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Digital stethoscope use by non-physician primary care health workers on children under five years of age in rural Bangladesh: a feasibility study

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Abstract

Lung auscultation is not included in the WHO Integrated Management of Childhood Illness algorithm, partly due to concerns regarding feasibility and reliability when performed by non-physician primary health workers in low-resource settings. In this feasibility study, we evaluated whether non-physician primary care health workers (community health care providers (CHCPs)) can record quality lung sounds from children aged 2-59 months.

Feasibility was predefined as more than 50% of children having quality recordings at the overall sample level. After receiving three days of structured training, nine CHCPs recorded lung sounds from four chest positions using a digital stethoscope (Sonavi Labs, United States) in 990 children attending first-level rural clinics in Bangladesh between November 2019 and December 2020, with enrolment paused during the COVID-19 pandemic. A blinded paediatrician listening panel, trained to a standardised interpretation protocol, classified the recordings. A quality recording was defined a priori as the panel classifying three of four chest positions on a participant as interpretable. Lung sounds were recorded from 990 children, and the panel classified 867 children as having a quality recording (87.6%; 95% confidence interval: 85.4%, 89.6%). Among children with quality recordings and available timing data, 89.8% (766/853) were recorded within five minutes. This study demonstrates CHCPs at rural, first-level clinics in Bangladesh are capable of timely, quality recordings of lung sounds from most children using a digital stethoscope.

Keywords: Preschool Child, Infant, Pneumonia, Stethoscopes, Digital Auscultation, Community Health Workers, Developing Countries

Introduction

Although there has been a significant decline in the incidence, morbidity, and mortality of pneumonia over recent years¹, it remains a leading cause of death in children under-5-years-of-age globally². The World Health Organisation's (WHO) South-East Asia and African Regions contribute more

than 75% of pneumonia-related deaths in this age group³. Bangladesh remains among the high-burden countries, where pneumonia continues to be the leading cause of child mortality, accounting for approximately 24% of deaths among children under five years of age⁴.

The WHO and United Nations Children's Fund (UNICEF) developed the Integrated Management of Childhood Illness (IMCI) strategy to guide pneumonia diagnosis and treatment in low- and middle-income countries (LMICs). IMCI relies on simple clinical signs, most notably age-specific fast breathing and chest indrawing, to identify and manage pneumonia⁵. The IMCI approach supports non-physician healthcare workers in delivering primary healthcare services from frontline clinics, including pneumonia treatment, in community settings⁶.

While the IMCI algorithm is highly sensitive, and ensures that children with possible pneumonia are identified, its low specificity indicates that a large proportion of children without true pneumonia are classified as needing antibiotics. Studies evaluating the clinical signs used in IMCI similarly show high sensitivity but limited specificity; for example, age-specific fast breathing demonstrated a sensitivity of approximately 92% and a specificity of 22%, while lower chest indrawing showed a sensitivity of 74% and a specificity of 15% for radiographic pneumonia in children under five⁷. This low specificity results in avoidable treatment, increased costs for families and health systems, and added pressure on antibiotic resistance⁸⁻¹⁰. In Bangladesh, inappropriate antibiotic prescribing for childhood respiratory

illness has been documented, underscoring the importance of improving diagnostic specificity^{11,12}.

Lung auscultation is not included in the IMCI pneumonia classification algorithm⁵. This exclusion reflects well-recognised challenges, particularly in LMIC settings, including limited auscultation training among non-physician providers, subjectivity in lung sound interpretation, and high inter-observer variability when using conventional analogue stethoscopes¹³⁻¹⁵. These constraints have limited the feasibility and reliability of auscultation as a routine diagnostic tool in community-based primary care.

Digital stethoscopes represent a technological development that enables electronic recording and storage of lung sounds, allowing for subsequent review and potential standardisation of auscultation findings^{16,17}. Such devices may help support non-physician health workers by facilitating reproducible lung sound recording in busy primary care environments¹⁸. Conceptually, incorporating lung sound recording into primary care assessments may offer a pathway toward improved pneumonia classification by supplementing existing IMCI clinical signs, with the potential to reduce diagnostic uncertainty and unnecessary antibiotic use; however, this remains a hypothesis that requires validation through diagnostic accuracy and clinical outcome studies. Before such approaches can be evaluated for clinical effectiveness, it is essential to establish their operational feasibility in real-world settings.

Despite growing interest in digital auscultation and artificial intelligence (AI)-supported diagnostics, there remains limited evidence on its feasibility when used by non-physician primary care health workers on young children in resource-constrained settings¹⁶. Existing studies have largely focused on device development or hospital-based applications and have not adequately addressed real-world implementation challenges. In particular, there is a lack of evidence on whether non-physician primary healthcare workers can reliably collect lung sound recordings under routine service conditions.

Given the critical role of these workers in community-based healthcare delivery, we aimed to evaluate the operational feasibility of non-physician health workers recording lung sounds with a digital stethoscope on children attending primary care community clinics in Bangladesh. The primary outcome was the proportion of children's lung sound recordings that were of sufficient quality to be interpretable upon expert review. The secondary outcome was the time required for successful completion of recording procedures. We hypothesised that digital lung sound recording by non-physician health workers would be feasible, defined a priori as more than 50% of patients having 'quality' lung sound recordings. 'Quality' was defined as at least 75% interpretable lung sound segments per patient (i.e., 3 out of 4 chest positions). This study focuses on feasibility as a prerequisite for future implementation and diagnostic studies.

Materials and methods

Study design, area and period

This was an operational feasibility study conducted in nine rural primary care clinics called community clinics (CCs) in Zakiganj sub-district of Sylhet in Bangladesh between November 2019 and December 2020. Enrolment was suspended between April and August 2020 due to the COVID-19 pandemic. Bangladesh has established about 13,000 CCs, roughly translating to one CC per 6,000 population¹⁹. Each CC is staffed by a non-physician health worker called a community health care provider (CHCP) with at least a 12th grade education and three months of preservice training, including the IMCI algorithm. We purposively selected nine out of 24 CCs in Zakiganj sub-district of Sylhet district in Bangladesh, based on patient volume, specifically focusing on those that provided care to the highest number of under-5-year-old children in the year preceding the study and had consistent staffing and functional infrastructure to support study procedures. This approach was intended to maximise exposure to eligible children and operational learning. The selected CHCPs received a three-day training that included child assessment according to IMCI guidelines, identification of respiratory danger signs (head nodding, tracheal tugging, nasal flaring, grunting, intercostal retractions, stridor when calm), pulse oximetry, anthropometric measurements (weight, height/length, mid-upper arm circumference), use of a digital stethoscope, transfer of recorded sound files, completion of case record forms, and obtaining consent. Following training, CHCPs completed supervised practice sessions and were required to demonstrate correct performance of key procedures (IMCI assessment steps, pulse oximetry,

anthropometry, and lung sound recording and file transfer) before initiating study activities; however, no formal competency scoring was conducted. Competency was assessed qualitatively through supervised practice sessions. Further details on the study design and setting have been described elsewhere²⁰.

