematic search in PubMed, Embase, the Cochrane Library, Scopus, Global Health, World Health Organization–Libraries, and Latin American and Caribbean Health Sciences Literature of studies comparing LUS diagnostic accuracy against a reference standard. We used a combination of controlled key words for age 18 years, pneumonia, and ultrasound. We identified 1475 studies and selected 15 (1%) for further review. Eight studies (765 children) were retrieved for analysis, of which 6 (75%) were conducted in the general pediatric population and 2 (25%) in neonates. Eligible studies provided information to calculate sensitivity, specificity, and positive and negative likelihood ratios. Heterogeneity was assessed by using Q and I² statistics.

RESULTS: Five studies (63%) reported using highly skilled sonographers. Overall methodologic quality was high, but heterogeneity was observed across studies. LUS had a sensitivity of 96% (95% confidence interval [CI]: 94%-97%) and specificity of 93% (95% CI: 90%-96%), and positive and negative likelihood ratios were 15.3 (95% CI: 6.6-35.3) and 0.06 (95% CI: 0.03-0.11), respectively. The area under the receiver operating characteristic curve was 0.98. Limitations included the following: most studies included in our analysis had a low number of patients, and the number of eligible studies was also small.

CONCLUSIONS: Current evidence supports LUS as an imaging alternative for the diagnosis of childhood pneumonia. Recommendations to train pediatricians on LUS for diagnosis of pneumonia may have important implications in different clinical settings.
Pneumonia is the leading cause of illness and death in children worldwide. It is estimated that pneumonia has a global annual incidence of 150 to 156 million cases\(^\text{1}\) in children <5 years of age, of whom ~11 to 20 million of cases need hospitalization and 1.1 million die of this condition.\(^\text{2}\) Pneumonia accounts for 18% of the total number of deaths in children <5 years worldwide, more than tuberculosis, AIDS, and malaria combined.\(^\text{2}\)

Pediatric pneumonia still remains a diagnostic challenge in resource-limited settings.\(^\text{3}\) Signs and symptoms of pneumonia vary depending on a child’s age and the etiology of infection.\(^\text{4–7}\) Moreover, presenting signs and symptoms have poor diagnostic specificity, which may further complicate the diagnosis.

The American Academy of Pediatrics recommends the use of chest radiographs (CRs) cautiously for different reasons. First, ionizing radiation in young children may have potential late adverse effects.\(^\text{8–10}\) Second, the lack of findings on CR does not rule out the diagnosis if there is a strong suspicion of pneumonia.\(^\text{3}\) Finally, although a chest computed tomography (CT) scan has a higher level of diagnostic accuracy than CR, it is almost never used for the diagnosis of pneumonia because of higher ionizing radiation exposure, difficulty in patient cooperation, frequent need for sedation, and cost.\(^\text{11}\) Other disadvantages of both techniques as a tool for the diagnosis of pneumonia, especially in resource-poor settings, include availability and lack of portability. Even when CR is available, there may be a considerable time delay between the time when a CR is ordered and a final reading is available.

There has been recent interest in developing new tools aimed at increasing the feasibility and accuracy of pneumonia diagnosis while simultaneously decreasing exposure to ionizing radiation. Advances in ultrasound technology have made lung ultrasound (LUS) an attractive option for the diagnosis of pneumonia. Moreover, ultrasound is safe, portable, inexpensive, and relatively easy to teach. Our group recently published a meta-analysis supporting the use of LUS for the diagnosis of pneumonia in adults;\(^\text{12}\) however, evidence for the use of LUS in children is limited. In this article, we summarized information available on the diagnostic accuracy of LUS for the diagnosis of childhood pneumonia.

**METHODS**

**Search Strategy**

Two information specialists from Welch Medical Library developed and conducted the search strategy after input from clinical investigators in the research team. A systematic literature search was applied to PubMed (1946 to present). The search was adapted for Embase (1974 to present), the Cochrane Library (1898 to present), Scopus (1966 to present), Global Health (1973 to present), World Health Organization Global Health Regional Libraries (1980 to present), and Latin American and Caribbean Health Sciences Literature (1980 to present). We used a combination of controlled vocabulary and key words for age (<18 years), pneumonia, and ultrasound (see the Supplemental Information). We did not limit our search to studies based on publication dates or language. We did not seek to identify research abstracts from meeting proceedings or unpublished studies because these are not commonly subjected to exhaustive peer review. Results of the search were then reviewed by the research team. We also provided the 2 information specialists with 3 studies\(^\text{13–15}\) as a test set to check the completeness of the search results. All titles and abstracts relevant to our study were retrieved and searched for full texts. References from included studies and review articles were hand-searched to identify any additional relevant studies for analysis. The literature search and data analysis were performed in July 2014.

