BMJ Public Health

Assessment of radiological capacity and disparities in TB diagnosis: a comparative study of Mozambique, South Africa and Spain

Isabelle Munyangaju ,[1,2,3] Benedita José,[4] Quique Bassat,[1,3,5,6,7] Ridwaan Esmail,[8] Liebe Hendrietta Tlhapi,[9] Mqondisi Maphophe,[9] Crimenia Mutemba,[4] Loide Cossa,[4] Patricia Perez,[10] Megan Palmer,[11] Vanessa Mudaly,[12] Eliseo Vañó Carruana,[13] Richard D Pitcher,[14] Elisa Lopez Varela,[2] Isabelle Thierry-Chef[1,2,3]

To cite: Munyangaju I, José B, Bassat Q, *et al*. Assessment of radiological capacity and disparities in TB diagnosis: a comparative study of Mozambique, South Africa and Spain. *BMJ Public Health* 2024;**2**:e001392. doi:10.1136/bmjph-2024-001392

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bmjph-2024-001392).

Received 29 April 2024
Accepted 3 September 2024

Check for updates

© Author(s) (or their employer(s)) 2024. Re-use permitted under CC BY-NC. Published by BMJ.

For numbered affiliations see end of article.

Correspondence to
Dr Isabelle Munyangaju; imunyangaju@gmail.com

ABSTRACT

Background Tuberculosis (TB) remains a significant global health challenge, particularly in children, where diagnosis is challenging. Radiological resources such as chest X-rays and CT scans play a crucial role in early screening and diagnosis, especially in the absence of microbiological confirmation of disease. However, radiological capacity and access vary widely across regions and countries.

Methods This study retrospectively audited licensed X-ray and CT units in Mozambique, South Africa and Spain in 2022. Population data were used to calculate units per million people. The study used choropleth maps to visualise regional disparities and to explore potential interactions between radiological capacity, population density and TB notifications.

Results Mozambique had the lowest radiological capacity, with 3.6 X-ray units and 0.4 CT units per million people, compared with South Africa's 34.2 X-ray units, 5.8 CT units and Spain's 811.5 X-ray units and 19.3 CT units. The private sector exhibited higher capacity than the public sector in all countries. Regional disparities were evident, particularly in Mozambique, highlighting urban–rural discrepancies and in-country inequalities.

Conclusion This study underscores significant disparities in radiological capacity between low-income, middle-income and high-income countries, with economic factors playing a pivotal role. Addressing these disparities is crucial for improving TB and other disease diagnostic capabilities, particularly in resource-limited settings. Potential solutions include establishing dedicated national radio-diagnostic departments, developing national guidelines and integrating portable AI-powered X-ray or point-of-care ultrasonography technology. These findings provide valuable insights for policymakers and stakeholders to advocate for improved radiological resources and equitable healthcare access.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Imaging technologies such as chest X-rays and CT scans are essential for early tuberculosis detection and management but are unevenly distributed, particularly in low-income and middle-income countries (LMICs).

WHAT THIS STUDY ADDS

⇒ The study highlights significant disparities in radiological capacity between Mozambique and other countries, revealing regional inequalities within countries and suggesting that economic factors may have a greater impact on radiological resource availability than disease burden.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The study highlights the need for targeted interventions to improve radiological infrastructure in LMICs, including dedicated national radiological departments, national guidelines and advanced technologies.

INTRODUCTION

Tuberculosis (TB) still exists as a global health problem and remains one of the leading causes of mortality by an infectious agent every year.[1] Although the highest burden of TB disease is in adults, children make up 10%–20% of TB cases.[2 3] There are significant challenges related to TB diagnosis in infancy and childhood,[4 5] where forms of the disease differ considerably from those seen in adults. In TB diagnosis, microbiological examination can confirm the disease, but radiological resources (such as chest X-rays (CXR) and computed tomography (CT) scans) play a crucial role in early screening and diagnosis. For screening, imaging can identify intrathoracic abnormalities before symptoms appear, aiding in early detection.[6–8] In the context of diagnostic algorithms, these tools are valuable for early diagnosis, which can

Table 1 Registered radiological units in absolute numbers and per million people, including population density and TB notifications (for country, highest and lowest resourced provinces/regions)

Country: province/ autonomy (population, 10^6)	Population density (people/km^2)	TB notifications 2022 (per 100 000)	X-ray			CT scan		
			Public	Private	Number per million	Public	Private	Number per million
Mozambique								
Total (31.6)	39.4	350	95	20	3.6	6	6	0.4
Niassa (2.1)	16.5	245.5	5	0	2.3	2	0	0.9
Zambezia (5.9)	55.8	383.8	8	0	1.4	0	0	0
Sofala (2.6)	38.2	509.9	14	4	6.9	1	2	1.2
Maputo City (1.1)	3257.4	579	6	5	9.7	1	4	4.4
South Africa								
Total (62.0)	50.8	362.4	–	–	34.2	106	251	5.8
Northern Cape (1.4)	3.6	529.2	–	–	59.0	1	4	3.7
Gauteng (15.1)	830.6	210.8	–	–	34.6	27	94	8.0
Eastern Cape (7.2)	42.8	650.7	–	–	19.4	6	8	1.9
Free State (3.0)	22.8	334.8	–	–	46.9	9	18	9.1
Spain								
Total (47.5)	94.0	7.7	–	–	811.5	–	–	19.3
Melilla (0.08)	6764.1	7.2	–	–	444.7	–	–	12.0
Andalucía (8.5)	97.6	5.6	–	–	798.0	–	–	19.3
Extremadura (1.1)	25.3	2.7	–	–	832.6	–	–	27.5

TB, tuberculosis.

significantly reduce disease progression, transmission rates and mortality, especially in populations such as children and people living with HIV, who often present with paucibacillary disease.[9–11]