Study population

Children aged 2-59 months presenting to the selected CCs with a respiratory illness characterised by cough and/or difficulty breathing were eligible for enrolment in the study. Children were excluded if they showed any IMCI-defined clinical danger signs (inability to drink or breastfeed, persistent vomiting, convulsions, lethargic or unconscious, stridor in a calm child), assessed according to the IMCI 2014 chart booklet⁵. Children with hypoxemia (low blood oxygen levels defined by a peripheral oxyhaemoglobin saturation (SpO_2) <90%) measured using a Masimo Rad-5 pulse oximeter, were also excluded. Additional exclusion criteria were prior enrolment in this study within the past 30 days: non-residency within the CC catchment area, as reported by the caregiver at registration; or lack of parental consent.

Sample size calculation

This feasibility study was nested within a larger diagnostic accuracy study evaluating an AI algorithm for identifying adventitious lung sounds from recordings collected by CHCPs among children, compared with a paediatrician reference listening panel²⁰. The sample size for the parent study was calculated a priori. A total of 990 children were enrolled and

included in this feasibility analysis. For the feasibility component, a minimum sample size of 384 participants was required to estimate the proportion of successful lung sound recordings by CHCPs, assuming a success rate of 50%, with an absolute precision of $\pm 5\%$ at 95% confidence level. However, a total of 990 children were included in the analysis, thereby increasing the precision and strength of the feasibility estimates.

Study procedure

After obtaining informed consent, CHCPs examined the child for fast breathing by manually counting the respiratory rate over one minute and observing for lower chest wall indrawing (bilateral inward pulling of the lower ribs and subcostal tissue during inspiration). Lung sounds were recorded using a digital stethoscope (Sonavi Labs, United States)²¹ from four chest locations sequentially – left and right back, left and right front – for 10 seconds in each position, allowing for the recording of 3-4 breath cycles per position. This recording duration was selected to balance sound capture with child cooperation in routine primary care settings. The stethoscope was used with manufacturer-default settings, and no additional calibration or firmware modification was performed during the study period. CHCPs also measured the SpO₂ using a pulse oximeter (Masimo Rad5, United States) with a paediatric clip probe while the child breathed in room air, temperature with a calibrated digital thermometer, and anthropometry (weight, height/length and mid-upper arm circumference) using standard tools and techniques following national guidelines. Immunization status was assessed primarily by

reviewing the child's immunization card; when the card was unavailable, caregiver report was used. Children were examined while either sitting upright or being held by a caregiver, depending on age and cooperation. Background noise was not formally measured; recordings were obtained during routine clinic hours, reflecting real-world primary care conditions. Periodic quality control checks for all measurements were conducted by a physician to ensure measurement accuracy and consistency.

A listening panel of five paediatricians were trained and standardised in listening and classifying recordings to identify adventitial lung sounds. Training consisted of guided listening sessions using reference lung sound recordings from Pneumonia Etiology Research for Child Health (PERCH) study with consensus expert labels^{17,22} to familiarise panellists with wheeze and crackles and to harmonise classification criteria. Each child's lung sound files were randomly sent to any two panel members. These panel members were blinded to all participants clinical information, including pneumonia classification, IMCI findings, and other panel interpretations. They independently listened to the recordings using high quality headsets (Sennheiser HD 599 SE) while simultaneously viewing the sound spectrograms in Audacity (Version 2.3.1 and 2.3.2; <https://www.audacityteam.org/>). Panellists entered their classification either normal (no wheeze and no crackles), only wheeze, only crackles, both wheeze and crackles, or uninterpretable into an online electronic platform. They could listen to the recordings with the freedom to stop or repeat parts

or the entire recording, if necessary. Panellists were not allowed to discuss recordings or resolve disagreements through consensus discussions. Each child's summary classification across all chest locations by two panel members was compared. If the two reviewers agreed that classification was accepted. If disagreement occurred, a senior member of the study team (EDM), also masked to participant information and other recording interpretations, reviewed the recordings independently and assigned a final classification, which was considered definitive. Inter-rater reliability statistics between the primary listeners were performed. No AI-based analysis was used in this study.

Study outcomes

Primary outcome: A "quality recording" was defined as a recording in which at least 75% of pre-defined chest position segments per child were interpretable, corresponding to a minimum of three out of four anterior and posterior chest positions being judged interpretable by the listening panel.

Secondary outcome: Time required to complete lung sound recordings.

Study definitions

Pneumonia: The presence of cough and/or difficulty breathing, along with fast breathing for age (respiratory rate ≥ 50 breaths/minute for 2 to <12 month olds, ≥ 40 breaths/minute for 12 to 59 month olds) and/or lower chest wall indrawing, and the absence of any IMCI-defined clinical danger signs, severe malnutrition, or hypoxemia⁵.

No pneumonia: The presence of cough and/or difficulty breathing but

without fast breathing for age and without lower chest wall indrawing, and without any IMCI-defined clinical danger signs, severe malnutrition, and hypoxemia.