**Study Eligibility**

We pursued all studies with the following inclusion criteria: children with clinical suspicion (signs and symptoms) of pneumonia and/or confirmation with CR or chest CT scan. The evaluation of pneumonia was based on a combination of clinical data, laboratory results, and chest imaging by CR or chest CT scan. We included all relevant neonatal studies. We excluded studies that enrolled adults (ie, participants ≥18 years of age). Two investigators (M.A.P. and M.A.C.) independently evaluated all relevant studies for eligibility criteria. Data obtained (by M.A.P. and M.A.C.) from these studies were then compared. We defined a priori that disagreements would be resolved via consensus between 3 members of the study team (M.A.P., M.A.C., and W.C.).

**Data Extraction**

The following data were extracted from each study: sample size, gender proportion, mean age, LUS technique, areas of the chest that were evaluated, time lapse between CR and LUS, average time to perform LUS, operator expertise, blinding, LUS pattern definitions, and number of true-positives, true-negatives, false-positives, and false-negatives. We also contacted the author of one of the selected articles to obtain missing information for our data analysis. Furthermore, we contacted the authors of some of the selected studies\(^\text{13,15,16}\) to gather additional information that was relevant to our analysis.

**Methodologic Quality Assessment**

Methodologic quality was assessed by using the QUADAS-2 (Quality Assessment of Diagnostic Accuracy...
Studies 2) criterion. Both reviewers (M.A.P. and M.A.C.) scored the 7-item tool independently and disagreements were resolved by consensus (between M.A.P., M.A.C., and W.C.) via a face-to-face discussion about each disagreement.

**Biostatistical Methods**

The primary objective was to estimate pooled measurements of diagnostic accuracy: pooled sensitivity and specificity with the use of the Mantel-Haenszel method and pooled positive and negative likelihood ratios (LRs) by using the DerSimonian-Laird method. We also calculated an overall area under the receiver operating characteristic curve. Heterogeneity was assessed by using the Cochran Q-statistic and the inconsistency (I²) test. An I² > 20% was considered as indicative of significant variation. Subgroup sensitivity analyses were also conducted by reference standard, acute care setting, age of child, and level of expertise in sonography to determine the robustness of findings. We used MetaDiSc 1.4 (Unit of Clinical Biostatistics team, Ramón y Cajal Hospital, Madrid, Spain; www.hrc.es/investigacion/metadisc_en.htm) and R (R Foundation, www.r-project.org) for statistical analyses.

**RESULTS**

**Overview of Literature Search**

Our search strategy identified 1475 studies of which we selected 15 (1%) for further evaluation on the basis of inclusion criteria and content (Fig 1). We excluded 3 review articles, 1 study in adults, and 3 studies that did not fit our methodologic criteria. We selected 8 studies for analysis, of which 6 (75%) were conducted in the general pediatric population and 2 (25%) were conducted in neonates, 28 days of age. Three studies were conducted in emergency departments, 2 in hospital wards, 1 in the pediatric intensive care unit, and 2 in the neonatal intensive care unit.
Characteristics of Selected Studies

In Table 1, we show the main characteristics of eligible studies. Overall, there were 765 children across the 8 studies. The mean age was 5 years (range: 0–17 years) and 52% were boys. One study (12%) was conducted in multiple centers and the remaining were single-center studies (88%). Seven studies (88%) were blinded to outcomes of CR before LUS performance and interpretation.13–16,21–23 Five studies were conducted in Italy,13,14,16,21,23 1 in China,22 1 in the United States,15 and 1 in Egypt.24 Only 3 studies (38%) followed the disease course until the consolidation was resolved.15,16,22 Two studies (25%) enrolled patients with suspected neonatal pneumonia and severe disease,22,24 and 6 studies (75%) enrolled children with suspected community-acquired pneumonia,13–16,21,23 One study15 enrolled 9 children aged ≥18 years, and the information on these participants was not included in our analysis.

