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RESEARCH ARTICLE

Implementation of digital chest radiography for childhood tuberculosis diagnosis at district hospital level in six high tuberculosis burden and resources limited countries

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Abstract

Objectives: Chest x-ray (CXR) plays an important role in childhood tuberculosis (TB) diagnosis, but access to quality CXR remains a major challenge in resource-limited settings. Digital CXR (d-CXR) can solve some image quality issues and facilitate their transfer for quality control. We assess the implementation of introducing d-CXR in 12 district hospitals (DHs) in 2021–2022 across Cambodia, Cameroon, Ivory Coast, Mozambique, Sierra Leone and Uganda as part of the TB-speed decentralisation study on childhood TB diagnosis.

Methods: For digitisation of CXR, digital radiography (DR) plates were setup on existing analogue radiography devices. d-CXR were transferred to an international server at Bordeaux University and downloaded by sites' clinicians for interpretation. We assessed the uptake and performance of CXR services and health care workers' (HCW) perceptions of d-CXR implementation. We used a convergent mixed method approach utilising process data, individual interviews with 113 HCWs involved in performing or interpreting d-CXRs and site support supervision reports.

Results: Of 3104 children with presumptive TB, 1642 (52.9%) had at least one d-CXR, including 1505, 136 and 1 children with one, two and three d-CXRs, respectively, resulting in a total of 1780 d-CXR. Of them, 1773 (99.6%) were of good quality and 1772/1773 (99.9%) were interpreted by sites' clinicians. One hundred and sixty-four children had no d-CXR performed despite attending the radiography department: 126, 37 and 1 with one, two and three attempts, respectively. d-CXRs were not performed in 21.6% (44/203) due to connectivity problem between the DR plate captor and the computer. HCW reported good perceptions of d-CXR and of the DR plates

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provided. The main challenge was the upload to and download from the server of d-CXRs due to limited internet access.

Conclusion: d-CXR using DR plates was feasible at DH level and provided good quality images but required overcoming operational challenges.

KEYWORDS
children, digital chest x-ray, implementation, resources limited countries, tuberculosis

INTRODUCTION

Tuberculosis (TB) is one of the leading infectious causes of death worldwide in children, with 183,000 deaths in 2022 [1]. Modelling suggests that more than 95% of these children were not treated, hence likely not diagnosed at the time of death [2].

Microbiological confirmation of childhood TB is difficult due to challenges in obtaining respiratory samples in young children and the paucibacillary nature of TB in children resulting in low sensitivity of bacteriological tests from respiratory samples [3,4]. Consequently, the majority of children are based on clinical evaluation and chest x-ray (CXR) [5]. CXR plays a critical role in the recent treatment decision algorithm proposed by World Health Organization (WHO) for TB in children [6,7].

In high TB burden and low and middle income countries (LMIC), the use of CXR faces several difficulties: (i) radiology services are often only available in district or regional hospitals [8], hence requiring referral for CXR of children with presumptive TB seen at Primary Health Centres (PHC), inducing additional transport costs and affecting access to CXR; (ii) clinicians lack training in interpreting CXR for paediatric TB diagnosis, especially at peripheral healthcare facilities, affecting the reliability of CXR results; and (iii) films and reagents for analogue radiography device often suffer from shortage and expiries, leading to poor CXR quality [9].

Digital CXR (d-CXR) could contribute to improving the quality of CXR interpretation in LMIC by overcoming the issue of shortage and poor quality films and reagents [10]. d-CXR could also allow remote interpretation for advice or external reading for quality control purpose. In addition, digital technologies can enable future use of computer aid detection (CAD) for TB, already validated for adults and under evaluation in children [11]. The implementation of d-CXR for childhood TB diagnosis has been poorly documented in LMIC.

In the TB-Speed Decentralisation study that aimed to strengthen paediatric TB diagnosis of low healthcare levels, d-CXR was implemented in order to improve quality of CXR and facilitate image transfer for external quality assurance [12] of CXR interpretation. Analogue radiographies devices were equipped with digital radiography (DR) plates (Agfa DR14eC, AGFA N.V., France), which produce a digital radiographic image instantly on a computer. The DR plates were chosen because of their rapidity between exposure and image acquisition and their ease of adaptation with analogue radiography device, which could be a suitable alternative to DR devices for LMIC.

