FIND
Diagnosis for all

AI-assisted diagnostics

for TB, COVID-19, and other respiratory diseases in low- and middle-income countries

1. Executive Summary

The application of artificial intelligence (AI) in health, and specifically to diagnostic tools that target high burden global diseases, is an emerging area, where only a limited number of products have achieved regulatory approval and the ability to scale.

Diagnostic tools that incorporate AI may be of value in resource-limited settings, especially given the known shortage of healthcare workers and diagnostic infrastructure in these settings. Whilst the results of projects exploring such use cases have been published in academic literature, the technology has only recently started to be used on a wider scale.

Comprehensive information on commercially available AI-assisted respiratory diagnostics that can be used to target high burden global diseases in low- and middle-income countries (LMICs) is not readily available. FIND has already worked in the space of computer-aided detection for chest radiograph (CXR-CAD) evaluation and there is interest in understanding the broader AI diagnostics market, where there are promising new tools. As a result, FIND commissioned this landscape, undertaken in 2022, to identify potential solutions and technologies that utilise AI to produce a diagnostic result for tuberculosis (TB), coronavirus disease 2019 (COVID-19), or pneumonia in LMICs. The aim of this report is to inform policymakers, healthcare providers, researchers, and patients, by providing an overview of the field, and to enable stakeholders to identify those technologies that may be most fit for their use.

THIS REPORT IS DIVIDED INTO THE FOLLOWING SECTIONS:

- METHODOLOGY USED FOR THE LANDSCAPE ANALYSIS
- HIGH-LEVEL SUMMARY OF FINDINGS BY TECHNOLOGY CATEGORY
- DETAILED ANALYSIS BY TECHNOLOGY CATEGORY
- DISCUSSION
- LIMITATIONS
- APPENDICES:
  - APPENDIX 1: READING LIST
  - APPENDIX 2: LIST OF PRODUCTS EVALUATED IN THIS LANDSCAPE

In summary, of 159 solutions identified by an initial analysis, 63 met inclusion criteria and were considered in scope.

Most developers of these solutions had headquarters based in Asia, North America or Europe, with few solutions developed by companies based in LMICs. In-scope solutions fell into the following categories: CXR-CAD, breathalysers, cough analysers, smart auscultation, and point-of-care (POC) ultrasound software. CXR-CAD products represented variable levels of maturity, while most products in the other categories were in the development phase.

The majority of products were healthcare provider facing. Limited data were available on training data and algorithms used by AI-based software, and the impact of the solutions on health outcomes. For solutions with regulatory approval, authorization was often limited to specific conditions or outcomes.

This analysis provides global health stakeholders, including policymakers, healthcare providers, researchers, and patients, with a user-friendly overview of AI-based solutions for diagnosis of TB, COVID-19 or other pneumonia that are commercially available or under development.

2. Introduction

Digital diagnostics that leverage AI have the potential to transform health care globally.

In settings where patients live far from care centres, and in healthcare settings with limited trained providers or advanced diagnostics tests, the use of AI can improve the efficiency of the diagnostic evaluation and can inform decisions to seek care.[1] Given the disproportionate gap in access to appropriate diagnostics in LMICs, it is reasonable that the global health community would explore diagnostic tools that incorporate AI-based diagnostics into care. Enthusiasm for AI to address shortages of providers and limited access to health care diagnostics is not new. However, recent advances in computing power and AI model development have increased the availability of AI-based diagnostics globally. As a result, there is value in defining the current state of the market.

The application of AI in health, specifically in diagnosing of diseases and conditions, is an emerging area, with relatively few products having achieved regulatory approval in countries with a stringent regulatory authority (SRA). However, the use of computer-aided detection (CAD) software to interpret chest radiographs (CXR) in individuals at risk for TB, COVID-19, and other respiratory infections, is a rapidly advancing field.[2] Over the past decade, there has been a marked growth in the number of new CXR-CAD products available for TB and other respiratory diseases.[3] Additionally, a number of other novel technology solutions that use AI to support diagnosis of these respiratory infections are now in development or commercially available.

These technologies may allow providers to efficiently address TB, COVID-19, and other respiratory infections that cause pneumonia, which led to an estimated 4.5 million deaths in 2022 with over 1 million deaths in children.[4,5]

Comprehensive information on the broad array of AI-assisted respiratory diagnostics that are fit for use in LMICs is not readily available. To address this knowledge gap, FIND commissioned Outsight International, along with other partners, to perform a landscaping analysis to identify AI-based diagnostics that are currently available or in development for use in LMICs to evaluate patients for TB, COVID-19, and other pneumonia. Key classes of AI-based diagnostics are described, in terms of product maturity and user characteristics, as well as use cases and inherent limitations. This landscaping analysis can be used as a resource by researchers, healthcare system providers, and health ministries considering evaluation and adoption of these technologies as a component of healthcare delivery.

3. Methodology

To identify available technologies in this space, FIND commissioned a landscape analysis by Outsight International (https://outsight.international/, Geneva, Switzerland) to identify and characterize AI-based diagnostics to be considered for potential inclusion. Outsight International drew from their network of key opinion leaders in public health and performed a review of published literature to compile an initial list of diagnostic products for review.

After this list was shared with FIND, an underrepresentation of products from South American, African, and Asian markets was identified. FIND therefore commissioned a second analysis by Newhappy Consulting (Beijing, China) specifically to address Asian market products, and leveraged contacts in the African and South American regions to identify additional domain experts for Outsight International to interview from these regions.