Imaging forms an important component of comprehensive screening and diagnostic algorithms that also include clinical assessments, microbiological tests and other relevant investigations.[4 6 12] Subclinical TB (the presence of active *Mycobacterium tuberculosis* bacteria in the body without the accompanying typical symptoms) can also be detected with radiological techniques before overt clinical symptoms appear, allowing early treatment and containment.[13] Moreover, microbiological detection in young children is challenging due to difficulties in obtaining good-quality sputum samples, which are often insufficient or contaminated with saliva. This underscores the importance of imaging in diagnosing TB in children.[11 14] Current WHO guidelines recommend the use of radiological imaging (especially CXR) as a screening and diagnostics tool for TB.[6]

These resources are, however, unevenly accessible, and the efficiency of their utilisation differs between different regions and countries. Past studies in low-income and middle-income countries (LMICs) highlight the challenges and disparities in radiological capacity. For example, the WHO recommends one X-ray and one ultrasound machine for every 50 000 people, or 20 units per million people, in LMICs to fulfil imaging needs.[15] Studies in Africa reveal that Uganda, Tanzania, Zambia and Ghana fall short of this benchmark (9–14 X-ray units per million people). In contrast, Zimbabwe, Kenya and South Africa while exceeding the WHO recommendation, still lag behind the Organisation for Economic Cooperation and Development (OECD) countries in imaging capacity. In all studies, regional disparities were also the norm within a country.[16–21] No similar benchmark was found for CT scan machines.

Two recent Lancet commissions[22 23] underscored the critical need for improved access to imaging technologies, particularly CXR and CT scans, for the diagnosis and management of various diseases including TB. The findings reveal significant variations in the availability and distribution of radiological equipment, with many LMICs facing shortages and inadequate infrastructure. The studies also emphasise the importance of strengthening healthcare systems and implementing policies to address these gaps in radiological capacity, ultimately improving TB and pulmonary disease management in LMICs.

Despite several studies conducted in LMICs to assess radiological capacity,[16–25] data on Mozambique's availability and capacity are scarce. Furthermore, no studies have compared Mozambique's radiological capacity with its socioeconomic status and disease burden. These research gaps create a significant knowledge void regarding the distribution and adequacy of radiological

Munyangaju I, *et al*. *BMJ Public Health* 2024;**2**:e001392. doi:10.1136/bmjph-2024-001392

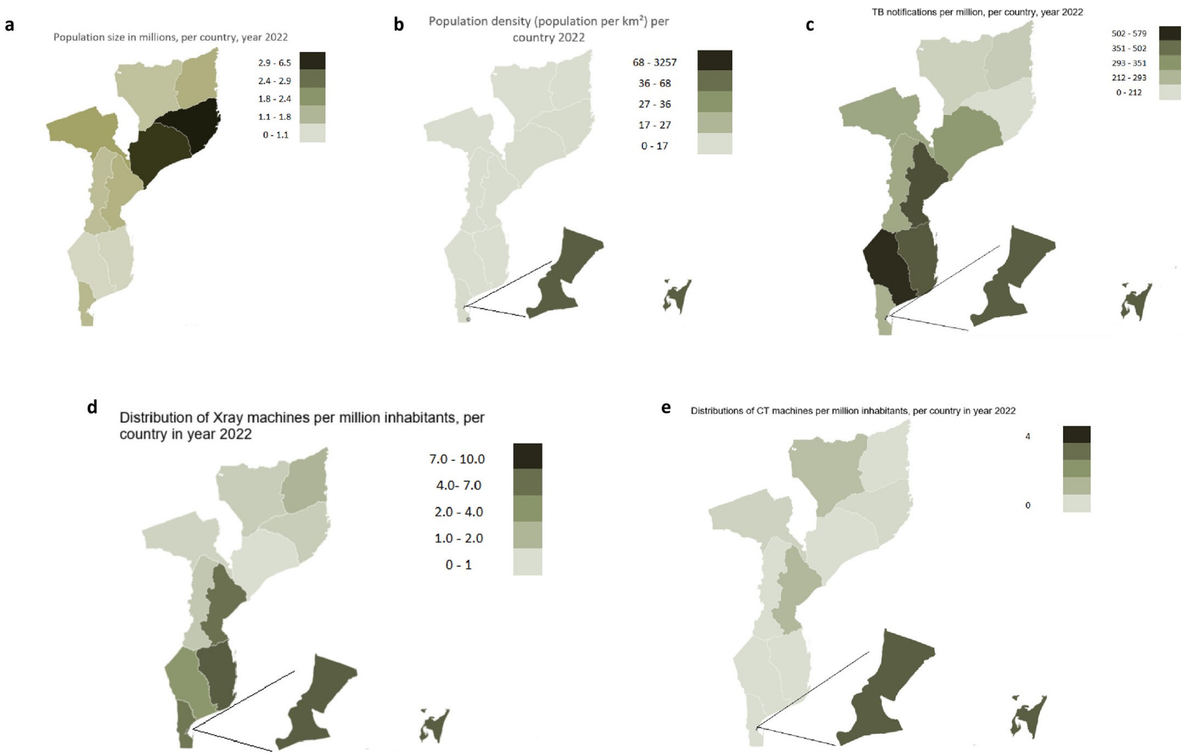

Figure 1 Choropleth map for Mozambique (Source: prepared by author).

resources across different global health contexts. A country's radiological capacity can be impacted by many factors, including its economy, availability of specialised workforce, incidence of trauma and various disease burdens.

In this study, we use TB as a paradigmatic disease that requires radiological evaluation, serving as a potential proxy (although imperfect) for radiological requirements. We aim to assess Mozambique's radiological capacity and compare it with diverse socioeconomic and TB disease burden settings. Additionally, we aim to contextualise Mozambique's reality by comparing it with a middle-income and high-income country as well as a high TB burden and a low TB burden country. Specifically, we focus on Spain as an example of a high-income country and South Africa as an example of a middle-income country.