Documenting and learning from the challenges and solutions found in operational settings is essential to inform implementers and decision makers on the use of d-CXR at lower levels of care. Using the experience of the TB-Speed decentralisation study, we assessed the implementation of d-CXR in 12 DHs of six high TB incidence and resource-limited settings in terms of the uptake of d-CXR, performance of CXR services and health care workers' (HCW) perspectives on use of d-CXR.

METHODS

Study setting

The TB-Speed decentralisation study was an operational research to assess the effect of implementing a comprehensive diagnostic approach on paediatric TB case detection at district hospital (DH) and PHC levels. The approach included symptomatic TB screening of all sick children (<15 years) arriving at the health facility to identify children with presumptive TB, clinical evaluation for all children with presumptive TB, microbiological testing using Xpert MTB/RIF Ultra on a nasopharyngeal aspirate and a stool or sputum sample, and d-CXR. The study compares two decentralisation strategies at the DH and PHC levels in two rural or semi-rural health districts in Cambodia, Cameroon, Ivory Coast, Mozambique, Sierra Leone and Uganda [13]. In the DH-decentralised strategy, the diagnostic approach was deployed at DH and children with presumptive TB after being screened at PHC were referred to DH for diagnosis. In the PHC-decentralised strategy, the diagnostic approach was decentralised at PHC, except for CXR that was only available at DH. In the DH-decentralised strategy all children with presumptive TB had a CXR, while in the PHC-decentralised strategy children seen at PHC were referred to DH for CXR only in case of persisting symptoms after 1 week. The study comprised an observation period to document baseline situation followed by a lead-in phase to setup and build capacity, and a 12-month of intervention period.

Baseline assessment, digital radiography setup and supervision

Prior to implementation of the intervention, a baseline site assessment was conducted, including assessment of radiography capacity at DH level. Of 12 DH, 8 (83%) had an analogue radiography device and only 1 had a DR device

(Sierra Leone). Electrical power instability and cuts were reported in DH of four countries and all radiology departments had at least one radiographer (Table 1) [14].

In all DH, except one in Sierra Leone, analogue radiographies were equipped with the DR plates and in two DH in Uganda, a portable radiography was provided and x-ray department was renovated with the installation of lead doors. Sites received support to strengthen internet connexion if needed and to reinforce protective measures when necessary. One person in each country received an online training in setting up and using DR plates by the manufacturer, who then trained radiographers at DH (two per DH). Tablets, internet connectivity and electrical stabilisers were provided to all facilities (Table 1).

Sites' radiographers were trained on how to convert Digital Imaging and Communication in Medicine (DICOM) images' format into Joint Photographic Experts Group (JPEG) format and to upload them on the international File Transfer Protocol Secure (FTPS) server at the University of Bordeaux (France). Sites' clinicians and radiographers were trained on how to download d-CXR images on tablets for interpretation and on assessing the quality of CXR using standardised criteria as part of a 1.5-day training course [15]. CXR were performed using antero-posterior and lateral CXR for children younger than 5 years and postero-anterior CXR for children older than 5 years. If a CXR was assessed as uninterpretable due to poor quality, another CXR was performed immediately. The interpretation was recorded by readers in an electronic Case Report Form (CRF) data on the REDCap clinical database on tablets.

Support supervision activities were implemented to support implementation of the diagnostic approach, including CXR with visits conducted by representative of national TB programs, paediatricians and study country coordinators, guided by a standardised support supervision tool documenting both quantitative and qualitative data related to performance, challenges observed and/or discussed and immediate actions taken or recommendations made for further action.

Study design and population

We conducted an implementation study, using a convergent mixed methods design. Quantitative process data were obtained from the clinical database for children below 15 years with presumptive TB enrolled in the TB-Speed Decentralisation study. These children were recruited between August 2019 and September 2021. Qualitative interviews were conducted among HCWs who were either directly involved in performing the d-CXR (radiographers), and/or who read and interpreted images (medical doctors and nurses) and/or who took part in other components of the diagnosis approach, such as screening, and observed the d-CXR process (midwifes and paramedics). Support supervision quantitative and qualitative data was retrieved from site supervision reports.