Five studies (63%) reported that a highly skilled physician performed LUS,16,21–24 but only 1 (12%) of the studies adequately mentioned that their physicians had performed at least 100 procedures.21 One study (12%) used 15 physicians with different degrees of expertise.15 Two studies (25%) trained physicians to perform the procedure.14,15 One study14 (12%) trained a pediatric resident with limited experience and explained that the training approach consisted of a 3-hour lecture on LUS and 4 hours of practical, hands-on training. LUS was performed by an emergency physician in 1 study.13

Methodologic Heterogeneity

The quality of most of the studies included in this meta-analysis was high (Table 2). Seven studies (88%) enrolled patients who would have had a CR as part of usual clinical practice.13–16,21,23,24 Only 1 (12%) study included controls who did not have CRs.22 All studies described their selection criteria with sufficient detail and conducted LUS immediately after chest imaging was obtained. One (12%) study used the same radiologist to read both the CR and LUS.24 Seven (88%) studies assessed LUS results independently and were blinded to CR results.13–16,21–23 LUS techniques were described in sufficient detail in each of these studies. LUS sonographers were not blinded to clinical data. Furthermore, 5 (63%) studies used clinical criteria and CR as a diagnosis standard13,21–24 and 3 included laboratory results as additional diagnostic tools21,22,24 (Table 3). Chest CT scan was not used as a gold standard in any of the studies; however, 3 studies (38%) used chest CT scan for clinical purposes.13,21,24 In 1 (13%) study, chest CT scan was used to confirm the diagnosis of pneumonia in 4 children who had discrepancies between the CR and LUS results.13 In these 4 children, CR did not reveal evidence of pneumonia, whereas LUS and chest CT findings were both consistent with a diagnosis of pneumonia.

All of the studies used a linear probe (Table 4), with frequencies ranging from 6 to 12 MHz.13–16,21–24 In addition, a convex probe with frequencies ranging from 2 to 6.6 MHz was used in conjunction with the linear probe in 3 of the 8 studies.13,14,16 LUS methods were consistent between 5 of the studies that used the approach described by Copetti and Cattarossi in 2008.13–15,21,23 Two studies mentioned the length of time to perform LUS and noted the examination took a maximum of 10 minutes.15,21

Overall Meta-analysis

The overall pooled sensitivity and specificity (Fig 2) for the diagnosis of pneumonia were 96% (95% confidence interval [CI]: 94%–97%) and 93% (95% CI: 90%–95.7%), respectively. Positive and negative LRs (Fig 2) were 15.3 (95% CI: 6.6–35.3; Cochran Q-statistic = 14.6; \( P = .04 \)) and 0.06 (95% CI: 0.03–0.11; Cochran Q-statistic = 14.3; \( P = .05 \)), respectively. All \( I^2 \) values were >.45. The area under the receiver operating characteristic curve was 0.98 (95% CI: 0.96–1; Fig 3).

Subgroup Analyses

All 8 studies used CR as a diagnostic tool for pneumonia; however, 5 studies used both CR and clinical criteria as

### TABLE 2 QUADAS-2 Risk of Bias Assessment

<table>
<thead>
<tr>
<th>Study</th>
<th>Risk of Bias</th>
<th>Applicability Concerns</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Patient Selection</td>
<td>Index Test</td>
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<tr>
<td>Reali et al16,21</td>
<td>L</td>
<td>L</td>
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<tr>
<td>Liu et al22</td>
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<td>Esposito et al14</td>
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<td>Shah et al15</td>
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<td>Caiulo et al23</td>
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<td>Seif El Dien et al24</td>
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<tr>
<td>Iuri et al16</td>
<td>L</td>
<td>L</td>
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<tr>
<td>Copetti and Cattarossi15</td>
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QUADAS-2, Quality Assessment of Diagnostic Accuracy Studies 2. L, low; H, high; U, unclear.
the reference standard to identify pneumonia,13,21–24 whereas 3 studies used CR alone as the reference standard.14–16 In subgroup analysis, we estimated the sensitivity and specificity only using the CR results in all 8 studies as a reference standard and found that LUS had a sensitivity of 96% (94%–98%) and a specificity of 84% (80%–88%) for the diagnosis of pneumonia. In the 6 studies (75%) that enrolled children excluding neonates,13–16,21,23 LUS had a sensitivity of 96% (93%–98%) and a specificity of 92% (88%–95%); and in the 2 studies that were limited to only neonates, LUS had a sensitivity of 96% (90%–98.5%) and a specificity of 100% (92%–100%).22,24 Three studies were conducted in emergency departments and had a combined sensitivity of 94% (88%–98%) and specificity of 90% (85%–94%).13,15,16 Studies conducted in hospital settings other than in an emergency department had a combined sensitivity of 96% (94%–98%) and a specificity of 97% (93%–99%).14,21–24 In the 4 studies that reported having an experienced physician or radiologist perform LUS, we found a sensitivity of 97% (93%–99%) and a specificity of 99% (94%–100%).16,22,24 In studies that used emergency department physicians, general practitioners, residents, or health care professionals otherwise not specified, LUS had a pooled sensitivity of 95% (95% CI: 91%–97%) and a specificity of 91% (87%–95%).13–15,21