KEY ASPECTS OF THE SEARCH STRATEGY ARE DETAILED BELOW:

1. **ARTICLES IDENTIFIED FOR RELEVANT TECHNOLOGY** were identified through PubMed, Google Scholar, and interviews with experts. A bibliography of included references is provided in **APPENDIX 1.**
2. **KEY OPINION LEADERS AND DOMAIN EXPERTS** were interviewed to identify potential tools for inclusion. Experts from academia, non-governmental organizations (NGOs), health technology start-ups, and philanthropic organizations were included in these interviews, and provided recommendations regarding in-scope technologies and products for further consideration.
3. **FIND, IN PARTNERSHIP WITH STOPTB,** maintains an online resource of commercial CXR-CAD products for TB.[6] CXR-CAD developers in this database were included in the landscape even if not identified in commissioned interviews or the literature review.

This search revealed 159 solutions that were potentially in scope. After the search was complete, all identified developers were contacted to schedule interviews. If a developer did not respond to an initial request by email, a second email was sent within 14 days and, if possible, an attempt to contact them was made through social media. In instances where contact was established, a survey form was shared to collect details of their product, and synchronous interviews were performed to clarify questions regarding function, fit for use, and potential to scale in LMIC markets.

Products were included in this landscape and further evaluated if they met the following criteria:

1. Solutions that were applicable to TB, COVID-19 or pneumonia
2. Solutions that were feasible to scale for use in LMIC markets
3. Solutions that were commercially available or in the late stages of development

The majority of the solutions identified corresponded to AI-enabled software used in the interpretation of results from medical imaging technologies. Of these, only solutions applicable to CXR or POC ultrasound were considered in scope. AI-based software developed for advanced imaging modalities, such as computed tomography (CT) and magnetic resonance imaging (MRI) were considered out of scope due to the current challenges in scaling-up the use of such imaging modalities in resource-constrained settings.

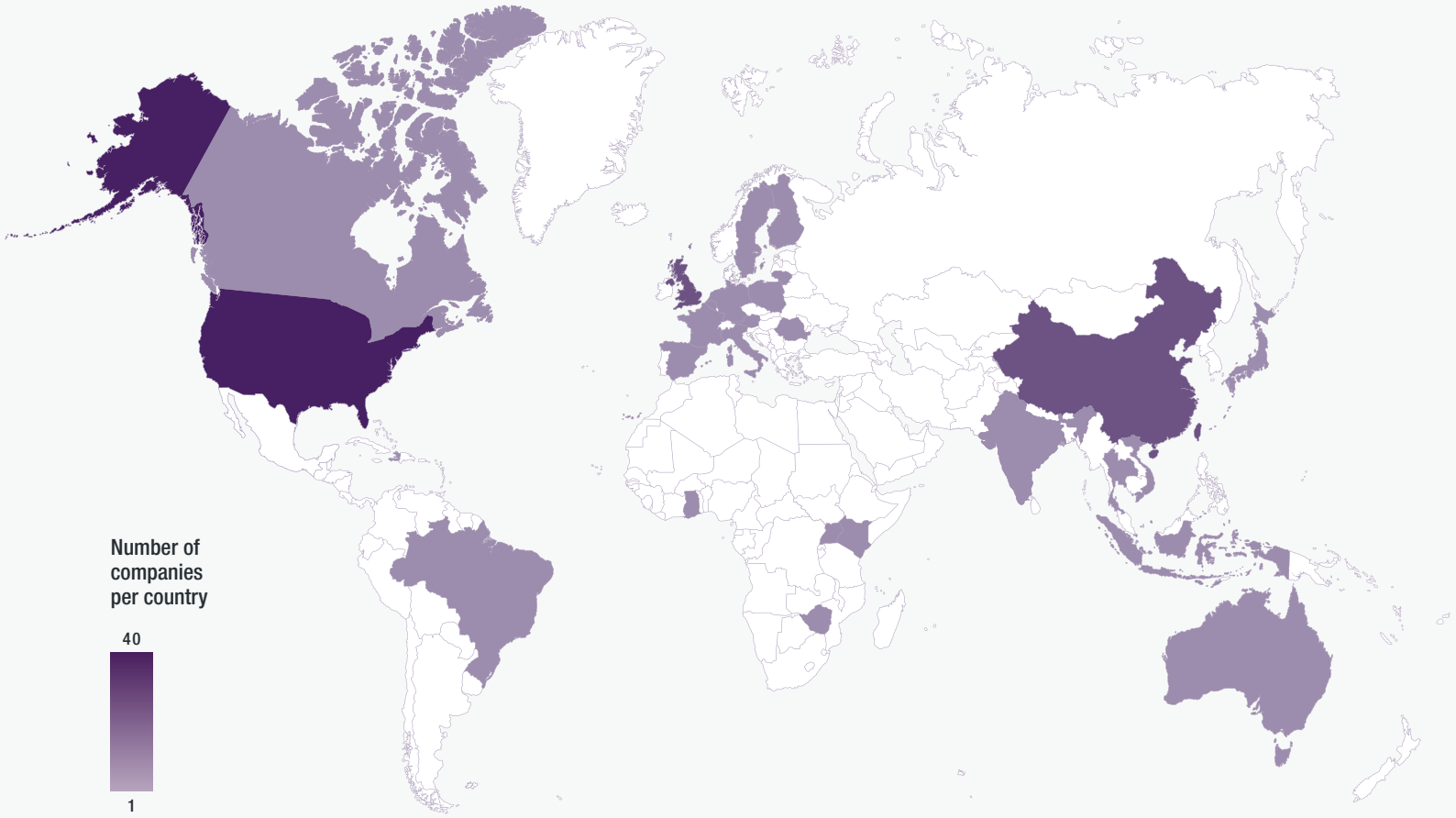
As a result of this process, 63 products were included for analysis. When a product was considered in scope, follow up interviews were performed to further clarify product maturity, regulatory status, and scale. Note that regulatory status were based on manufacturer claims. Where possible, stringent regulatory approval (SRA) claims were independently verified by FIND. Products were grouped by category based on the type of digital data collection (i.e. sounds, medical images, etc.) and the type of hardware involved in digital data capture (i.e. stethoscope, CXR).