Statistical analysis

Descriptive statistics were used to summarise the characteristics of the children, including age, sex, nutritional and immunisation status, and clinical signs of pneumonia. Lung sound recording details, including interpretability in ≥ 3 chest positions and across different chest positions, were also described. The distribution of sound files, including the number recorded, transferred to the laptop, and classified as interpretable, was presented. Feasibility was assessed at the overall study population level, defined as $>50\%$ of enrolled children having quality recordings. The predefined feasibility threshold of $>50\%$ quality recordings was selected as a pragmatic and exploratory benchmark to reflect minimum operational viability in routine primary care settings, rather than a validated standard. All analyses were reported as frequencies and percentages, along with exact binomial confidence intervals (CIs). The time required to record quality lung sounds was documented. Children were categorised into pneumonia and no pneumonia, and all analyses were stratified accordingly. Missing data were not imputed. Associations between categorical variables were assessed using the chi-square test or Fisher's exact test, as appropriate. Two sample tests of proportions were used to compare differences between proportions. To examine the association between chest position and interpretability of

collected sound files while accounting for clustering, a mixed-effects logistic regression model was fitted. The model included a random intercept for each child to account for repeated measurements (multiple recordings per child) and a random intercept for each CHCP to account for clustering of children within CHCP. Adjusted odds ratios (ORs) with 95% confidence intervals were reported. To provide marginal estimates, predicted probabilities of interpretability for each chest position were obtained from the fitted model using post-estimation. These estimates account for the hierarchical structure of the data and provide adjusted probabilities that are directly interpretable. To evaluate the relationship between CHCP enrolment volume and the probability of successfully obtaining interpretable lung sound recordings (≥ 3 chest positions), mixed-effects logistic regression models with random intercepts for CHCP were fitted. Additional predictors were not included in multivariable models due to low event frequency in certain categories and concerns regarding model stability and potential overfitting. Predicted probabilities were obtained from the model and presented graphically. Inter-rater reliability between the two primary listeners for classification of lung sounds (interpretable vs. uninterpretable) was assessed using Cohen's Kappa and prevalence-adjusted bias-adjusted Kappa (PABAK), with corresponding 95% confidence intervals. Data analysis was performed using Stata (Version 18.0; StataCorp, College Station, TX, USA; <https://www.stata.com/>), and R (Version 4.4.1; R Core Team; <https://www.r-project.org/>) with statistical significance set at a p-value of <0.05 .

Ethical approval and consent to participate

We obtained ethical approval for this study from the National Research Ethics Committee of Bangladesh Medical Research Council, Bangladesh (Registration Number: 09630012018), and Academic and Clinical Central Office for Research and Development Medical Research Ethics Committee, NHS, Lothian, Edinburgh, UK (REC Reference: 18-HV-051). Written informed consent was obtained from parents or legal guardians of the children. All data, including lung sound recordings, were stored on password-protected systems with restricted access. Personal identifiers were removed prior to analysis to ensure participant confidentiality. All methods were performed in accordance with the relevant guidelines and regulations, including the Declaration of Helsinki.

Results

Figure 1 presents the Standards for Reporting of Diagnostic Accuracy Studies (STARD) flow diagram. Out of 2,434 children screened, 1,046 (42.9%) were eligible for the study. Of these 1,046 children, 56 (5.3%) children's carers declined enrolment, most commonly due to time constraints or reluctance to participate in additional procedures, leaving a total of 990 children enrolled. Among these 990 children, 389 (39.3%) were classified as having pneumonia. Of the 389 children with pneumonia, lung sounds from any chest position were recorded in 385 (99.0%) children. Similarly, among the 601 children without pneumonia, lung sounds were recorded in 595 (99.0%) children from any chest position (Figure 1). Lung

sound files in 381 (97.9%, 381/389) children in the pneumonia group and 593 (98.7%, 593/601) children in the no pneumonia group, were successfully transferred from the digital stethoscope to a secure study laptop. Lung sounds from ≥ 3 chest positions were transferred to the laptop in 378 (98.2%, 378/385) children in the pneumonia group and 588 (98.8%, 588/595) in the no pneumonia group.

Children's characteristics

Table 1 shows the characteristics of children in the pneumonia and no pneumonia groups. The majority of children were 12 months or older (74.7%, 740/990). The male-to-female ratio among enrolled children was 1:0.8. The proportion of children fully immunised for age was 83.7% (829/990), while 86.2% (853/990) of children had received age-appropriate PCV vaccination.

Clinical features

The CHCPs identified fast breathing for age, lower chest wall indrawing and any respiratory danger signs in 37.6% (372/990), 2.5% (25/990) and 4.7% (47/990) of children, respectively (**Table 2**).

Lung sound recordings

Table 3 presents the distribution of lung sound recordings by the number of chest positions, as well as the number of quality recordings identified by the listening panel. CHCPs recorded lung sounds from ≥ 3 chest positions in 98.3% ((973/990); 95% CI: 97.3%, 99.0%) of children. There was no statistically significant difference in the percentage of children with ≥ 3 chest position recordings between the pneumonia and the no pneumonia groups

($p=0.73$). However, recording quality varied by age group, with children under 12 months having a lower proportion of ≥ 3 interpretable chest position recordings (82.0%) compared with older children (89.5%) ($p < 0.001$), likely reflecting greater movement and reduced cooperation in younger infants (**Supplementary table 1**).

Quality recordings (≥ 3 chest position recordings of a child were interpretable)

Overall, the listening panel assessed 87.6% ((867/990); 95% CI: 85.4%, 89.6%) of children to have quality recordings (**Table 3**), though this proportion varied by CHCP, ranging from 73.1% (19/26) to 94.7% (177/187) (**Supplementary table 2**). The mixed-effects logistic regression model, with a random intercept for each CHCP to account for clustering of children within CHCPs, indicated a positive association between the number of quality recordings and enrolments per CHCP (OR 1.008; 95% CI: 1.004, 1.013, $p < 0.001$). (**Supplementary figure 1 and supplementary table 4**). **Table 4** shows the number of chest positions recorded, deemed interpretable by chest positions, and the association between chest position and interpretability. To examine the association, a mixed-effects logistic regression model was fitted, accounting for clustering of children within CHCPs, and repeated measurements per child. There was little variation in successfully recorded lung sounds by chest position, although the success rate was significantly higher for both back positions (left and right back) compared to both front positions (left and right front) (92.0% (1782/1938) vs 87.9% (1690/1923); OR 0.31, 95% CI: 0.22–0.45;

$p < 0.01$). All mixed-effects models accounted for clustering at both the child level (multiple recordings per child) and the CHCP level.

Lung sound classification

Among quality recordings, **Table 5** shows the distribution of lung sounds classified by the listening panel. Adventitious lung sounds were identified more frequently in the pneumonia group than in the no pneumonia group (36.7% (126/343) pneumonia, 27.9% (146/524) no pneumonia, $p = 0.01$). Thus, in the pneumonia group, 63.3% (217/343) of children had normal lung sounds according to the listening panel. Although the frequency for only wheeze, only crackles, and both wheeze and crackles was higher in the pneumonia group than the no pneumonia group, these differences did not reach statistical significance.