**DISCUSSION**

In our meta-analysis comparing the use of LUS against a reference standard for the diagnosis of childhood pneumonia, we found overall high sensitivity and specificity. In subgroup analysis13–16,21–24 when the reference standard was limited to findings based on CR alone, we
found that the sensitivity of LUS was similar to that when both clinical criteria and CR were used to define childhood pneumonia, but specificity decreased to 84%, likely reflecting that CR alone is inadequate for the diagnosis of pneumonia. Nonetheless, both of these results suggest that LUS appears to be a reliable imaging alternative in children who present with suspected pneumonia. Findings from another meta-analysis\textsuperscript{25} that included both adults and children found a similar degree of pooled diagnostic accuracy (sensitivity of 97% and specificity of 94%). However, the inclusion of

<table>
<thead>
<tr>
<th>Study</th>
<th>Ultrasound</th>
<th>Time of Procedure</th>
<th>Area Examined</th>
</tr>
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<tbody>
<tr>
<td>Reali et al\textsuperscript{21}</td>
<td>Esaote MyLab 25 (Esaote Medical Systems, Florence, Italy); linear probe 7.5–10 MHz</td>
<td>Mean of 10 min</td>
<td>Anterior, lateral, and posterior; longitudinal, oblique, and parallel scans</td>
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<tr>
<td>Liu et al\textsuperscript{22}</td>
<td>GE Voluson E8/6 (General Electric Healthcare, Little Chalfont, United Kingdom); linear probe 9–12 MHz</td>
<td>Not mentioned</td>
<td>Chest divided in 3 areas by anterior and posterior axillary lines; parallel to rib scans</td>
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<td>Esposito et al\textsuperscript{14}</td>
<td>Esaote MyLab 25 Gold (Esaote Medical Systems, Florence, Italy); linear probe 7.5–12 MHz and convex probe 2.5–6 MHz</td>
<td>Not mentioned</td>
<td>Anterior, lateral, and posterior; perpendicular, oblique, and parallel scans</td>
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<tr>
<td>Shah et al\textsuperscript{15}</td>
<td>Sonosite Micromaxx (Sonosite, Bothell, USA), Sonosite, and Siemens GS60 (Siemens Healthcare, Malvern, USA); linear probe 7.5–10 MHz</td>
<td>7 ± 2 min</td>
<td>6-zone lung ultrasound imaging protocol similar to Copetti and Cattarossi\textsuperscript{13}</td>
</tr>
<tr>
<td>Caiulo et al\textsuperscript{25}</td>
<td>Toshiba Nemio (Toshiba Medical Systems Corp., Tochigi, Japan); KONTRON Meical Agile (KONTRON Medical, Saint Germaine en Laye Cedex, France); linear probe 6–12 MHz</td>
<td>Not mentioned</td>
<td>Anterior, lateral, and posterior; longitudinal, oblique, and parallel scans; similar to Copetti and Cattarossi\textsuperscript{13}</td>
</tr>
<tr>
<td>Seif El Dien et al\textsuperscript{24}</td>
<td>Toshiba Nemo XG SSA-580A (Toshiba Medical Systems Corp., Tochigi, Japan); linear probe 7 MHz</td>
<td>Not mentioned</td>
<td>Lung regions that were explored by auscultation; transverse, longitudinal, and inclined transverse or inclined longitudinal</td>
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<tr>
<td>Iuri et al\textsuperscript{16}</td>
<td>Philips ATL HDI 5000 (Philips Ultrasound, Bothell, USA); linear probe 5–12 MHz and convex probe 2–5 MHz</td>
<td>Not mentioned</td>
<td>Entire anterior and posterior chest wall; longitudinal and axial scans</td>
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<tr>
<td>Copetti and Cattarossi\textsuperscript{13}</td>
<td>Esaote Megas CVX (Esaote Medical Systems, Florence, Italy); linear probe 7.5–10 MHz and convex probe 3.5–5 MHz</td>
<td>Not mentioned</td>
<td>Anterior, lateral, and posterior; perpendicular, oblique, and parallel scans</td>
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FIGURE 2