4. Findings

4.1. Reviewed products

The initial review identified 159 technology solutions from 139 companies (**Appendix 2**). By continent, identified companies had headquarters based in Asia (n=49, 35%), North America (n=42, 30%), Europe (n=38, 27%), Oceania (n=5, 4%), Africa (n=4, 3%), and South America (n=1, 1%) (**Figure 1**). Only 12 solutions were developed by companies based in LMICs.

Figure 1. Location of company headquarters for developers of all identified solutions



Products were included in this landscape and further evaluated if they met the following criteria:

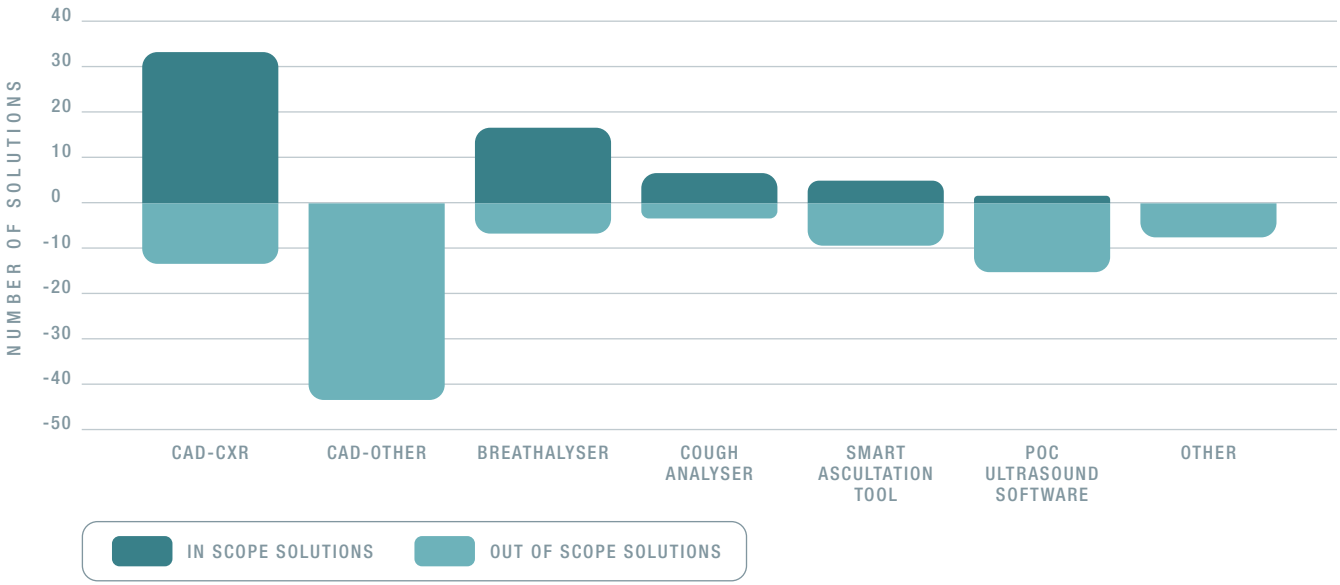
1. Read and interpret CXRs (CXR-CAD)
2. Interpret ultrasound images or movies (POC ultrasound software)
3. Read advance imaging modalities, like CT and MRI (CAD-other)
4. Interpret audio cough recordings (cough analyser)
5. Evaluate breath sounds by auscultation +/- other vitals (smart auscultation tool)
6. Evaluate exhaled breath condensate (breathalyser)

Other technologies, including pulmonary function testing and respiratory rate monitoring, which did not fit clearly into the above categories, were also included (Other).

4.2. Products in scope for the review

Of the 159 AI products evaluated, 63 products were deemed in scope for the landscape. The geographic distribution of the countries in which developers were based was similar for in scope products to that for all identified products (**Appendix 2**). As noted above, all software identified that did not leverage CXR or ultrasound based imaging were deemed out of scope for further review given the limited access to these imaging modalities in most high burden settings globally. An additional proportion of initially evaluated technologies was considered out of scope because there was no diagnostic output for the priority diseases for this review (TB, COVID-19, or other pneumonia). The total number of products identified in each category, including the number deemed in scope for the landscape, are shown in **Figure 2**.