Agreement of interpretable and uninterpretable lung sounds by two primary listening panel members

Agreement between the two primary listening panel members on the classification of lung sounds as interpretable or uninterpretable was very high, with an observed agreement of 96.6% (941/974). Most recordings were classified as interpretable by both listeners (928 cases), while disagreement was relatively rare (33 cases) (**Supplementary table 5**). Despite this high level of agreement, Cohen's Kappa indicated only moderate agreement ($\kappa = 0.42$; 95% CI: 0.26–0.58). This discrepancy is likely due to the highly imbalanced distribution of ratings, with the vast majority of recordings categorized as interpretable (97.1% by Listener 1 and 96.8% by Listener 2).

Such an imbalance inflates the expected agreement by chance, thereby reducing the Kappa statistic—a phenomenon commonly referred to as the “Kappa paradox.” To address this limitation, the prevalence-adjusted and bias-adjusted kappa (PABAK) was calculated. The PABAK value was 0.93 (95% CI: 0.90–0.95), indicating almost perfect agreement between the two listeners after accounting for the effects of prevalence and bias. Overall, these findings suggest that the two listeners demonstrated a very high level of consistency in classifying lung sounds.

Duration of quality recordings

The mean duration (SD) of quality lung sound recordings was 2.56 (2.58) minutes. CHCPs completed quality recordings in 56.6% (483/853) of children within one minute and in 89.8% (766/853) within five minutes (**Figure 2**). The recording time for participants with quality recordings ranged from 1 to 18 minutes. Recording durations exceeding five minutes were attributed to technical issues with the digital stethoscope.

Child cooperation during lung sound recordings

The proportion of cooperative and quiet children during lung sound recordings was high in both the pneumonia (81.6%, 314/385) and no pneumonia (78.7%, 468/595) groups ($p=0.27$) (**Table 6**).

Discussion

Based upon the high proportion of acutely ill children with both timely and quality recordings obtained, our study demonstrates non-physician health workers in Bangladesh called CHCPs can feasibly use a digital stethoscope to

record lung sounds from children presenting to care at rural primary care clinics, although performance varied across CHCPs. However, the feasibility threshold should be interpreted as an operational benchmark rather than a definitive or validated criterion for feasibility. Digital auscultation is a new technology for non-physician frontline health workers, such as CHCPs in Bangladesh, where conventional stethoscopes are not typically used in routine care. To the best of our knowledge, this is among the first studies to investigate the ability of frontline, community-based health workers to record lung sounds in first-level facilities in LMICs. Previous studies, such as the PERCH study, trained either nurses or physicians to record lung sounds in hospital settings with a digital stethoscope¹⁷. In PERCH, a listening panel classified 89.5% of 792 pneumonia cases and 92.4% of 301 controls as interpretable, which closely aligns with our findings; however, the PERCH paper defined interpretability as at least one out of eight chest positions was interpretable (12.5% of positions compared to 75% in our study)²². Our study extends these evidence rural primary care clinics and to CHCPs with no or limited prior experience in auscultation. CHCPs work in crowded and noisy environments and often face time pressure from a high-volume of patients, limiting the amount of time available to calm ill, often scared, and agitated children. Although we did not formally measure patient load or ambient noise, understanding whether quality lung sounds can be obtained under such conditions is critical when considering the feasibility of digital auscultation by frontline healthcare workers with minimal training.

In this study, a substantial proportion of children classified as having pneumonia under the IMCI algorithm exhibited normal lung sounds, a finding that warrants careful interpretation. This observation is consistent with the well-recognised diagnostic characteristics of IMCI, which prioritises high sensitivity to avoid missed cases at the expense of specificity, and may therefore classify children with fast breathing but without lower airway involvement as pneumonia⁵. Hazir et al. demonstrated that 82% of children with IMCI-defined pneumonia had normal chest radiographs²³. Importantly, IMCI classification in this study served as a clinical categorisation tool rather than a reference standard for lung sound abnormalities. As such, the absence of abnormal lung sounds among these children is more plausibly explained by clinical misclassification inherent to IMCI criteria than by limitations in recording quality or device performance.

In this study, CHCPs followed a sequential recording procedure refined from our prior methodology²², starting with two recordings on the back followed by two on the front, screening both upper and lower lung lobe fields of each hemithorax. CHCPs successfully recorded lung sounds in 97.6% of children, with no difference in the success rate between those with and without pneumonia. Importantly, CHCPs recorded lung sounds from only one or two chest positions in just seven children overall and failed to record any lung sounds from any of the chest positions in only ten children. These failures were primarily due to stethoscope malfunction or software errors during the sound file transfer from the stethoscope to the laptop. This finding suggests that,

with appropriate tools and training, lung sounds from under-five-years-old children can often be recorded at first-level facilities, although device reliability remains a key determinant of feasibility.

Our overall hypothesis for this analysis was that if CHCPs could record lung sounds from three or four chest positions, and if at least three of these recordings were deemed interpretable by the paediatric listening panel, the overall process would meet a minimum quality threshold. The rationale for this threshold is that such recordings would capture sounds from at least three of the five major lobes and from both hemithoraces. Typically, in children younger than five years, inflammation from pneumonia is present in multiple lobes of the lung, and so these criteria would balance feasibility with identifying most pneumonia cases. In this study, 87.6% of children had quality recordings according to the listening panel, identifying the presence of only wheeze, only crackles, both, or neither, with no significant difference in the frequency of quality recordings between children with and without pneumonia.

In our study, the proportion of children with three or more interpretable lung sound recordings per CHCP ranged from 73.1% (19/26) to 94.7% (177/187), indicating considerable variability in performance across providers. While most CHCPs achieved high interpretability, one provider demonstrated substantially lower performance; it remained above the implied feasibility threshold. CHCPs with the lowest enrolment numbers (26 and 38 children) had the lowest success rates (73.1% (19/26) and 76.3% (29/38), while those with the highest enrolment numbers (187 and 179 children) achieved the highest

success rates (94.7% (177/187) and 92.7% (166/179)). Our data show that the percentage of successful recordings increased by 1% with every ten children recorded. This suggests a learning curve, with CHCPs becoming more proficient in obtaining quality recordings over time as they gained experience. Although encouraging, we did not quantify the strength or precision of this association. Importantly, the observed variability, particularly the lower performance of one provider, suggests that feasibility may vary by provider experience, training, and case exposure, and that additional standardisation, supervision, and refresher training may be required to ensure consistent performance across providers.