Outcomes

The d-CXR implementation outcomes included the uptake of d-CXR, performance of CXR services and HCW perspectives on use of d-CXR. The uptake of d-CXR assessed by the cascade of care from the CXR prescription to its interpretation: (1) number of children with (i) presumptive TB, (ii) at least one d-CXR performed (one, two and three d-CXR performed) and (iii) any CXR attempts (visit to x-ray department) but without d-CXR performed (one, two and three attempts); (2) number of d-CXR (i) performed, (ii) of good quality defined as readable and (iii) interpreted; (3) reasons for not performing a d-CXR presented per category as recorded by sites' clinicians including: technical problems with x-ray machine, connectivity problem between the DR plate detector and the computer, electrical problems, absence of radiographer, administrative reason and non-specified technical issues.

Performance of CXR services was assessed during site supervision through three quantitative indicators: (1) d-CXRs performed as prescribed, assessed by the availability of a d-CXR images for children with presumptive TB at the DH in the last 2 weeks; (2) upload and download of d-CXR images, assessed by the ability of the site radiographer and site reader to upload and download d-CXR image; (3) d-CXRs interpretation, assessed by the presence of at least two d-CXR interpretation reports from the last 2 weeks. Performance outcomes were scored using a Likert scale as follows: 1—Never: the task is not done completely; 2—Rarely: performance of task is below average; 3—Sometimes: performance of task is average; 4—Often: performance of task is above average; 5—Always. They included also action taken and recommendations following supervision visits.

Individual HCWs' experiences and perception of d-CXR included operational challenges and contextual conditions that made d-CXR possible or not [16](Table 2).

Data collection and analysis

Quantitative d-CXR uptake data were computed from real-time patient-level individual data, collected during study intervention for enrolled children by site HCW assigned to the study and directly entered into an electronic CRF. They are presented as counts, proportions, medians and interquartile ranges (IQR). Paper-based site supervision reports were entered into a REDCap dedicated database by research assistants. We calculated the median scores' and IQR for the three CXR outcomes. Quantitative data were analysed with the R software (version 4.2.1, R Foundation for Statistical Computing).

Regarding qualitative data of performance of CXR services, reasons for d-CXR not performed were retrieved from the REDCap clinical database, and supervision visits qualitative notes made by supervisors were extracted from site supervision reports and entered as free text into the REDCap supervision database. Challenges to perform d-CXR and mitigations strategies were grouped into global deductive thematic categories.

TABLE 1 Baseline digital x-ray capacity and setup of digital x-ray per district hospital and country during pre-intervention implementation.

		Baseline capacity					Setup of digital x-ray						
Countries	District referral hospital	Availability of x-ray unit	Availability of analogic functional x-ray machine	Availability of digital x-ray	Electrical power issue	Number of radiographers in x-ray ward	Electricity provided by the study	Renovation of x-ray ward	Provision of x-ray machine	Provision of power stabilisers	Provision of DR plate and its accessories	Number of radiographers trained	Provision of internet
Cambodia	Batheay	Yes	Yes	No	No	2	No	No	No	Yes	Yes	2	Yes
	Angroka	Yes	Yes	No	No	2	No	No	No	Yes	Yes	2	Yes
Cameroon	Obala	Yes	Yes	No	No	2	No	No	No	Yes	Yes	2	Yes
	Bafia	Yes	Yes	No	No	2	No	No	No	Yes	Yes	2	Yes
Ivory coast	Sassandra	Yes	Yes	No	Yes	3	No	No	No	Yes	Yes	2	Yes
	Danane	Yes	Yes	No	No	5	No	No	No	Yes	Yes	5	Yes
Mozambique	Manjacaze	Yes	Yes	No	No	3	No	No	No	Yes	Yes	2	Yes
	Chokwe	Yes	Yes	No	No	2	No	No	No	Yes	Yes	2	Yes
Sierra Leone	Bo	Yes	Yes	Yes	Yes	5	No	No	No	No	No	5	Yes
	Port Loko	Yes	Yes	No	Yes	2	No	No	No	Yes	Yes	2	Yes
Uganda	Rakai	No	No[a]	No	Yes	1	No	Yes	Yes	Yes	Yes	1	Yes
	Kanungu	No	No[a]	No	Yes	2	No	Yes	Yes	Yes	Yes	2	Yes

Abbreviation: DR, digital radiography.

[a]The machine was faulty and was last used 10 years back before TB-Speed intervention.