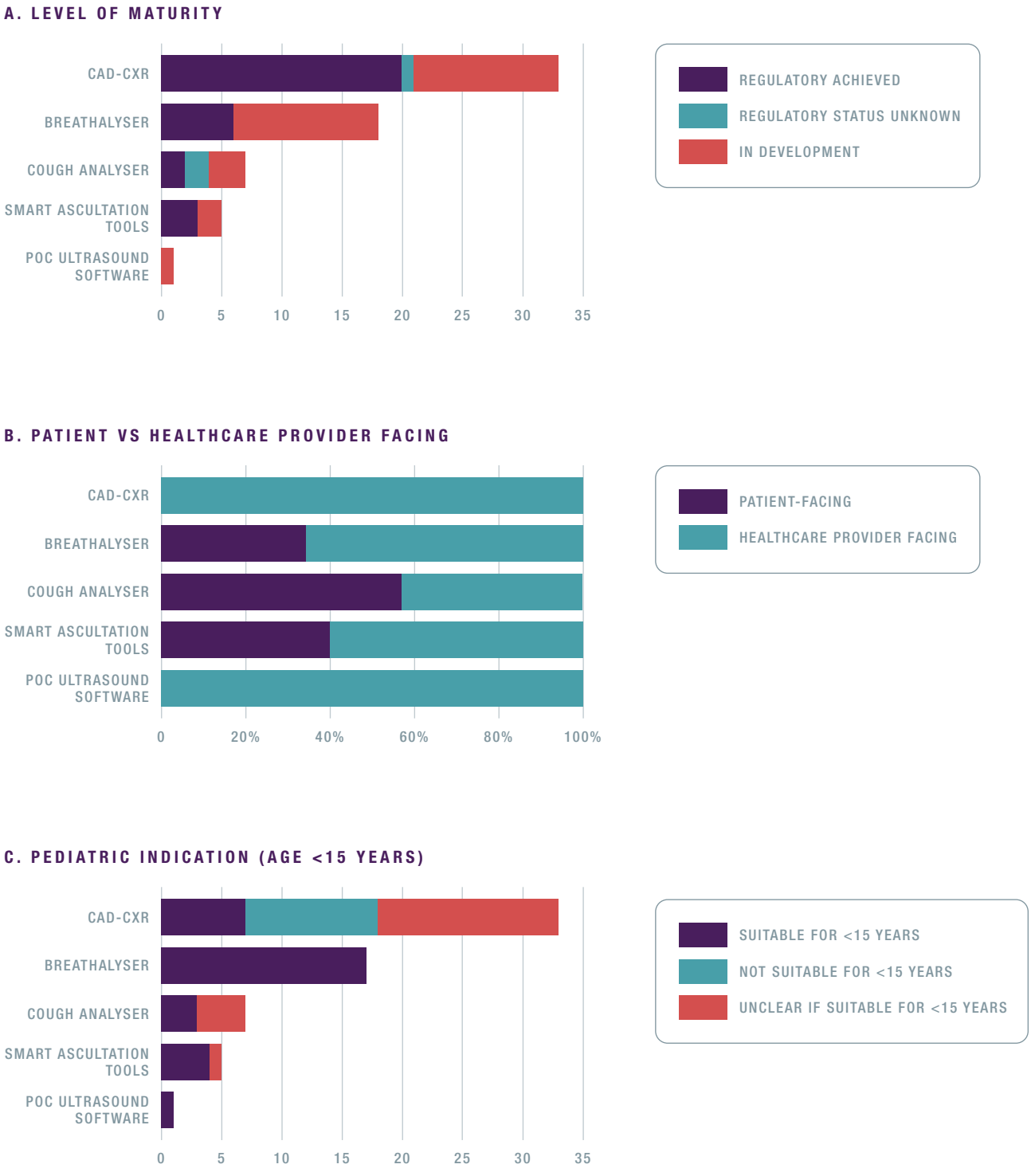
Figure 2. The different categories of solutions identified and their fit for use in the study



4.3. Description of in-scope AI-based products by category

Included technologies were placed in one of five categories of AI-based diagnostics for this review: CXR-CAD, POC ultrasound software, cough analysers, breathalysers and smart auscultation tools. These categories are detailed further in this section and in **Figure 3**. Overall, the field is in its early stages, with a wide range of intended future use cases among the technologies.

Figure 3. Overview and comparison of the different technologies for in-scope solutions



4.3.1. Computer-Aided Detection from Chest Radiographs (CXR-CAD)

Most (52%, n=33) of the AI-based solutions deemed in scope in this review were identified as CXR-CAD products (**Table 1**). This category included CAD software that reads digitized chest radiograph images and interprets the probability of findings consistent with a specific disease (TB, COVID-19, and/or pneumonia). For use of CAD software, a separate investment in a digital chest radiograph machine, or a method for digitizing analogue CXRs, is required. Of the CXR-CAD software reviewed, 28 products (85%) in this category gave an output for TB, 12 products (36%) gave a score or probability for COVID-19, and 12 products (36%) gave a probability score for other pneumonia. Only 3 of the identified products gave a probability score for all 3 diseases; these were JLD-02K (JLK Inspection, Inc.), DrAid (VinBrain), and DeepCheX (Taiwan AI Lab).

CXR-CAD products represented variable levels of maturity, with 20 products (61%) having achieved some regulatory approval for use, and 12 products (36%) still in development or validation; the status was not obtained for 1 product (3%). In most instances, FIND was unable to independently confirm whether regulatory approval was for the specific use cases evaluated (diagnosis of TB, diagnosis of COVID-19 or diagnosis of other pneumonia) and relied on developers for this information. However, most CXR-CAD developers sought regulatory approval for other indications as well, including differentiating normal vs. abnormal CXRs and identifying radiographic findings. Additionally, FIND is aware that many of the COVID-19 algorithms in this class have been removed from the market as the pandemic has evolved, likely further decreasing products with this use case.