The sequential recording approach that started on the participant's back was intended to balance optimising child cooperation with identifying most pneumonia cases, as in our experience children are often more comfortable when facing their carer being held, which allows the health worker access to the child's back. Our findings revealed no significant variation in the success rate of lung sound recordings across the four chest positions. However, there was a significant difference in interpretability with recordings obtained from the back more likely to meet quality criteria than those from the front (92.0% (1782/1938) vs 87.9% (1690/1923)); $p < 0.01$). This may reflect greater child comfort and reduced movement during posterior recordings, particularly as these were performed earlier in the sequence. Despite these variations, three out of every four children remained cooperative and quiet throughout.

The time required to obtain quality recordings was also encouraging, with 89.8% (766/853) of children having at least three interpretable chest position recordings captured under five minutes. This finding suggests that incorporating digital auscultation into the IMCI algorithm is unlikely to significantly increase the workload of frontline health workers. However, this study did not assess diagnostic accuracy, clinical decision-making, or antibiotic use. Therefore, any potential role of digital auscultation in improving pneumonia classification or supporting antibiotic stewardship remains hypothesis-generating and should be evaluated in future studies. Interestingly, there was no relationship between the number of children enrolled and the overall time taken by the CHCP to record the lung sounds. However, several challenges were consistently identified when recordings took longer than one minute. The device occasionally froze, requiring the CHCP to either perform a complete restart or drain the device's battery charge. Children younger than five years of age can be active, and although most children were initially cooperative, some became agitated during the recording process. In such cases, CHCPs had to pause recording and take additional time to calm the child down before reattempting to record the lung sounds. Additionally, ambient noise, such as loudspeaker announcements outside the CC or calls for prayer, which can occur multiple times per day in Bangladesh, sometimes interrupted the recording process. CHCPs had to delay recordings until the background noise had subsided.

This study has several limitations. First, we purposively selected nine out of 24 CCs in the Zakiganj sub-district of Sylhet District, Bangladesh. This may limit the generalisability of our findings to other CCs with different patient volumes, case mixes, or clinical environments. Second, this study only included non-severe pneumonia cases, as children with IMCI danger signs or hypoxaemia were excluded because the CCs lack the capacity to manage severe pneumonia, which requires parenteral antibiotics, hospitalisation, and urgent referral regardless of their lung sounds findings. Therefore, our findings may not be generalisable to children with severe disease or those requiring referral-level care. Moreover, non-severe disease was targeted in this study as children with severe disease get antibiotics and hospitalisation regardless of their lung sounds. Third, several technical issues were identified with the digital stethoscope. These included recordings stopping prematurely, recordings failing to stop, inadequate durability of the device hardware, freezing of the device software during the recording process, and in some cases, the battery losing its charge too quickly¹⁸. However, operational failure metrics (e.g., frequency of device freezing, recording interruption, or battery depletion) were not systematically collected; therefore, the feasibility findings primarily reflect recording quality rather than comprehensive device performance. This highlights the need for addressing these issues to ensure future versions of the device are more effective and user-friendly for a LMIC clinical environment. Fourth, the fact that the digital stethoscope requires charging once daily is a limitation for its use in remote first-level facilities in

LMICs, where the power supply is erratic or there is no power supply at all. Providing alternative power solutions, such as solar panels and portable power banks to charge the stethoscope may solve this issue. Fifth, a substantial variability was observed across CHCPs, which may reflect differences in training, workload, or contextual factors. Sixth, the use of a 10-second recording duration per chest position was based on pragmatic field considerations (e.g., child cooperation and workflow) rather than empirical evidence. However, it was expected that 3 to 4 breath cycles would be captured in a 10-second recording. This duration has not been formally validated or supported by pediatric auscultation literature, and its adequacy for capturing representative lung sounds remains uncertain, potentially affecting recording quality and diagnostic interpretation. Seventh, this study was carried out in overcrowded and noisy settings; however, no measurements were taken to quantify these conditions. Eighth, although the CHCPs received a formal three-day training, the quality and fidelity of the CHCP training were not formally documented. Finally, data collection occurred during a period affected by the COVID-19 pandemic, which may have influenced clinic workflows and care-seeking behaviour.

Beyond technical recording performance, broader feasibility domains, including acceptability, demand, implementation, and practicality, have been examined in detail in a separate publication¹⁸. The findings presented here should therefore be interpreted alongside that complementary work, particularly when considering integration of digital auscultation into routine

care under realistic CHCP workloads characterised by high patient volumes and competing clinical responsibilities. Policy adoption will also depend on addressing implementation barriers such as device cost, training and refresher requirements, maintenance and replacement cycles, and reliable power supply in remote settings. Finally, although this study provides evidence from rural Bangladesh, heterogeneity in health system organisation, workforce capacity, and resource availability across LMICs limits wider generalisability, highlighting the need for context-specific implementation and policy evaluation in future research.

Conclusions

This study demonstrates that, under the conditions of this study and in selected primary care settings, non-physician health workers called CHCPs at first-level primary care facilities in Bangladesh were able to record quality lung sounds in under-five-year-old children using a digital stethoscope under routine conditions. While several challenges exist in these settings, including a lack of provider training and experience auscultating the lungs of children, the active and sometimes uncooperative nature of young children, and a noisy environment, CHCPs in this study were generally able to complete recordings within a reasonable time. These findings reflect feasibility only and do not assess diagnostic accuracy or clinical effectiveness. Further multi-site studies are needed to evaluate recording performance across diverse contexts, as well as to assess diagnostic validity, provider variability, and implementation considerations before broader adoption.

Data availability

The data are available from the corresponding author on reasonable request.

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Author contributions

SA, EDM, HN and AHB conceptualised and designed this study. SA advised on the implementation of the study. AAI organised the data collection. NHC managed the data curation. MSI conducted the data analysis with support from SA, AMK, NHC, HN, SC and EDM. EDM, LG, MMJ, IJ, and MW interpreted the recorded lung sound files. SA wrote the first draft of the manuscript. AMK, AHB, SC, HN and EDM provided critical feedback on the manuscript structure and

contents. All authors contributed to interpreting the results, reviewed the manuscript, and approved the submitted version.

Competing interests

The authors declare no competing interests.