MATERIALS AND METHODS

Study design

We conducted a retrospective audit of licensed X-ray and CT units registered as active in 2022 in Mozambique.[26] To carry out the comparative analysis, we equally carried out a similar audit in South Africa and Spain. The study was conducted between March and October 2023, in collaboration with the Mozambican National TB Programme and National Imaging Division, the South African Health Products Regulatory Authority (SAHPRA) and the Spanish Nuclear Security Council (Consejo de Seguridad Nuclear).

Study area

The study was conducted in three countries with different income statuses and TB disease burden: Mozambique, South Africa and Spain. Mozambique is a low-income country with a high TB and HIV burden (TB incidence of 361 cases per 100 000 and HIV prevalence of 11.6% in the 15–49 years age group).[1 27] Mozambique has a gross domestic product (GDP) per capita of US$558.3 and health expenditure per capita of US$34.28.[28] The National Health Service of Mozambique operates on four levels of healthcare: primary, secondary, tertiary and quaternary. Health services are provided by both public and private sectors, with the public sector being the main provider. Integrated primary healthcare is the primary focus of the health system.[29 30]

As of 2019, HIV/AIDS, neonatal disorders, TB, malaria and stroke were the top causes of all age groups mortality in Mozambique.[31 32] Data from 2014 to 2015 indicate that about 90% of Mozambicans used public health facilities, 3.9% used private health facilities and 5.2% sought traditional medicine services. As of 2019, the ratio of public to private health facility utilisation was 88:12. Private health facilities were primarily present at the primary and secondary healthcare levels, with no significant presence at higher care levels.[33] A large proportion of Mozambique's population (66.7%) resides in underserved areas, where walking to a health clinic takes more than 60 min.[34] Additionally, for 76.7% of the population, the average distance to a health clinic is 10 km, further complicating access to primary healthcare centres.[35]

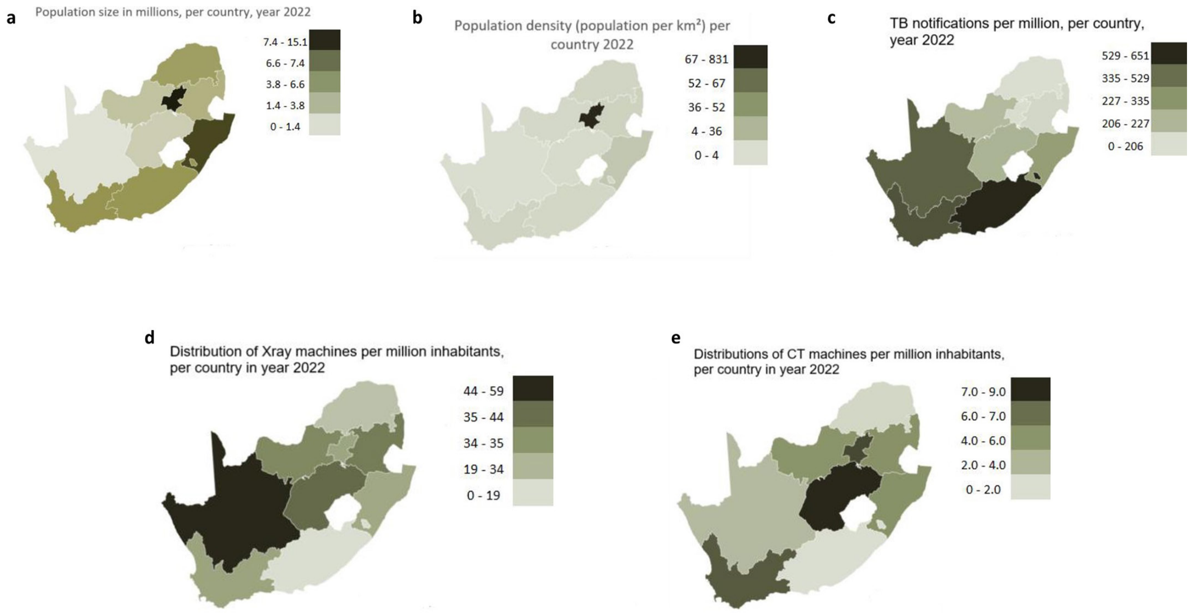

Figure 2 Choropleth map for South Africa (Source: prepared by author).

South Africa is a middle-income country with a high TB and HIV burden (TB incidence: 468 per 100 000; HIV prevalence (15–49 years): 17.8%).[1 27] South Africa has a GDP per capita of US$6766.5 and a health expenditure of US$489.64.[28] Significant inequalities exist between South Africa's public and private healthcare sectors. Nearly three-quarters of the population (71%) is served by an underfunded public sector, financed by the state. Around 27% of the population is served by the private sector, which is largely funded by individual contributions to medical aid schemes.[36] While infectious diseases like HIV/AIDS, lower respiratory infections and TB continue to impose a significant burden on the healthcare system, there has been a notable rise in the prevalence of non-communicable diseases such as ischaemic heart disease, stroke and diabetes.[32 37]

Spain is a high-income country with low TB and HIV burdens (TB incidence: 6.9 per 100 000; HIV prevalence (15–49 years): 0.2%).[1 27] It has a GDP per capita of US$29 674 and a health expenditure per capita of US$2900.65.[28] The Spanish healthcare system (SNS) consists of three main subsystems: the universal national health system, mutual funds for civil servants and the armed forces and judiciary, along with collaborative mutualities. Spain's residents receive comprehensive benefits through the national health system, funded through general taxes. Regional health authorities oversee regional planning, resource allocation and purchasing decisions while the Ministry of Health oversees national health planning and regulations. In Spain, 96.5% of the population is served by the SNS while 3.5% is served by private entities.[38] Despite recent increases, health expenditure in Spain remains below the European Union average.[39] In Spain, non-communicable diseases pose the greatest burden in terms of health impact.[32 40]

Data collection

In Mozambique, TB programme provincial focal points were responsible for manual data collection, which was subsequently double-checked by the national imaging division, since reorganised. In South Africa, data were extracted from SAHPRA's official database. Data from Spain were collected from the Spanish Nuclear Safety Council's Report to the Congress and Senate for 2022, as well as the National Catalogue of Hospitals for 2023 (updated as of 31 December 2022).[41 42] The data were compiled into a dedicated Excel spreadsheet and stratified by imaging techniques (X-rays and CT scans), regions and healthcare sectors (the public vs private). All other imaging techniques were excluded from the analysis.