Encouragingly, many CXR-CAD products were from LMIC-based developers, including Qure, DeepTek, Endimension, Artelus, Yantraakshi (India), Vinbrain (Vietnam), Dr CADx (Zimbabwe), Neural Labs Africa (Kenya), and Minohealth AI (Ghana). All CXR-CAD products required CXR equipment, were provider facing, and relied on trained healthcare providers for appropriate image acquisition, and appropriate use and optimization. Paediatric indications for use (age <15 years) were included for only 7 (21%) of these products. A significant number (n=15, 45%) did not clearly indicate whether use in children was indicated and 11 products (33%) were developed for use in adults only. A number of independent studies have evaluated CXR-CAD performance in LMICs populations for TB, and FIND has been active in this space.[2,3,7] Additionally, there is policy guidance from the World Health Organization (WHO) regarding this use case.[8]

Table 1. In-scope Computer-Aided Detection from Chest Radiographs (CAD-CXR) solutions

Technology Name	Company/ Institution Name	Company Headquarter location	Diseases and/or Lesions identified	Stage of development	Planned Market Entry	Stringent Regulatory Approval (SRA)*	Patient-facing vs healthcare professional-facing tool	Suitable for children under 15 years?
AXIR	RadiSen	Republic of Korea	Abnormalities; Tuberculosis	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	No
CAD4TB	Delft Imaging	Netherlands	Tuberculosis; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
Chest X-Ray Package	RADLogics	United States	Tuberculosis; COVID-19; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
Chest X-ray Pneumonia Detection Engine DoctorNet JLK-CRP	Doctor-NET Inc.	Japan	COVID-19; Pneumonia; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
ChestAI	ChestAI	United States	Tuberculosis; Pneumonia; Abnormalities	Late stage development (fully functional prototype)	Already on the market (commercialized)	Not applicable	Healthcare professional-facing	Unknown
Chexnet / Quibim	Standford ML group	United States	Pneumonia	Early stage development (partial prototype)	Unspecified Market Entry	Not applicable	Healthcare professional-facing	Unknown

Technology Name	Company/ Institution Name	Company Headquarter location	Diseases and/or Lesions identified	Stage of development	Planned Market Entry	Stringent Regulatory Approval (SRA)*	Patient-facing vs healthcare professional-facing tool	Suitable for children under 15 years?
CheXVision	Rayscape (formerly Xvision)	Romania	Tuberculosis; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
COVID-19 (CT + X-ray) algorithm	RADLogics	United States	COVID-19; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieve for some indications	Healthcare professional-facing	Unknown
DeepCheX	Taiwan AI Lab	Taiwan, Republic of China	Pneumonia; COVID-19; Tuberculosis; pneumothorax, nodule, ILD, and other lesions	Validation	Already on the market (commercialized)	Not applicable	Healthcare professional-facing	No
Dr CADx	Dr CADx	Zimbabwe	Tuberculosis; Lung cancer; Abnormalities	Validation	Unspecified Market Entry	Not applicable	Healthcare professional-facing	Yes
DrAid	VinBrain	Vietnam	Pneumonia; COVID-19; Tuberculosis; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	No
EIRL Chest Nodule	LPIXEL	Japan	Lung cancer; Tuberculosis; Pneumonia; Abnormalities	Early stage development (partial prototype)	Unspecified Market Entry	Not applicable	Healthcare professional-facing	No
ENDIM-AI-CXR	endimension	India	COVID-19; Abnormalities	Early stage development (partial prototype)	Unspecified Market Entry	Not applicable	Healthcare professional-facing	Unknown
Genki	Deeptek	India	Tuberculosis; COVID-19; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
ImagInfer	Yantraakshi	India	Tuberculosis; Abnormalities	Validation	Unspecified Market Entry	Not applicable	Healthcare professional-facing	Unknown
InferRead DR Chest	inferVISION	China	Tuberculosis; Pneumonia; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
INSIGHT CXR	Lunit	Republic of Korea	Tuberculosis; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
Inspectra CXR	Perceptra	Thailand	Tuberculosis; Pleural effusion; Lung opacity; Pulmonary oedema; Mass; Nodule; Cardiomegaly; Atelectasis	Regulatory achieved	Already on the market (commercialized)	Unclear if they have or are in the process for SRA	Healthcare professional-facing	No
JF CXR-2	JF Healthcare	China	Abnormalities; Tuberculosis; Pneumonia	Validation	Already on the market (commercialized)	Not applicable	Healthcare professional-facing	No
JLD-02K (JVIEWER-X)	JLK group	Republic of Korea	Tuberculosis; COVID-19; Pneumonia	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
Magic TB	Shenzhen Zhiying Medical Technology	China	Tuberculosis	Regulatory achieved	Already on the market (commercialized)	Unclear if they have or are in the process for SRA	Healthcare professional-facing	Unknown
minoHealth AI	MinoHealth AI Labs	Ghana	Abnormalities; Tuberculosis	Regulatory achieved	Already on the market (commercialized)	Unclear if they have or are in the process for SRA	Healthcare professional-facing	Unknown

Technology Name	Company/ Institution Name	Company Headquarter location	Diseases and/or Lesions identified	Stage of development	Planned Market Entry	Stringent Regulatory Approval (SRA)*	Patient-facing vs healthcare professional-facing tool	Suitable for children under 15 years?
NeuralSight for Chest Imaging	Neural Labs Africa	Kenya	Pneumonia; COVID-19; Tuberculosis; Musculoskeletal; Breast cancer	Validation	Unspecified Market Entry	Not applicable	Healthcare professional-facing	Unknown
OpenTB (provisional)	UFRJ	Brazil	Tuberculosis; Abnormalities	Early stage development (partial prototype)	Unspecified Market Entry	Not applicable	Healthcare professional-facing	No
qXR	qure.ai	India	Tuberculosis; COVID-19; Abnormalities; Lung cancer	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
RADIFY	Envisionit DEEP AI	United Kingdom	Tuberculosis; COVID-19; Pneumonia; Lung cancer; Pneumonia; Cardiac disease; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
Red Dot CxR	Behold.ai	United Kingdom	COVID-19; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	No
SenseCare Chest X-Ray	SenseTime	China	Abnormalities; Pneumonia; Tuberculosis	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
TiSepX TB	Medical IP	Republic of Korea	Tuberculosis; COVID-19; Abnormalities	Validation	Already on the market (commercialized)	Not applicable	Healthcare professional-facing	No
T-Xnet	Artelus	India	Abnormalities; Tuberculosis; Pneumonia	Validation	Unspecified Market Entry	Not applicable	Healthcare professional-facing	No
VUNO Med-Chest X-Ray, Pro	VUNO	Republic of Korea	Tuberculosis; Pneumonia; Lung cancer; Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	No
X1	VisionairyHealth	United States	Tuberculosis; Chronic obstructive pulmonary disease (COPD); Abnormalities	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
XrayAME	EPCON	Belgium	Tuberculosis; Abnormalities	Regulatory status unknown	Already on the market (commercialized)	Unknown	Healthcare professional-facing	Unknown