Figure legends

Figure 1: Standards for Reporting of Diagnostic Accuracy Studies (STARD) flow diagram

Figure 2: Time to obtain quality recordings by non-physician health workers

References

- 1 GBD 2016 Lower Respiratory Infections Collaborators. Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory infections in 195 countries, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. *Lancet Infect Dis* **18**, 1191-1210, doi:10.1016/s1473-3099(18)30310-4 (2018).
- 2 Perin, J. *et al.* Global, regional, and national causes of under-5 mortality in 2000-19: an updated systematic analysis with implications for the Sustainable Development Goals. *Lancet Child Adolesc Health* **6**, 106-115, doi:10.1016/s2352-4642(21)00311-4 (2022).
- 3 McAllister, D. A. *et al.* Global, regional, and national estimates of pneumonia morbidity and mortality in children younger than 5 years between 2000 and 2015: a systematic analysis. *The Lancet Global Health* **7**, e47-e57 (2019).

- 4 National Institute of Population Research and Training (NIPORT) & ICF. Bangladesh Demographic and Health Survey 2022: Final Report. (NIPORT and ICF, Dhaka, Bangladesh, and Rockville, Maryland, USA, 2024).
- 5 World Health Organization. Integrated Management of Childhood Illness; Chart Booklet. (World Health Organization, Geneva, Switzerland, 2014).
- 6 Bhutta, Z. & Saeed, M. Childhood infectious diseases: overview. *International encyclopedia of public health*, 620 (2008).
- 7 Rees, C. A. *et al.* An analysis of clinical predictive values for radiographic pneumonia in children. *BMJ global health* **5** (2020).
- 8 Grant, G. B. *et al.* Recommendations for treatment of childhood non-severe pneumonia. *The Lancet infectious diseases* **9**, 185-196 (2009).
- 9 Peyrani, P., Mandell, L., Torres, A. & Tillotson, G. S. The burden of community-acquired bacterial pneumonia in the era of antibiotic resistance. *Expert review of respiratory medicine* **13**, 139-152 (2019).
- 10 Nguyen, P. T., Robinson, P. D., Fitzgerald, D. A. & Marais, B. J. The dilemma of improving rational antibiotic use in pediatric community-acquired pneumonia. *Frontiers in Pediatrics* **11**, 1095166 (2023).
- 11 Hassan, M. Z. *et al.* Antibiotic use for acute respiratory infections among under-5 children in Bangladesh: a population-based survey. *BMJ global health* **6** (2021).
- 12 Ghosh, P. K. *et al.* Factors contributing to antibiotic use among children younger than five years old with fever, acute respiratory illness, and

- diarrhea in Bangladesh. *The Journal of Infection in Developing Countries* **17**, 1268-1276 (2023).
- 13 Goodman, D. *et al.* Challenges in the diagnosis of paediatric pneumonia in intervention field trials: recommendations from a pneumonia field trial working group. *The Lancet Respiratory Medicine* **7**, 1068-1083 (2019).
- 14 Ramgopal, S. *et al.* Interrater reliability of pediatric respiratory auscultation findings. *Hospital pediatrics* **15**, e431-e435 (2025).
- 15 Rees, C. A., du Toit, J. D. & Keitel, K. Unpacking the Unreliability of Interrater Reliability of Pediatric Auscultation. *Hospital pediatrics* **15**, e453-e455 (2025).
- 16 Ahmed, S. *et al.* Digital auscultation as a diagnostic aid to detect childhood pneumonia: A systematic review. *Journal of global health* **12** (2022).
- 17 McCollum, E. D. *et al.* Digital auscultation in PERCH: Associations with chest radiography and pneumonia mortality in children. *Pediatr Pulmonol* **55**, 3197-3208, doi:10.1002/ppul.25046 (2020).
- 18 Joarder, T. *et al.* End-user acceptability of a prototype digital stethoscope to diagnose childhood pneumonia-a qualitative exploration from Sylhet, Bangladesh. *BMC Digital Health* **1**, 26 (2023).
- 19 Riaz, B. K. *et al.* Community clinics in Bangladesh: A unique example of public-private partnership. *Heliyon* **6**, e03950 (2020).

- 20 Ahmed, S. *et al.* Digital auscultation as a novel childhood pneumonia diagnostic tool for community clinics in Sylhet, Bangladesh: protocol for a cross-sectional study. *BMJ open* **12**, e059630 (2022).
- 21 Elhilali, M. & West, J. E. The Stethoscope Gets Smart: Engineers from Johns Hopkins are giving the humble stethoscope an AI upgrade. *IEEE Spectrum* **56**, 36-41 (2019).
- 22 McCollum, E. D. *et al.* Listening panel agreement and characteristics of lung sounds digitally recorded from children aged 1-59 months enrolled in the Pneumonia Etiology Research for Child Health (PERCH) case-control study. *BMJ open respiratory research* **4**, e000193 (2017).
- 23 Hazir, T. *et al.* Chest radiography in children aged 2-59 months diagnosed with non-severe pneumonia as defined by World Health Organization: descriptive multicentre study in Pakistan. *Bmj* **333**, 629 (2006).

Table 1 Baseline characteristics of children

Selected child characteristics at enrolment	Total	Pneumonia	No pneumonia	p-value
	N (%)	n (%)	n (%)	
Number of children	990	389	601	
Age group				
2-11 months	250 (25.3)	92 (23.7)	158 (26.3)	0.35
12-59 months	740 (74.7)	297 (76.3)	443 (73.7)	
Sex				
Male	552 (55.8)	231 (59.4)	321 (53.4)	0.07
Female	438(44.2)	158 (40.6)	280 (46.6)	
Weight for age				
Normal (Z Score \geq -2)	626 (63.2)	249 (64.0)	377 (62.7)	0.66

Selected child characteristics at enrolment	Total	Pneumonia	No pneumonia	p-value
	N (%)	n (%)	n (%)	
Mild underweight (Z Score ≥ -3 to < -2)	251 (25.4)	93 (23.9)	158 (26.3)	
Severe underweight (Z Score < -3)	113 (11.4)	47 (12.1)	66 (11.0)	
Height for age				
Normal (Z Score ≥ -2)	532 (53.7)	203 (52.2)	329 (54.7)	0.10
Mild stunting (Z Score ≥ -3 to < -2)	286 (28.9)	106 (27.2)	180 (30.0)	
Severe stunting (Z Score < -3)	172 (17.4)	80 (20.6)	92 (15.3)	
Weight for height				
Normal (Z Score ≥ -2)	822 (83.0)	322 (82.8)	500 (83.2)	0.97
Mild wasting (Z Score ≥ -3 to < -2)	129 (13.1)	51 (13.1)	78 (13.0)	
Severe wasting (Z Score < -3)	39 (3.9)	16 (4.1)	23 (3.8)	
Diarrhoea within the past two weeks				
Yes	171 (17.3)	69 (17.7)	102 (17.0)	0.76
No	819 (82.7)	320 (82.3)	499 (83.0)	
Immunisation status (all vaccines)				
Fully immunised for age	829 (83.7)	326 (83.8)	503 (83.7)	1.00
Partially immunised for age	143 (14.4)	56 (14.4)	87 (14.5)	
Unvaccinated	18 (1.8)	7 (1.8)	11 (1.8)	
PCV Vaccination status				
Fully immunised for age	853 (86.2)	334 (85.9)	519 (86.4)	0.81
Partially immunised for age	106 (10.7)	44 (11.3)	62 (10.3)	
Unvaccinated	31 (3.1)	11 (2.8)	20 (3.3)	