Forest plots showing the diagnostic accuracy of lung ultrasound for the diagnosis of pneumonia. A, sensitivity; B, specificity; C, negative likelihood ratio (LR); and D, positive LR. Inconsistency ($I^2$) describes the percentage of total variation across studies due to heterogeneity.
...size, 26 as mentioned previously, and offset by the relative small lung may explain the relative high pleura and be within an intercostal a consolidation needs to reach the To identify pneumonia by LUS, standards in both diagnosis and population, necessitating different from that seen in the adult disease found in children may differ Similarly, the spectrum of adults, 12 we found a slightly lower sensitivity and speci...values of body habitus and thorax thorax size; however, the range in ...no expert trained physicians. In the study conducted by Esposito et al, 14 a pediatric resident with only 7 hours of training in LUS obtained a high sensitivity (98%) and specificity (95%). Also, Bedetti et al 31 demonstrated that beginners were able to detect pulmonary interstitial syndrome after 30 minutes of training. And the International Liaison Committee on Lung Ultrasound considered LUS as a basic sonographic technique that is easy to learn. 32 Nevertheless, more studies are needed to validate the accuracy of LUS in novice users and to outline the training necessary to obtain satisfactory results. There are some limitations to our analysis. First, most studies included in our analysis did not have large numbers of children. In addition, the total number of studies was also small and there was significant heterogeneity between studies. Second, not all studies compared LUS results with a clinical diagnosis and, in some studies, the final diagnosis was based solely on CR findings without the influence of clinical data, 14–16 thus likely contributing to the heterogeneity of results reported in our study. Most studies excluded children who had a history of congenital heart...
used a nonstandard technique to perform LUS, which may help explain the heterogeneity in our analyses. Most of the studies were performed in a single center, and most of the studies were conducted in settings in high-income countries or with adequate resources. Despite all of these limitations, this meta-analysis included 765 participants and found useful results that provide evidence for the importance of future cost-benefit analysis with the utilization of this diagnostic technique and support for potential training programs geared to teach physicians this diagnostic tool. Furthermore, these results could have an even more powerful impact on intervention trials in poor-resource settings. The only diagnostic guideline in place in such settings is the World Health Organization case management algorithm for pneumonia. If LUS technology can provide improved diagnostic capacity in areas where CR technology is difficult to implement, there is potential for increased diagnostic accuracy and decreased inappropriate use of antibiotics.

**CONCLUSIONS**

Despite significant heterogeneity across studies, LUS performed well for the diagnosis of pneumonia in children. Although the sensitivity and specificity are best in the hands of expert users, our study provides evidence of good diagnostic accuracy even in the hands of nonexperts. Recommendations to train general pediatricians on LUS for the diagnosis of childhood pneumonia may have an important impact in different clinical settings, especially in resource-poor countries and small primary care clinics where CRs may not be commonly available.

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**POTENTIAL CONFLICT OF INTEREST:** The authors have indicated they have no potential conflicts of interest to disclose.

**REFERENCES**


**BAGGING THE PEAKS:** The other day I was interviewed for a local news broadcast. While waiting for the cameraperson to get adjusted, the reporter asked me about a picture of a local mountain I had on my office wall. I told her it was a favorite hike of mine. She then asked if I was a “46er,” which is the local term for someone who has climbed the 46 high peaks of the Adirondacks. All of these 46 peaks are higher than 4,000 feet. If you climb them all you are entitled to a special patch. While hikers west of the Mississippi might not consider a 4,000 foot mountain much of a mountain at all, compared to many states that lack high terrain, hiking a four thousand foot peak would be quite an accomplishment.

As reported on CNN (Travel: January 16, 2015), many hikers like to “bag” the highest peak in every state. In some, this can be done in a few minutes without breaking a sweat. For example, in Delaware the highest point is Ebright Azimuth, at 442 feet above sea level. A sign beside a road in suburban Wilmington, Delaware marks the spot. The summit of Britton Hill, the state of Florida’s highest point, is 345 feet above sea level. True peak baggers, those committed to climbing the highest peak in each state, can knock this off in just a few minutes compared to the weeks of preparation it takes to plan and hike Alaska’s 20,237 foot-tall Mount Denali (aka Mount McKinley), the highest peak in North America. While I am intrigued by the thought of climbing the tallest peak in each state, I think I will stay more local. I told the reporter that I was not yet a 46er, but I had plans to be one soon.

*Noted by WVR, MD*
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