Mozambique was the only country able to provide data disaggregated by public and private sectors for all imaging modalities (CXR and CT scan). In South Africa and Spain, only CT scan data were disaggregated by the public versus private sector.

Additionally, in Mozambique, particularly in the central and northern regions, private clinics did not have radiological services. Instead, they relied on public sector radiology services for a fee. This lack of data made it difficult to precisely calculate the units per million people covered by the public sector for all three countries.

Data analysis

Based on the latest population estimates in the three countries, the results for each imaging technique were tabulated as units per million people by country and region. In Mozambique, we used the population projections for the year 2022 provided by the National Institute of Statistics.[43] For Spain, we used continuous population statistics from the National Institute of Statistics for the

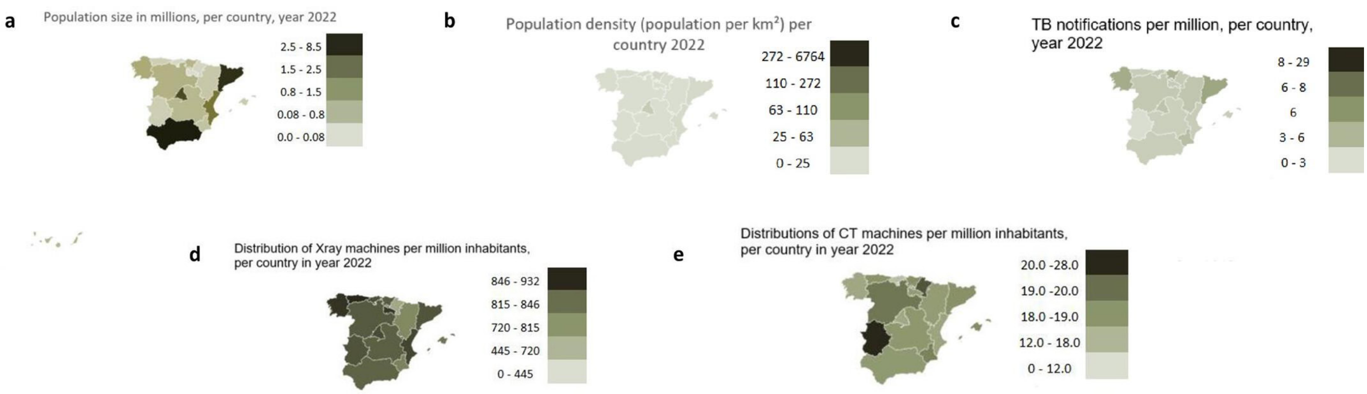

Figure 3 Choropleth map for Spain (Source: prepared by author).

year 2022.[44] The South African population data came from Statistics South Africa's census of 2022.[45]

To analyse in-country radiological inequalities, we used choropleth maps (with Excel Bing maps) to compare, within each country, the distribution of X-ray and CT units per million people with regional population, population density and TB notifications. Additionally, we conducted a regression analysis to further explore the observed relationship between independent variables (population density and TB notifications) and the dependent variable (X-ray or CT capacity) using IBM SPSS Statistics V.22.0, with a significance level of 0.05.

Population density was calculated using the formula population density=number of people/land area (km²). Land area data for each country were obtained from the following sources: Mozambique (https://en.wikipedia.org/wiki/Provinces_of_Mozambique), South Africa (https://en.wikipedia.org/wiki/List_of_South_African_provinces_by_area) and Spain (https://en.wikipedia.org/wiki/Autonomous_communities_of_Spain).

The TB notification rates for Mozambique were obtained from the National TB Programme's monitoring and evaluation unit. For South Africa, the TB notification rates were sourced from DS-TB data from ETR.Net (2018) and TIER.Net (2019–2022), and DR-TB data from EDRWeb (Aurum Institute). In Spain, the TB notification rates were obtained from the Spanish Tuberculosis Prevention and Control Plan.[46]

Finally, we compared the data with previous studies and with OECD data, particularly focusing on CT scan capacity.

Patient and public involvement

This study did not involve the public or patients in its design, as it focused on a retrospective analysis of radiological capacity using data from national registries. Due to the nature of the research, which did not involve direct interactions or interventions with patients or the public, their involvement in the study design was not required.

RESULTS

Radiological capacity by country

In 2022, Mozambique had a total of 115 X-ray machines and 12 CT scanners nationwide, with the numbers varying from 5 to 18 for X-ray machines and 0 to 5 for CT scanners across the provinces. In terms of units per million people, Mozambique had 3.6 X-ray units per million people, ranging from 1.4 to 9.7 units per million people depending on the province. For CT scans, Mozambique had 0.4 CT units per million people, ranging from 0 to 4.4 units per million people depending on the province. Assuming that the public sector serves 90% of the population and the private sector serves 3.9% in Mozambique (with the remaining population served by traditional healers),[33] the X-ray capacity per million people is 3.34 in the public sector compared with 16.22 in the private sector. For CT scans, the capacity per million people is 0.21 in the public sector and 4.86 in the private sector.