TABLE 2 Summary of the analytical approach.

	Endpoints	Endpoint measures	Population	Primary source of information
Uptake of d-CXR	CXR cascade of cares	Number of children with presumptive TB Number of children with CXR performed Number of CXR performed per child Number of children with CXR attempts	Children with presumptive TB enrolled in the TB-Speed decentralisation study	REDCap clinical Database
		Number of CXR attempts Number and proportion of CXR performed Number and proportion of good quality CXR Number and proportion of interpreted CXR	CXRs attempts at district hospital level	REDCap clinical Database
	Reasons for CXR not performed	Technical problem with the x-ray machine Problems of connectivity between with the DR plate Electrical problems Other technical problems Absence of radiographer Administrative issues	CXR attempts without any CXR performed	REDCap clinical Database
Performance of CXR services	Site supervision performance indicators	Median score of d-CXRs performed as indicated Median score of d-CXR loaded on/from the server as indicated Median score of d-CXRs interpreted as indicated	Supervisors	REDCap database of site supervision reports
	d-CXR challenges and recommendations identified by supervisors	Loading of d-CXR Technical problem with DR plates Issues with internet connection Delays in d-CXR interpretation Quality issues Dysfunction of the x-ray machine	Supervisors	REDCap database of site supervision reports
Health care workers' perspectives	Perception of d-CXR by health care workers	Experience and views of health care workers regarding d-CXR	HCWs involved in diagnosis of tuberculosis in children	Semi-structured interviews

Abbreviations: CXR, chest x- ray; d-CXR, digital CXR; DR, digital radiography; HCW, healthcare worker; TB, tuberculosis.

Regarding qualitative data of HCWs' perspectives, individual interviews were conducted by trained social science research assistants using a semi-structured guide, between June and August 2021. Interviews aimed at investigating overall experiences and perceptions of the childhood TB diagnosis approach [17], including the use of d-CXR. Among the 113 HCWs interviewed, median age was 36 years (IQR; 31, 41) and 64 (57%) were female. More than half of the HCWs interviewed were nurses (Table S1). Interviews were conducted face-to-face or by telephone (when transportation to the site was not possible due to corona virus disease 2019 restrictions) and were recorded if respondents permitted. Data were anonymised using numerical identification codes. A thematic analysis was performed in three steps: we first developed a codebook based on the themes that were predefined by the semi-structured interview guides. We then coded the data using the Nvivo release qualitative data management software, QSR International Private Ltd. Version 1.5, 2021. Recurring themes were identified and grouped into overarching thematic categories related to d-CXR, and later on summarised.

Ethics statement

This study was approved by each implementing country's National Ethics Committees, the WHO Ethical Review Board, and the National Institute of Health and Medical Research (INSERM Ethics Evaluation Committee). Individual consent was obtained from interviewed HCWs and from parents/guardians of enrolled children and the child's assent was obtained when the child was old enough as per countries regulation and from interviewed HCWs.

RESULTS

Uptake of d-CXR and performance CXR services

Of 3104 children with presumptive TB, 1642 (52.9%) had at least one d-CXR performed, of which 1505, 136 and 1 children had one, two and three d-CXR performed, respectively, giving a total of 1780 d-CXR. Of them, 1773 (99.6%) were of good quality, and 1772/1773 (99.9%) were interpreted (Table 3).

A total of 51 site supervision visits were performed in DH. The median score of the performance indicator assessing if d-CXR were performed as indicated was between 4 and 5 in all countries, while the median score regarding the process of loading of the d-CXR images was below 3 in three DH (Cote d'Ivoire, Mozambique and in Uganda). The median score for the d-CXR interpretation indicator was between 4 and 5 in all DH (Table 4).

Comparing performance of CXR services in Sierra Leone, where one DH (Bo) used DR device and one DH was equipped with DR plates (Port Loko), in Bo DH reasons for not performing the CXR were due to non-specified technical (18/21, 75.0%) and administrative issues (3/21, 14.2%), while in Port Loko DU it was technical problem of the radiography analogue device (34/57, 59.6%), non-specified technical issues (16/57, 28.0%) and administrative issues (7/57, 12.2%) (Table S3).

HCWs' perception, operational challenges and mitigation actions

HCWs interviewed valued the digital equipment provided, its technical features, the quality of images taken, and thereby being able to provide quality care to patients.