PCV - pneumococcal conjugate vaccine

Table 2 Distribution of signs during enrolment identified by community healthcare providers (multiple responses)

Clinical signs	Total	Pneumonia	No pneumonia
	N (%)	n (%)	n (%)
Number of children	990	389	601
Age-specific fast breathing	372 (37.6)	372 (95.6)	0 (0.0)
Chest indrawing	25 (2.5)	25 (6.4)	0 (0.0)
Any respiratory danger sign	47 (4.7)	47 (12.1)	0 (0.0)
Axillary temperature $\geq 100.4^{\circ}\text{F}$	76 (7.7)	42 (10.8)	34 (5.7)

Table 3 Recorded and interpretable lung sounds

Children with chest position	Recorded lung sounds				Interpretable lung sounds			
	Total	Pneumonia	No pneumonia	p-value	Total	Pneumonia	No pneumonia	p-value
	% (95% CI) [n]	% (95% CI) [n]	% (95% CI) [n]		% (95% CI) [n]	% (95% CI) [n]	% (95% CI) [n]	
Number of children	N = 990	n = 389	n = 601		N = 990	n = 389	n = 601	
≥ 3 chest positions	98.3 (97.3, 99.0) [973]	98.5 (96.7, 99.4) [383]	98.2 (96.7, 99.1) [590]	0.73	87.6 (85.4, 89.6) [867]	88.2 (84.5, 91.2) [343]	87.2 (84.2, 89.8) [524]	0.65
≤ 2 chest positions	0.7 (0.3, 1.5) [7]	0.5 (0.1, 1.8) [2]	0.8 (0.3, 1.9) [5]	0.56	6.5 (5.0, 8.2) [64]	5.9 (3.8, 8.7) [23]	6.8 (4.9, 9.1) [41]	0.57
No recording or all four positions uninterpretable	1.0 (0.5, 1.8) [10]	1.0 (0.3, 2.6) [4]	1.0 (0.4, 2.2) [6]	0.96	6.0 (4.6, 7.6) [59]	5.9 (3.8, 8.7) [23]	6.0 (4.2, 8.2) [36]	0.96

CI - Confidence interval

Table 4 Distribution of the number of sound files recorded, transferred from the digital stethoscope to a laptop, and interpretable by chest position

Position	Number of sound files recorded	Number of sound files transferred from digital stethoscope to laptop	Percentage of sound files interpretable by the panel	OR (95% CI) [p-value]	Percentage of sound files interpretable by the panel (Model based)
	n	n	% (95% CI) [n]		% (95% CI) [p-value]
Position 1: (left back)	977	968	92.6 (90.7, 94.1) [896]	Ref	90.1% (86.9%, 93.2%) [p < 0.001]
Position 2: (right back)	978	970	91.3 (89.4, 93.0) [886]	0.63 (0.37, 1.05) [p = 0.078]	87.6% (84.1%, 91.2%) [p < 0.001]
Position 3: (left front)	968	960	88.0 (85.8, 90.0) [845]	0.24 (0.15, 0.41) [p < 0.001]	82.2% (78.7%, 85.6%) [p < 0.001]
Position 4: (right front)	971	963	87.7 (85.5, 89.8) [845]	0.24 (0.15, 0.40) [p < 0.001]	82.2% (78.7%, 85.6%) [p < 0.001]
Back (left back and right back)	1955	1938	92.0 (90.6, 93.1) [1782]	Ref	88.8% (85.8%, 91.9%) [p < 0.001]
Front (left front and right front)	1939	1923	87.9 (86.3, 89.3) [1690]	0.31 (0.22, 0.45) [p < 0.001]	82.2% (79.0%, 85.4%) [p < 0.001]

CI - Confidence interval

Table 5 Distribution of lung sounds classification

Classification	Pneumonia	No pneumonia	p-value
	% (95% CI), [n]	% (95% CI), [n]	
Number of children	343	524	
Normal sounds (No wheeze and no crackle)	63.3 (57.9, 68.4), [217]	72.1 (68.1, 75.9), [378]	0.01
Adventitious sounds	36.7 (31.6, 42.1) [126]	27.9 (24.1, 31.9), [146]	0.01
Wheeze only	15.5 (11.8, 19.7), [53]	11.3 (8.7, 14.3), [59]	0.07