South Africa had a total of 2124 X-ray machines and 357 CT scanners nationwide in 2022, with the numbers varying from 80 to 522 for X-ray machines and 5 to 121 for CT scanners across provinces. Based on units per million people, South Africa had 34.2 X-ray units per million people, ranging from 19.4 to 59.0 X-ray units per million people across provinces. For CT scans, South Africa had 5.8 CT units per million people, ranging from 1.9 to 9.1 CT units per million people across provinces. In South Africa, the public sector serves 71% of the population and has 2.41 CT scan units per million people while the private sector serves 27% of the population and has 14.98 units per million people. Traditional healers serve the remaining population.[36]

Spain had a total of 38 553 X-ray machines and 919 CT scanners nationwide in 2022, with the numbers varying from 37 to 6797 X-ray machines and 1 to 164 CT machines across autonomous regions. According to the data per million people, Spain had 811.5 X-ray units per million people, ranging from 444.7 to 932.2 X-ray units per million people across autonomous regions, and 19.3 CT units per million people, ranging from 12.0 to 27.5 CT units per million people across autonomous regions. In Spain, the public sector serves 96.5% of the population[38] and has 13.69 CT scan units per million people.

Table 2 Comparison of radiological resources, economic status and population of current study countries, previous studies and OECD countries

	LMICs in Africa					OECD countries (Colombia at lower end, Japan at higher end)		
	Mozambique	Uganda	Zimbabwe	Zambia	South Africa	Colombia	Spain	Japan
Population (10^6)*	32	47	15	20	62	52	47	125
Area (km^2)†	801 537	241 038	390 745	752 614	1.2 mil	1.14 mil	506 030	377 973
GDP per capita ($) (2022)‡	558	964	1307	1453	6766	6842	29 674	33 851
Current health expenditure per capita ($) (2020)‡	34	34	51	54	490	477	2901	4388
X-ray units (per 10^6 inhab.)	3.6	12.8	26	14.3	34.2		811.5	
CT scan units (per 10^6 inhab.)	0.4	0.6	1.5	0.79	5.8	6	19.3	116

*Macrotrends.net.
†Wikipedia.
‡World Bank.
GDP, gross domestic product; LMICs, low-income and middle-income countries; OECD, Organisation for Economic Cooperation and Development.

In contrast, the private sector serves 3.5% of the population[38] and has 175 CT scan units per million people.

Table 1 presents the registered radiological units in absolute numbers and per million people, alongside population density and TB notifications, both at the country and provincial levels. We specifically highlight the provinces with the highest and lowest resources (X-ray and/or CT) in each country. For a comprehensive reference to all provinces per country, please refer to online supplemental file 1.

Existing disparities within countries

In the choropleth map of Mozambique (figure 1a–e), there is inequity in access to radiology services between the southern and the northern provinces. Provinces with the highest TB notifications were found to have a high number of X-ray units per million people. Maputo City, which is also the most densely populated area in Mozambique, has a high concentration of CT machines.

The choropleth maps for South Africa (figure 2a–e) and Spain (figure 3a–e) show that the distribution of radiological units (X-ray and CT scan) does not align with population density or TB notifications. Despite the Eastern Cape in South Africa having the highest TB notifications in 2022, it has the lowest radiological capacity in the country.

The choropleth maps were not intended to establish definitive relationships, as radiological requirements are influenced by numerous factors unique to each country. Rather, they were used to provide a real-time visualisation of the distribution of radiological machines within countries and their potential interaction with factors such as population density or TB notifications.

Existing disparities between countries

In comparison and absolute numbers, South Africa has 18 times as many X-ray machines and 30 times as many CT scanners as Mozambique. In Spain, there are 30 times more X-ray units and 77 times more CT scan units than in Mozambique; and 18 times more X-ray units and 3 times more CT scanners than South Africa. In terms of relative numbers per population at risk, Mozambique has 3.6 X-ray units per million people while South Africa has 34.2 X-ray units per million people, and Spain has 811.5 X-ray units per million people. For CT scan units, Mozambique has 0.4 CT scan units per million people, compared with 5.8 CT scan units per million in South Africa and 19.3 CT scan units per million in Spain.

The table below presents the comparison of current data with past studies and OECD countries (lowest and highest performing countries in terms of CT scan units per million) (table 2, online supplemental file 2).

DISCUSSION

This comparative analysis of radiological capacity between a low-income, middle-income and high-income country with varying TB disease burdens represents the first detailed study of its kind. The research reveals not only stark disparities in radiological capacity between countries but also significant inequalities between the regions of each country. Low-income countries, despite having a high perceived necessity, including a high burden of diseases such as TB, which can be considered a good proxy for radiological requirements, are particularly underserved. The study suggests that radiological capacity is more influenced by a country's economic performance than by its disease burden. Additionally, the private sector consistently exhibits a greater radiological capacity for the population it serves than the public sector in all countries.

In Mozambique, the number of radiological units per million people in all provinces falls significantly below the WHO's recommended standard. This is concerning, particularly given the high disease burden, especially for respiratory infections like TB, for which X-ray diagnostics remain key to diagnostic decision-making in LMICs. Mozambique needs to strengthen its radiological capacity to improve diagnostic and treatment capabilities for these prevalent diseases.

The study uncovered significant regional disparities within countries, particularly notable in Mozambique. These findings align with previous research indicating disparities between urban and rural areas, with urban areas typically having higher radiological capacity.[21 24 47–49] Furthermore, we compared our findings to previous studies of countries with similar income levels to Mozambique and middle-income countries, highlighting a substantial gap in radiological capacity between lower and higher socioeconomic status countries.[16–21] Interestingly, a study conducted in Spain, despite its well-established healthcare system, revealed unequal distribution of resources among healthcare facilities, indicating that in-country disparities exist even in sophisticated healthcare systems.[50]

Consistent with previous findings, the private sector exhibits a higher radiological capacity per million people for the proportion of the population it serves compared with the public sector.[16–21] This disparity highlights the significant influence of economic factors on radiological capacity both within and across countries. It also presents an opportunity for collaboration between the private and public sectors to address existing gaps. Studies have also highlighted additional inequalities impacting radiological capacity in low-income countries, such as a shortage of qualified human resources in radiology, outdated equipment and inadequate infrastructure, including unreliable power supply.[51–53] These challenges highlight the complex interplay of factors influencing healthcare resource distribution and access in resource-constrained settings.