> "What is working well is that, there are many ways it can be answered. The x-ray machine itself, because it gives services to different people, other patients and specifically the TB Speed children. Also, the imaging system what we call the DR system is also working well (…) It's a sophisticated good machine" (Uganda, Radiographer).

HCWs were happy with the quality of d-CXR they received. Very few reported issues on quality requiring to repeat the d-CXR.

> "Technique of radiography is better though we follow up, we read the film x-ray through TB speed, most films have acceptable good quality" (Cambodia, Nurse).

Some HCWs regretted the absence of printed x-rays when using d-CXR. They suggested that printed x-rays would be more easily accessible for HCWs for interpretation and would create more opportunities for learning among HCWs.

> "Now, the chest x-ray they don't produce film, yes after the x-ray, the doctor will go there and interpret the x-ray so I don't have too have idea over it because I have not been there with the doctor to do the interpretation of the x-ray" (Sierra Leone, Nurse).

Regarding challenges, among reasons for not performing d-CXR reported in the clinical database, 44/203 (21.7%) were due to connectivity problem between the DR plate detector and the computer and 30 (14.8%) to electrical problems (Table 5). Difficulties in loading the d-CXR images, technical problems with the DR plate and issues with internet connection were also reported as common challenges in the supervision reports. During HCWs' interviews, ensuring stable electricity was overall reported as one of the main challenges for d-CXR, occasionally resulting in system errors while performing x-ray due to the interruption of the internet connection. This often requires additional cost for the parents who need to come back the next day.

I: What do you do then for example, child is coming and the electricity is off the whole day?

R: I usually ask them whether they have, relatives close by where they can sleep so that the next day I take the x-ray. In any case, if they go back for them to come back it costs a lot to the client and TB Speed, if I ask and they have somewhere to sleep, then that is to their advantage of the parent. If they don't have, I may admit them temporarily but if they cannot afford then they go back and choose another day to come back (Uganda, Radiographer).

To mitigate the problems of internet, HCWs from DH often came to the radiography department to directly read the d-CXRs on the monitor. Refresher training of loading d-CXR, use of social media or platforms were recommended by supervisors to mitigate the problems of loading of the d-CXR images (Table S2). During HCWs' interview, using social media tools for exchange d-CXR images or wireless telecommunication system were proposed as a mitigation action to the challenges with the loading of the image.

> "Regarding result, we have system like Telegram, for me, I don't have it but other staffs they have, my boss, and CXR film interpreter; for us, we don't know how to interpret CXR" (Cambodia, Midwife)

Many of the challenges raised by HCWs were not directly related to digitalisation but to the x-ray machine breakdown, human resources' absence and turn over, access issues (Table 5).

TABLE 3 Cascade of care of chest x-ray (CXR) in district hospitals per country, health district and overall.

Countries	Health district	Children with presumptive TB	Children with CXR performed, $n = 1780$			Children with d-CXR attempt but not performed, $n = 203$			d-CXR attempts			
			At least one	One	Two	Any	One	Two	CXR attempts	CXR performed, n (%)[a]	CXR of good quality, n (%)[a]	CXR interpreted, n (%)[a]
Cambodia	Batheay	171	171	170	1	2	2	0	174	172 (98.8)	172 (100.0)	172 (100.0)
	Angroka[b]	90	37	37	0	0	0	0	37	37 (100.0)	37 (100.0)	37 (100.0)
Cameroon	Bafia	303	297	284	13	7	6	1	318	308 (96.5)	306 (99.3)	306 (100.0)
	Obala[b]	374	207	199	8	11	11	0	226	215 (95.1)	214 (99.5)	214 (100.0)
Ivory coast	Sassandra	112	92	86	6	2	1	1	101	100 (99.0)	99 (99.0)	99 (100.0)
	Danane[b]	321	126	121	5	1	1	0	132	131 (99.2)	131 (100.0)	131 (100.0)
Mozambique	Manjacaze	112	108	56	52	1	0	1	162	161 (99.3)	160 (99.3)	160 (100.0)
	Chokwe[b]	482	102	66	37[c]	12	7	5[d]	159	139 (87.9)	139 (100.0)	139 (100.0)
Sierra Leone	Bo	354	323	321	1	21	21	0	344	324 (94.1)	324 (100.0)	324 (100.0)
	Port Loko[b]	53	14	14	0	36	17	20	71	14 (19.7)	14 (100.0)	14 (100.0)
Uganda	Rakai	137	22	17	5	0	0	0	27	27 (81.4)	26 (96.2)	26 (100.0)
	Kanungu[b]	595	143	134	9	70	60	10	232	152 (71.0)	151 (99.3)	150 (99.3)
	Overall	3104	1642	1505	137	164	126	38	1983	1780 (89.7)	1773 (99.6)	1772 (99.9)