*We requested developers to share information regarding any certification achieved through a stringent regulatory authority for the intended use in COVID-19, TB, or pneumonia diagnosis. However, FIND did not independently verify claims. In many settings, it is likely that COVID-19 specific regulatory authorization was achieved through the emergency use pathways established during the pandemic. Additionally, non COVID-19 related certification may represent an approval by a de novo pathway process, or an alternate clearance mechanisms allowed for software that demonstrate equivalence to existing products.

4.3.2. POC ultrasound software

We did not identify any commercialized AI-enabled software for interpretation of images captured by POC, portable ultrasound equipment that met the inclusion criteria. One AI-based software in development was identified. This software, in development by an academic institution (EPFL, Lausanne, Switzerland) relied on lung ultrasound data collected from Africa and Europe to detect TB, COVID-19, and other pneumonia. This product was provider facing and relied on trained healthcare providers for use of POC ultrasound and image acquisition. It is trained on both adults and paediatric populations. However, data on performance characteristics and the commercialization strategy are not yet available. Although the authors believe other AI-based software that use POC lung ultrasound are in development for pneumonia and TB diagnosis, no other products were identified in this review.

4.3.3. Cough analyser

Seven products were identified that evaluated cough sounds to diagnose TB, COVID-19 and/or other pneumonia (**Table 2**). All of the products were built for use with a smartphone, increasing the potential to scale in resource limited settings. One product (TimBre) also required use of an external microphone. Only three products had achieved regulatory approval for use. One product (Hyfe) was commercially available to capture cough frequency over time, which was out of the scope of this review. However, developers informed us that this product also has diagnostic algorithms for TB and other pneumonia in development. Four products (57%) had a TB use case, 4 products (57%) had a COVID-19 use case and 2 products (29%) had a pneumonia use case. Three products (43%) were developed by companies based in LMICs. Of the total cough products identified, 4 (57%) were patient facing and 3 (43%) were designed for use by healthcare providers. Three products (43%) were indicated for paediatric use (age <15 years). Published studies on the use of these products that were identified in this review were performed with support from developers.[9] FIND is aware of studies underway to independently verify performance in diagnosing TB and other disease diagnoses in LMICs, which should add to the understanding of potential benefit.

Table 2. In-scope cough analysers

Technology Name	Company/ Institution Name	Company Headquarter location	Diseases and/or Lesions identified	Stage of development	Planned Market Entry	Stringent Regulatory Approval (SRA)*	Patient-facing vs healthcare professional-facing tool	Suitable for children under 15 years?
CoVawe	Docturnal	India	COVID-19	Early stage development (partial prototype)	2022	Not applicable	Patient-facing	Unknown
COVID-19 AI hierarchical diagnosis system based on cardiopulmonary auscultation	Tongji Hospital	China	COVID-19; Pneumonia	Early stage development (partial prototype)	Unknown	Not applicable	Healthcare professional-facing	Yes
Helfie AI Cough Detection App	Helfie.ai	Australia	COVID-19; Tuberculosis	Regulatory status unknown	Already on the market (commercialized)	Unknown	Patient-facing	Unknown
Hyfe AI	Hyfe	United States	Cough count and pattern; Tuberculosis (in development)	CE Mark 1 approved, FDA in review	Already on the market (commercialized)	SRA in application for some indications (cough count), not currently for TB diagnostics	Patient-facing	Yes
ResApp	ResApp Health (subsidiary of Pfizer)	Australia	Pneumonia; Asthma; Bronchiolitis; Chronic obstructive pulmonary disease (COPD)	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
Swaasa	Swaasa	India	COVID-19; Tuberculosis	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Unknown
TimBre	Docturnal	India	Tuberculosis	Validation	2022	Not applicable	Healthcare professional-facing	Unknown

*We requested developers to share information regarding any certification achieved through a stringent regulatory authority for the intended use in COVID-19, TB, or pneumonia diagnosis. However, FIND did not independently verify claims. In many settings, it is likely that COVID-19 specific regulatory authorization was achieved through the emergency use pathways established during the pandemic. Additionally, non COVID-19 related certification may represent an approval by a de novo pathway process, or an alternate clearance mechanisms allowed for software that demonstrate equivalence to existing products.

4.3.4. Breathalyser

Seventeen of the in-scope technologies in this review were classified as breathalyser devices (**Table 3**). Breathalysers work by analysing exhaled compounds that are either volatile organic compounds (VOC) or respiratory droplet/breath aerosols. The compounds captured are analysed using sensors or mass spectrometry/gas chromatography. AI can then be used to interpret the pattern of signals and associate patterns with specific diseases. In this review, breathalyseR devices identified were in scope based on diagnosis of COVID-19. Breathalysers are a less invasive strategy for mass screening of viral infection than traditional swab testing, which may make them advantageous for diagnosing viruses. Although some products received an emergency use authorization during the pandemic, the ability of some of these tools to identify COVID-19 in a non-pandemic context with other circulating viruses has yet to be demonstrated.