The implications of radiological disparities[54] are particularly relevant for any disease requiring radiology for its confirmatory diagnosis. Perhaps a paradigmatic example of this relates to the diagnosis of paediatric TB, especially in low-income countries with a high TB burden like Mozambique. Disparities in radiological capacity can contribute to delayed or missed diagnoses (for TB and other respiratory problems), inadequate treatment, and other unforeseen consequences, especially in vulnerable populations such as children. The use of imaging tools to complement diagnostic algorithms is recommended to enhance paediatric TB case detection, facilitate early treatment and reduces transmission and mortality rates.[55] However, in countries where such disparities exist, there is a risk of not achieving global targets set by EndTB strategies. Addressing these disparities is crucial for ensuring equitable access to healthcare services and improving the efficiency and effectiveness of TB control programmes. This supports the importance of investing in and strengthening radiological services, particularly in low-income countries with high TB burdens, to achieve better health outcomes and contribute to global TB elimination efforts.

Various solutions have been proposed to address the lack of access to medical imaging LMICs. The Lancet Commission on Diagnostics and Lancet Oncology Commission on Medical Imaging and Nuclear Medicine has provided a roadmap for improving accessibility to imaging diagnostics in LMICs.[22 23] These recommendations emphasise the need for multipronged and context-specific solutions to radiological inequality. Simply increasing the number of radiological units is insufficient; there must also be a focus on increasing radiological human resources, as well as improving infrastructural and technological support systems. These elements must work in concert to achieve meaningful improvements in healthcare delivery and outcomes.

For instance, to enhance radiological services in Mozambique, establishing a dedicated radio-diagnostic department within the Ministry of Health, similar to what South Africa and Spain have done, could be beneficial. This would prioritise the country's radiological services effectively by mobilising funds, advocating for resources and identifying gaps promptly. Additionally, developing national guidelines in collaboration with the private sector (which has not yet surpassed the public sector in Mozambique) could standardise the distribution of imaging diagnostics. These guidelines could consider population demographics, disease burden and regions with the least access to resources to ensure equitable access to medical imaging across the country.

Integrating portable AI-powered X-ray technology with remote reading capabilities could offer a promising solution, particularly for low-income countries facing challenges with specialised human resources. This technology has the potential to enhance diagnostic capabilities, particularly in remote or underserved areas where access to radiological expertise is limited. However, to ensure the effective implementation of this solution, it is essential to provide an exhaustive training package for technicians operating the equipment, including comprehensive training in radiation protection protocols. By addressing both technical and human resource aspects, this approach could significantly improve access to high-quality radiological services in resource-constrained settings.[51 56] Artificial intelligence (AI) algorithms can be trained to detect TB-related abnormalities on CXR with high accuracy. By analysing large volumes of imaging data, AI can identify potential TB cases and flag them for further review. This automation process streamlines the radiologist's workflow by prioritising images based on detected abnormalities, thereby improving diagnostic efficiency and ensuring timely intervention for patients with TB.[57–59]

Additionally, the use of point-of-care ultrasonography (POCUS) as an imaging alternative in the diagnosis of paediatric TB is gaining popularity. POCUS is attractive due to its affordability, accessibility and lack of radiation exposure risk. Its portability and real-time imaging capabilities make it a valuable tool, especially in resource-limited settings where access to conventional imaging modalities may be limited. Further research and integration of POCUS into diagnostic algorithms for paediatric TB could significantly improve early detection and treatment outcomes.[60–62]

Spain's approach to addressing radiological inequities serves as a notable example of a country-tailored solution. The country identified certain health facilities with obsolete equipment and a lack of high-tech machines such as CT scans. To rectify this, Spain implemented the Investment Plan in High Technology Equipment (INVEAT), funded by the European Union. This plan aims to increase access to radio diagnostics by replacing obsolete high-tech machines and boosting the density of high-tech units by 15% per 100 000 people by 2026. Notably, the plan does not include X-rays, mammography and ultrasound machines. The INVEAT plan has been allocated €796.1 million for implementation.[63]

The study has some limitations that warrant consideration. First, it does not exhaustively consider all potential influencing factors on radiological capacity. The lack of data on the unit functionality status, including maintenance and usage, is a notable limitation as it could confound local differences and potentially lead to an overestimation of radiological capacity in cases where machines may be non-functional. Nevertheless, the study's findings shed light on significant variations in capacity, highlighting areas for improvement in service provision.

Additionally, there was a lack of disaggregated data on private and public sector X-ray machines in South Africa and Spain. Furthermore, the study did not address how the private and public sectors interact in terms of radiological services. While not exploring specific interactions between the private and public sectors, the findings highlight the importance of considering broader contextual factors in allocating healthcare resources to Mozambique.

In Mozambique, census data used for the study were projections provided by the National Statistics Institute, which are estimates and may not accurately represent the current population. While TB burden was used as an example to assess disease burden, it is important to note that radiological diagnostics are used for a wide range of diseases as referred to previously. Therefore, the findings should be interpreted with caution and not generalised beyond TB diagnostics. Lastly, using machines per population served for the public and private sectors as a measure of radiological capacity is a rough estimate and should be interpreted with caution. There may be a crossover between regions and sectors that are not accounted for in the current study.

While acknowledging these limitations, the study provides a comprehensive analysis of radiological capacity disparities and their underlying economic influences. To better inform targeted interventions aimed at reducing disparities in radiological capacity and improving diagnostic capabilities, particularly in resource-limited settings, future research should examine the complex dynamics of healthcare systems, incorporating qualitative factors and regional variations.

CONCLUSION

The study identifies significant disparities in radiological capacity across the studied countries, with Mozambique having the lowest capacity per million people and notable regional and intracountry differences. South Africa exhibited a much higher capacity, while Spain had the highest. These findings emphasise the need for further research and interventions to improve access to radiological services, especially in resource-limited settings. Addressing these disparities is critical for equitable healthcare access, improving TB control programmes and advancing global TB elimination efforts. Potential solutions include establishing dedicated national radiodiagnostic departments, developing national guidelines and integrating portable AI-powered X-ray or POCUS technology. This analysis will provide valuable insights for policy-makers in planning and advocating for improved radiological resources.