Abbreviations: d-CXR, digital CXR; TB, tuberculosis.
[a]The denominator corresponds to the number in the previous column.
[b]District in which the diagnostic package was decentralised at DH and PHC.
[c]A child had three CXR performed.
[d]A child had three CXR attempts and no d-CXR.

TABLE 4 Median score results of the performance indicators from the site supervision visits in the district hospitals by country and health district.

Characteristic	Cambodia		Cameroon		Côte d'Ivoire		Mozambique		Sierra Leone		Uganda	
	Angroka, N = 5	Batheay, N = 6	Bafia, N = 7	Obala, N = 6	Danane, NS	Sassandra, N = 3	Chokwe, N = 4	Manjacaze, N = 3	Bo, N = 6	Port Loko, N = 1	Kanungu, N = 5	Rakai, N = 3
d-CXRs performed as indicated (/5) median (IQR	5.0 (4.0–5.0)	5.0 (5.0–5.0)	5.0 (5.0–5.0)	5.0 (4.2, 5.0)	-	5.0 (5.0–5.0)	2.5 (1.7–3.2)	5.0 (5.0–5.0)	5.0 (4.2–5.0)	5.0 (5.0–5.0)	4.0 (4.0–4.0)	5.0 (4.0–5.0)
d-CXR upload/ downloaded as indicated (/5) median (IQR)	4.5 (3.2–5.0)	4.0 (4.0–4.7)	5.0 (5.0, 5.0)	5.0 (5.0, 5.0)	-	1.0 (1.0–1.0)	1.0 (1.0–1.7)	5.0 (5.0–5.0)	5.0 (4.2–5.0)	5.0 (5.0–5.0)	2.0 (1.0–3.5)	1.0 (1.0–1.0)
d-CXR interpreted as indicated(/5) median (IQR)	3.0 (2.0–4.0)	5.0 (5.0–5.0)	5.0 (5.0, 5.0)	4.0 (4.0, 4.7)	-	5.0 (5.0–5.0)	4.0 (3.2–4.0)	4.0 (3.5–4.0)	4.5 (4.0–5.0)	3.0 (3.0–3.0)	4.5 (4.0–5.0)	4.0 (4.0–4.0)

Abbreviation: d-CXRs, digital chest x-ray; IQR, interquartile ranges; NS, no data of site supervision.

> "The challenge is mainly around the distance and transport … But in most cases, the clients say they don't have money to reach the hospital …" (Uganda, Nurse).

> We have lost many patients because the patient will say I don't have money to do the x-ray. (Sierra Leone, medical doctor).

DISCUSSION

This study reports experience of implementing d-CXR for diagnosis of TB in children in high TB incidence and LMIC at district level. Overall, the use of d-CXR resulted in a very high proportion of good-quality CXR and this quality was very much appreciated by HCWs. The study also shows the efforts required in terms of equipment, training and supervision to setup d-CXR at the DH level and highlights the challenges faced during implementation and mitigation actions proposed by the end-users and the supervisors.

In terms of site readiness, in our study settings, only 1 out of 12 DHs in six countries already had digital x-ray, reflecting the low coverage of digital x-rays in resource-limited countries at DH levels. Although not representative of DHs in all resource-limited countries, pre-intervention findings highlight the level of investment and support that would be required for countries to setup digital x-ray at this level of health facility. However, this situation is expected to improve in the coming years with the introduction of mobile radiography and digital x-rays in the new Global Fund requests to increase access to radiography and ease the use of CAD currently recommended for TB screening in adults and under evaluation for diagnosis in children [18].

Several challenges can affect the use of d-CXR some being specific to the use of DR plates and others being related to the use of any digital system.