Despite making up the second-largest grouping of in-scope technologies, most breathalysers were still in development (n=11, 65%), with only 6 (35%) having achieved regulatory approval. None of the breathalyser developers were based in LMICs. Most solutions were developed for use by healthcare professionals (n=11, 65%) and only 6 products (35%) were patient facing. All breathalyser solutions identified in this review were indicated for use in adults and children (<15 years).

Table 3. In-scope breathalysers

Technology Name	Company/ Institution Name	Company Headquarter location	Diseases and/or Lesions identified	Stage of development	Planned Market Entry	Stringent Regulatory Approval (SRA)*	Patient-facing vs healthcare professional-facing tool	Suitable for children under 15 years?
ASU Detect CV-19	Canary Global	Canada	COVID-19	Validated/initial clinical studies	Unknown	Not applicable	Healthcare professional-facing	Yes
Avisa BreathTest	Allora Diagnostics	United States	Community-acquired pneumonia; Cystic fibrosis; Tuberculosis	Validated/initial clinical studies	Unknown	Not applicable	Healthcare professional-facing	Yes
BREATHGUARD	BreathDX.ai	United States	COVID-19; Colorectal cancer; Lung cancer	Validation	Unknown	Not applicable	Healthcare professional-facing	Yes
BreathX	MENSSANA Research UK	United Kingdom	Breast cancer; Lung cancer; Pulmonary tuberculosis	Validation	Unknown	Not applicable	Patient-facing	Yes
BreFence Go COVID-19 Breath Test System	Breathonix	Singapore	COVID-19	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
CoronaCheck	Exhalation Medical Technology	United Kingdom	COVID-19	Validated/initial clinical studies	Unknown	Not applicable	Healthcare professional-facing	Yes
DiaNose	Nanose Medical	Israel	COVID-19; Other respiratory diseases	Validated/initial clinical studies	Unknown	Not applicable	Patient-facing	Yes
DSA BREATHPASS	Deep Sensing Algorithms	Finland	COVID-19	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
GeNose C19	Swayasa Prakarsa	Indonesia	COVID-19	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
InspectIR PNY-1000	InspectIR Systems	United States	COVID-19	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
Moja Scan	Moja	Germany	COVID-19; Malaria; Tuberculosis	Validated/initial clinical studies	Unknown	Not applicable	Healthcare professional-facing	Yes
Rapid Biosensor	Rapid Biosensor Systems	United Kingdom	Tuberculosis	Validated/initial clinical studies	Unknown	Not applicable	Healthcare professional-facing	Yes
Sotech	Sotech Health	United States	COVID-19	Validation	Unknown	Not applicable	Patient-facing	Yes
ThEA Diagnostic Platform	RAM Group Global	Germany	COVID-19	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Patient-facing	Yes
TracieX Breathalyser	Silver Factory Technology	Singapore	COVID-19	Regulatory achieved	Unknown	SRA achieved for some indications	Healthcare professional-facing	Yes
TVD-2 Breathalyser	GreyScan	Australia	COVID-19; Other respiratory diseases	Validated/initial clinical studies	Unknown	Unknown	Patient-facing	Yes
ViraWarn	Opteev	United states	COVID-19; Influenza; RSV	Validation	Unknown	Not applicable	Patient-facing	Yes

*We requested developers to share information regarding any certification achieved through a stringent regulatory authority for the intended use in COVID-19, TB, or pneumonia diagnosis. However, FIND did not independently verify claims. In many settings, it is likely that COVID-19 specific regulatory authorization was achieved through the emergency use pathways established during the pandemic. Additionally, non COVID-19 related certification may represent an approval by a de novo pathway process, or an alternate clearance mechanisms allowed for software that demonstrate equivalence to existing products.

4.3.5. Smart auscultation tool

Five of the in-scope technologies identified in this review were classified as smart auscultation devices (**Table 4**). The devices used AI to interpret audio files from digital respiratory auscultation or breath sounds measurements. All devices (100%) had additional capabilities, and measured a combination of vital signs (including temperature, respiratory rate, pulse, and/or oxygen saturation), and vitals were used as a component of their diagnostic AI algorithm. For all of these devices, the product included both hardware and software in a single device, although all devices also required use of a connected smartphone for interpretation. Three products (60%) had achieved regulatory approval, and all devices were designed with a pneumonia use case. One device also indicated use in diagnosis of COVID-19 (Onescope). No devices had a TB- specific use case. Only one device (MamaOpe) was developed by a company based in an LMIC, and three devices (60%) were designed to be used by trained healthcare providers. Most devices (n=4, 80%) had a paediatric indication. Similar to the cough devices, identified publications for these products were developer supported.[10] Independent device evaluations would again be of value in better clarifying benefit in other clinically relevant populations.