Author affiliations
[1]Barcelona Institute for Global Health, Barcelona, Spain
[2]Medicine and Translational Research Department, University of Barcelona Faculty of Medicine and Health Sciences, Barcelona, Spain
[3]CIBER de Epidemiología y Salud Pública, Instituto de Salud Carlos III, Madrid, Spain
[4]National Tuberculosis Control Program, Ministry of Health, Maputo, Mozambique
[5]Centro de Investigação em Saúde de Manhiça (CISM), Maputo, Mozambique
[6]ICREA, Barcelona, Spain
[7]Pediatrics Department, Hospital Sant Joan de Déu, Universitat de Barcelona, Esplugues, Barcelona, Spain
[8]Radiation Oncology, Ministry of Health, Maputo, Mozambique
[9]Radiation Control, South African Health Products Regulatory Authority, Pretoria, South Africa
[10]National Paediatric TB Working Group, Maputo, Mozambique
[11]Desmond Tutu TB Centre, Department of Paediatrics and Child Health, Stellenbosch University, Stellenbosch, South Africa
[12]Service Priorities Coordination (SPC) Directorate, Department of Health, Cape Town, Western Cape, South Africa
[13]Department of Radiology, Universidad Complutense de Madrid Facultad de Medicina, Madrid, Spain
[14]Department of Medical Imaging and Clinical Oncology, Faculty of Medicine and Health Sciences, Stellenbosch University, Stellenbosch, South Africa

Acknowledgements We would like to recognise the hard work and valuable contributions of all colleagues and partners in this project. We thank the CSN in Spain, the NTP and DNAM in the Mozambique Ministry of Health, SAHPRA, and the Western Cape Department of Health in South Africa. We would like to specifically mention the support of Nelson de Jesus José, Lourdes Arjona Camí, Alex Albert, Debbie D. Coetzee, Emilio José Valverde and Aurum Institute. We would like to thank the Elizabeth Glaser Pediatric AIDS Foundation, Mozambique (EGPAF Mozambique) for logistic support during the study. We acknowledge the support from the Generalitat de Catalunya through the CERCA Program.

Contributors Conceptualisation: IM, ELV and IT-C. Investigation: IM, BJ, RE, CM, LC, PP, LHT, MM and EVC. Data curation: IM and BJ. Formal analysis: IM, BJ, ELV and IT-C. Methodology: IM, RE, MP, VM, RDP, ELV and IT-C. Project administration and resources: IT-C. Supervision: BJ, MP, LHT, MM, VM, ELV and IT-C. Validation: QB, ELV and IT-C. Writing–original draft preparation: IM, BJ, QB, ELV and IT-C. Writing–review and editing: all authors. IT-C as the guarantor of the article, accepted full responsibility for the finished work and/or the conduct of the study, had access to the data and controlled the decision to publish.

Funding IM, QB, ELV and IT-C acknowledge the support from the grant CEX2018-000806-S funded by MCIN/AEI/ 10.13039/501100011033. IM acknowledges the support of a fellowship from the 'La Caixa' Foundation (ID 100010434). The fellowship code is LCF/BQ/DI21/11860045. None of the funding sources had a role in the study's design, conduct and reporting. All other authors received no specific funding for this work. There was no additional external funding received for this study.

Map disclaimer The depiction of boundaries on this map does not imply the expression of any opinion whatsoever on the part of BMJ (or any member of its group) concerning the legal status of any country, territory, jurisdiction or area or of its authorities. This map is provided without any warranty of any kind, either express or implied.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval The study was approved by the Comité de Ética de la Investigación con medicamentos del Parc de Salut MAR—Spain (CEImPSMAR Ref: 2022/10358); Comité Nacional de Bioética para a Saúde—Mozambique (CNBS Ref: 614/CNBS/22) and Health Research Ethics Committee—South Africa (HREC Ref: N22/08/105).

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. The datasets and materials will be made available for access and utilisation whenever needed.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/.