Regarding the challenges of using the DR plates, the problems of connectivity between the DR plate's captors and the computer were a common reason for the failure of d-CXR. The DR plates chosen because of their rapidity between exposure and image acquisition had the disadvantage of have fragile DR plate detector that could not support shocks and high temperatures, which may explain the dysfunctionalities. The manufacturer has considered this problem and is designing more robust sensors for markets of resource-limited countries (AGFA, personal communication).

Even under study conditions, the process of loading images was challenging, especially in Mozambique, Cote d'Ivoire and Uganda and frequently reported by end-users. This process that is not specific to the use of DR plates can be complex and require good training and supervision, as highlighted in the site supervision reports and good quality of the internet connection. Despite the provision of an internet connection system to all DH during the d-CXR setup, several sites suffered from recurrent internet connection problems. To mitigate these issues, HCWs from DH had to come to the x-ray department

TABLE 5 Reasons for digital chest x-ray not performed by country.

	Cambodia	Cameroon	Ivory coast	Mozambique	Sierra Leone	Uganda	Overall *n* (%)
	n = 2	*n* = 19	*n* = 4	*n* = 20	*n* = 78	*n* = 80	*N* = 203
Technical problem of the x-ray machine	-	17	2	20	34	-	73 (35.9)
Problem of connectivity between the DR plates detector and the computer	2	2	-	-		40	44 (21.7)
Non-specified technical issues	-	-	-	-	34	6	40 (19.7)
Electrical power issues	-	-	1	-	-	29	30 (14.8)
Absence of radiographer	-	-	-	-	7	5	12 (5.9)
Administrative issues	-	-	1	-	3	-	4 (1.9)

Abbreviation: DR, digital radiography.

to read the CXR on the monitor and others were using social medial tools for d-CXR exchange, although this was a field adaptation by clinicians and was not planned in the intervention. This last solution is raising potential ethical issues related to the safeguarding of files and to the confidentiality in regards to the regulations in each country. Thus, when implementing digital x-ray, access rights and handling of personal data should be organised using state-of-the art procedures such as encryption security, pseudonymisation and logging [19–21].

Another important challenge affecting the use of d-CXR but that was not specific to the use of DR plates was the frequent power shortages. A recent study of 72 health facilities from all health districts in Sierra Leone found that only 13 (18%) of rural facilities were connected to the national power grid. The authors pointed out that digitisation of healthcare facilities should consider the use of renewable energy sources [22]. Digitalisation of x-ray at low level of healthcare would certainly require promoting the use of sustainable back-up systems for electricity, such as new wind or solar power.

The use of digitised x-ray requires a change in clinical practices, which may be challenging, as highlighted during interviews. There is still limited use of and experience in electronic data systems for healthcare at DH and many clinicians prefer having a printed CXR to be filed with the patient's medical chart and carried during clinical rounds or shared with colleagues to discuss cases [23]. It may indeed be challenging to incorporate a digitised tool requiring access to computers or tablets when patients' files are still paper-based. Digitised x-ray can be printed but this adds an additional cost and potential logistical and affordability issues.

Even if digital-related issues can be solved, structural problems that affect access to x-ray were commonly reported to explain the lack of d-CXR and raised by HCWs during interview. Breaking down of the radiography machine was the first cause of d-CXR not performed in the study. The lack of suitable maintenance system is a common problem in many resource-limited countries that rely often on private contractors at a high cost [24]. This raises questions about the sustainability of such interventions and the need to empower the health facilities to address most common technical issues with a back-up system for more complex ones.

The study has limitations. We did not collect data on the cost to setup the d-CXR using the DR plates. Therefore, we cannot discuss if the equipment of existing analogue radiography device with DR plates is an affordable solution for LMIC as compared to others digitalisation equipment. Also, we were not able to compare the process and performance outcomes between sites using DR device and analogue device equipped with DR plates because only one site was already equipped with DR device and all the other sites with DR plates.

In conclusion, d-CXR implemented at DH level in LMIC can provide good quality of CXR. It requires significant investment in terms of equipment, training, maintenance and supervision that may be difficult to maintain under routine conditions, and consecutively strong stakeholder engagement and buy-in to ensure its sustainability [25]. Hopefully, with the upcoming CAD systems and the development of portable x-ray machines and their inclusion in the budget forecast for international funders, we could expect increased access to digital x-ray in high TB burden and resource-limited countries in the coming years [26].

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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