Table 4. In-scope smart auscultation tools

Technology Name	Company/ Institution Name	Company Headquarter location	Diseases and/or Lesions identified	Stage of development	Planned Market Entry	Stringent Regulatory Approval (SRA)*	Patient-facing vs healthcare professional-facing tool	Suitable for children under 15 years?
Feelix Digital Stethoscope	Sonavi Labs	United States	Abnormalities; Pneumonia; Asthma; Cystic fibrosis	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
Isteso-D2	MinttiHealth	China	Pediatric pneumonia; Child asthma; Elderly bronchitis	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Healthcare professional-facing	Yes
MamaOpe	MamaOpe Medicals	Uganda	Pneumonia; Abnormalities	Early stage development (partial prototype)	Unspecified Market Entry	Not applicable	Patient-facing	Yes
Onescope	Onescope	Switzerland	COVID-19; Pneumonia; Asthma	Validation	2023	Not applicable	Healthcare professional-facing	Yes
StethoMe	StethoMe	Poland	Abnormalities; Pneumonia; Bronchitis; Asthma	Regulatory achieved	Already on the market (commercialized)	SRA achieved for some indications	Patient-facing	Yes

*We requested developers to share information regarding any certification achieved through a stringent regulatory authority for the intended use in COVID-19, TB, or pneumonia diagnosis. However, FIND did not independently verify claims. In many settings, it is likely that COVID-19 specific regulatory authorization was achieved through the emergency use pathways established during the pandemic. Additionally, non COVID-19 related certification may represent an approval by a de novo pathway process, or an alternate clearance mechanisms allowed for software that demonstrate equivalence to existing products.

5. Discussion

This landscape was developed to identify promising new digital tools that use AI to diagnose TB, COVID-19, and other respiratory infections. There are a number of key takeaways from this landscape to highlight.

First, the majority of the AI products we identified in this review leveraged medical imaging, including chest radiograph, ultrasonography, and other imaging modalities. This observation is similar to what is reported by stringent regulatory bodies. This finding mirrors landscapes of AI-based technologies reviewed by the FDA and other regulatory bodies for use in high income countries and demonstrates the relative maturity of AI for use with medical imaging.[11,12] CXR-CAD represented a large share of the products included in this setting, and this field has the potential to be a pathfinder in global health, given the established policy on use, the number of developers in the field, and the increasing availability of highly portable CXR equipment.[13] However, as new products and versions of CXR-CAD software reach the market, it is imperative that independent evaluations are conducted to define their use and limitations in high burden populations, and to drive informed decisions regarding procurement and implementation. We believe that use of AI with POC ultrasound may have the potential to further increase reach, as POC ultrasound is generally more portable that even the most highly portable digital CXR equipment, and use of ultrasound has potential for diagnosing other high burden diseases, including non-communicable diseases, which may further improve the return on investment. For our use cases, we felt that CT, MRI and other advanced imaging modalities were unlikely to scale in LMICs. However, there is vast heterogeneity in access to advance imaging modalities in LMICs settings, and new technologies exist which may increase access to these tools in the future.[14] Should this hardware be more available in the future, this would open up use of a number of other AI-based products which interpret advanced medical imaging data to diagnose high burden diseases.

Second, although evidence for the benefit of cough and digital auscultation tools is less well defined, these tools also have the potential to address shortages of healthcare providers, especially in the last mile. In instances where access to a cardiorespiratory physician is limited, which are commonly seen in settings where the burden of TB and other respiratory infections are high, these tools have the potential to augment the provider clinical exam, and improve the efficiency of triage, diagnosis, and treatment. Furthermore, some tools in this category are patient facing, and, in the instance of many cough tools, require only a smart phone to scale. However, as this field is nascent, more evidence is needed to define the diagnostic accuracy of these tools in different settings, their placement in the care pathway, the level of training needed for the user to optimize use, and how to scale.

Lastly, breathalysers have the potential to play a role in improving the diagnosis of pneumonia if this field matures. Similar to the use of cough and digital auscultation tools, better evidence is needed to define diagnostic accuracy. Additionally, as these tools are currently primarily used in laboratory settings, their ability to scale to the last mile would require development to allow for near-POC testing.

Given the shortage of professionally trained medical personnel, and the limited infrastructure of health systems in LMICs, it is important for global stakeholders to consider AI-assisted respiratory diagnostic tools, and to influence development and evidence generation to consider users and patients in high burden populations. Given the potential that these technologies could have in resource-constrained settings, and given that respiratory diseases are a leading cause of morbidity and mortality in LMICs, development and deployment of these tools to meet that need holds significant promise to impact health globally.

6. Overall limitations of the analysis

THIS ANALYSIS HAD A NUMBER OF INHERENT LIMITATIONS AS FOLLOWS:

1. First, despite our efforts at identifying new developers and technologies, we are aware that this field is rapidly evolving, and new evidence and products are likely to have evolved. As a result, **THE PRODUCTS REPRESENTED IN THIS LANDSCAPE MAY HAVE ADDITIONAL EVIDENCE FOR USE.** We encourage stakeholders considering use of these technologies to engage with content experts and developers to better inform decision making.

2. Second, this landscape was informed by conversation with key stakeholders and via a review of the literature listed in **APPENDIX 1**. We acknowledge that **THERE ARE INHERENT BIASES THAT INFLUENCED DEVELOPERS WHO WERE SOUGHT FOR INCLUSION IN THE LANDSCAPE.** Future literature reviews and landscapes by others in the AI space may further inform stakeholders.

3. Third, we relied on developers to provide information regarding these tools, including regulatory approval, uses, and priority populations considered in development. Therefore, **FUTURE INDEPENDENT VALIDATION IS NEEDED BY NEUTRAL BODIES** to substantiate developers' claims for use.

4. Lastly, we are aware that **THERE ARE A NUMBER OF COMMERCIALLY AVAILABLE TECHNOLOGIES WHICH WERE CONSIDERED OUT OF SCOPE** because, at the current time, these developers are focused on use cases in high income countries. It is likely that, as some of these developers scale their AI-based solutions, they may demonstrate benefit for use in LMIC populations and for the high burden diseases included in this review.

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Appendix 2: Detailed list of products considered for inclusion in this landscape

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