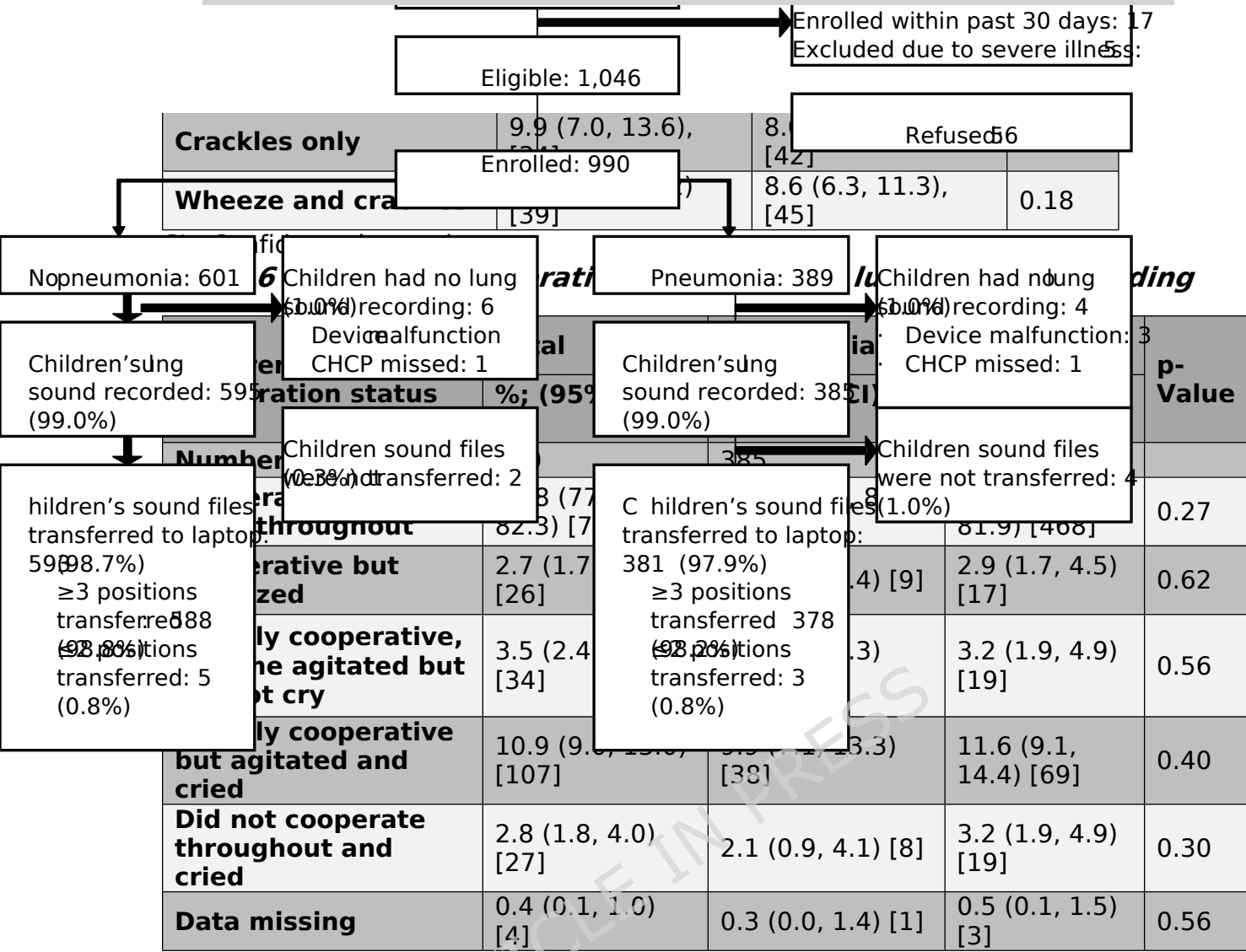


Figure 1: Standards for Reporting of Diagnostic Accuracy Studies (STARD) flow



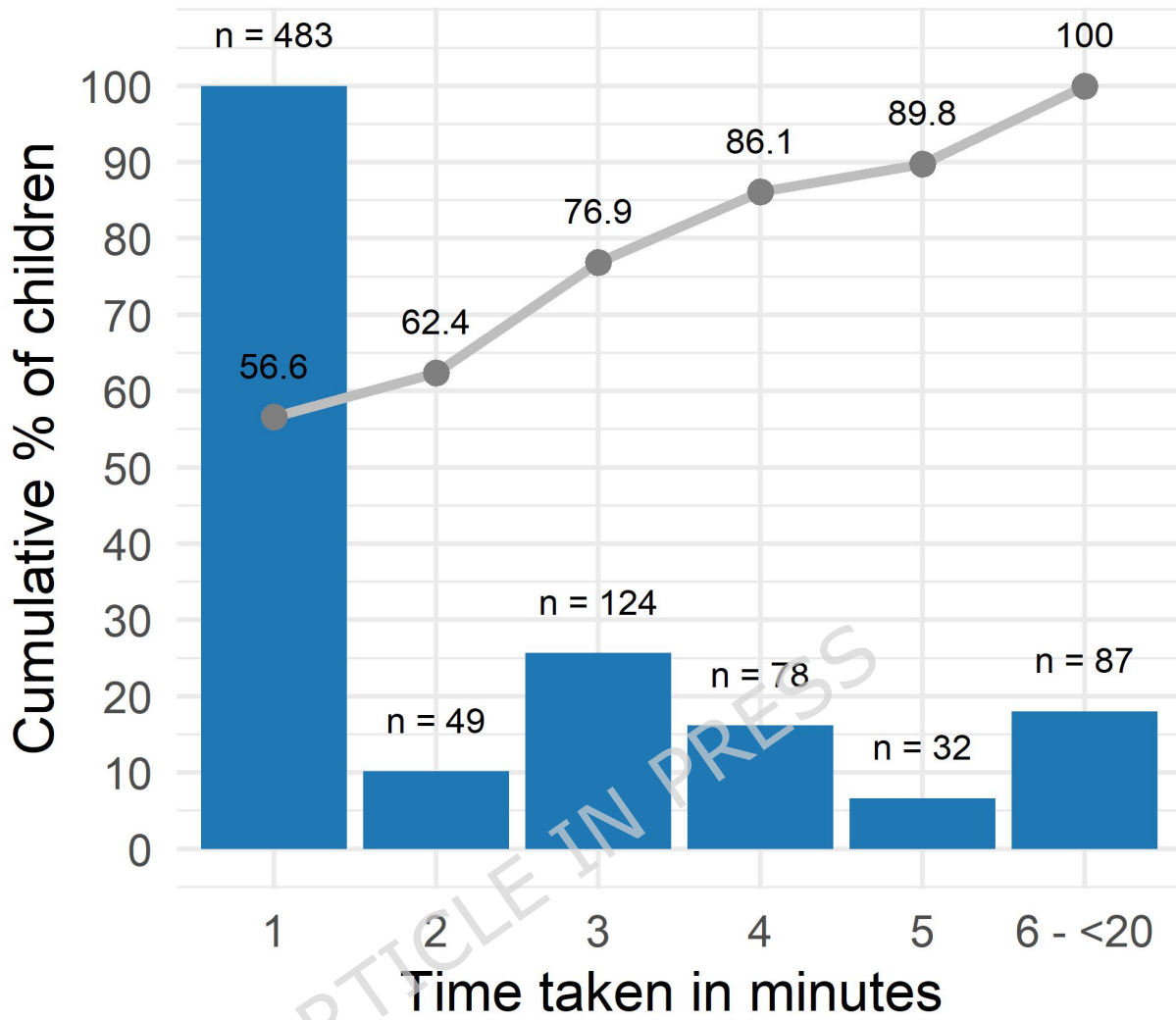


Figure 2: Time to obtain quality recordings by non-physician health workers