ORCID iD
Isabelle Munyangaju http://orcid.org/0000-0002-7190-6016

REFERENCES

1. WHO. Available from. Global tuberculosis report 2023. *Geneva*; World Health Organization. 75. Available: https://iris.who.int/bitstream/handle/10665/373828/9789240083851-eng.pdf?sequence=1 [accessed 11 Dec 2023]
2. Dodd PJ, Yuen CM, Sismanidis C, *et al*. The global burden of tuberculosis mortality in children: a mathematical modelling study. *Lancet Glob Health* 2017;5:e898–906.
3. López-Varela E, Augusto OJ, Gondo K, *et al*. Incidence of Tuberculosis Among Young Children in Rural Mozambique. *Pediatr Infect Dis J* 2015;34:686–92.
4. Gunasekera KS, Vonasek B, Oliwa J, *et al*. Diagnostic Challenges in Childhood Pulmonary Tuberculosis-Optimizing the Clinical Approach. *Pathogens* 2022;11:382.
5. Basile FW, Nabeta P, Ruhwald M, *et al*. Pediatric Tuberculosis Diagnostics: Present and Future. *J Pediatric Infect Dis Soc* 2022;11:S85–93.
6. World Health Organization. WHO consolidated guidelines on tuberculosis: module 5: management of tuberculosis in children and adolescents: web annex 5: overview of consolidated who recommendations. World Health Organization; 2022. Available: https://apps.who.int/iris/handle/10665/352512 [Accessed 11 Oct 2022].
7. Lau A, Lin C, Barrie J, *et al*. A comparison of the chest radiographic and computed tomographic features of subclinical pulmonary tuberculosis. *Sci Rep* 2022;12:16567.
8. Drain PK, Bajema KL, Dowdy D, *et al*. Incipient and Subclinical Tuberculosis: a Clinical Review of Early Stages and Progression of Infection. *Clin Microbiol Rev* 2018;31:e00021-18.
9. Bhalla AS, Goyal A, Guleria R, *et al*. Chest tuberculosis: Radiological review and imaging recommendations. *Indian J Radiol Imaging* 2015;25:213–25.
10. Bomanji JB, Gupta N, Gulati P, *et al*. Imaging in tuberculosis. *Cold Spring Harb Perspect Med* 2015;5:a017814.
11. Varela EL, Munyangaju I, Chabala C, *et al*. Tuberculosis in children and adolescents: a forgotten group in a forgotten disease. In: García-BasteiroAL, Öner Eyüboğlu F, Rangaka MX, eds. *The Challenge of Tuberculosis in the 21st Century (ERS Monograph) [Internet]*. Sheffield: European Respiratory Society, 2023: 210–34. Available: https://doi.org/10.1183/2312508X.10025322
12. Gunasekera KS, Marcy O, Muñoz J, *et al*. Development of treatment-decision algorithms for children evaluated for pulmonary tuberculosis: an individual participant data meta-analysis. *The Lancet Child & Adolescent Health* 2023;7:336–46.
13. Frascella B, Richards AS, Sossen B, *et al*. Subclinical Tuberculosis Disease-A Review and Analysis of Prevalence Surveys to Inform Definitions, Burden, Associations, and Screening Methodology. *Clin Infect Dis* 2021;73:e830–41.
14. Song R, Click ES, McCarthy KD, *et al*. Sensitive and Feasible Specimen Collection and Testing Strategies for Diagnosing Tuberculosis in Young Children. *JAMA Pediatr* 2021;175:e206069.
15. United Nations. Transforming our world: the 2030 Agenda for Sustainable Development, 2015. Available: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf
16. Maboreke T, Banhwa J, Pitcher RD. An audit of licensed Zimbabwean radiology equipment resources as a measure of healthcare access and equity. *Pan Afr Med J* 2019;34:60.
17. Kabongo JM, Nel S, Pitcher RD. Analysis of licensed South African diagnostic imaging equipment. *Pan Afr Med J* 2015;22:57.
18. Ngoya PS, Muhogora WE, Pitcher RD. Defining the diagnostic divide: an analysis of registered radiological equipment resources in a low-income African country. *Pan Afr Med J* 2016;25:99.
19. Bour BK, Sosu EK, Hasford F, *et al*. National inventory of authorized diagnostic imaging equipment in Ghana: data as of September 2020. *Pan Afr Med J* 2022;41:301.
20. Mbewe C, Chanda-Kapata P, Sunkutu-Sichizya V, *et al*. An audit of licenced Zambian diagnostic imaging equipment and personnel. *Pan Afr Med J* 2020;36:32.
21. Gathuru LM, Elias GDO, Pitcher RD. Analysis of registered radiological equipment in Kenya. *Pan Afr Med J* 2021;40:205.
22. Fleming KA, Horton S, Wilson ML, *et al*. The Lancet Commission on diagnostics: transforming access to diagnostics. *The Lancet* 2021;398:1997–2050.
23. Hricak H, Abdel-Wahab M, Atun R, *et al*. Medical imaging and nuclear medicine: a Lancet Oncology Commission. *Lancet Oncol* 2021;22:e136–72.
24. van Zyl BC, Barnard MM, Cloete K, *et al*. Towards equity: a retrospective analysis of public sector radiological resources and utilization patterns in the metropolitan and rural areas of the Western Cape Province of South Africa in 2017. *BMC Health Serv Res* 2021;21:991.
25. Frija G, Blažić I, Frush DP, *et al*. How to improve access to medical imaging in low- and middle-income countries? *EClinMed* 2021;38:101034.
26. Munyangaju I, José B, Esmail R, *et al*. Evaluation of radiological capacity and usage in paediatric TB diagnosis: A mixed-method protocol of a comparative study in Mozambique, South Africa and Spain. *PLoS One* 2024;19:e0299293.
27. UNAIDS. UNAIDS|Countries. Available: https://www.unaids.org/en/regionscountries/countries [Accessed 13 Aug 2021].
28. World Bank. GDP per capita (current US$): countries, 2024. Available: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD [Accessed 27 Jan 2024].
29. Direcção de Planificação e Cooperação. Maputo: Ministério da Saúde; Plano Estratégico do Sector da Saúde PESS 2014-2019 (Extensão 2020-2024): Moçambique, 2022. Available: https://www.misau.gov.mz/index.php/planos-estrategicos?download=2048:plano-estrategico-do-sector-da-saude-pess-2014-2019-extensao-2020-2024
30. Programa Nacional de Controle da Tuberculose. Maputo Ministério da Saúde; Plano Estratégico e Operacional 2014 – 2018, 2014. Available: https://www.misau.gov.mz/index.php/planos-estrategicos-da-tb?download=298:plano-estrategico-pnct-2014-2018
31. IHME. Mozambique | Institute for Health Metrics and Evaluation, Available: https://www.healthdata.org/research-analysis/health-by-location/profiles/mozambique [Accessed 1 Mar 2024].
32. Vos T, Lim SS, Abbafati C, *et al*. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet* 2020;396:1204–22.
33. JICA. Data collection survey on the health system in mozambique final report. *Japan International Cooperation Agency*; 2021. Available: https://openjicareport.jica.go.jp/pdf/1000045945.pdf

34 Dos Anjos Luis A, Cabral P. Geographic accessibility to primary healthcare centers in Mozambique. *Int J Equity Health* 2016;15:173.
35 Maulide Cane R, Sheffel A, Salomão C, *et al*. Structural readiness of health facilities in Mozambique: how is Mozambique positioned to deliver nutrition-specific interventions to women and children? *J Glob Health Rep* 2023;7:e2023074.
36 Rensburg R. The conversation. Healthcare in South Africa: how inequity is contributing to inefficiency, 2021. Available: http://theconversation.com/healthcare-in-south-africa-how-inequity-is-contributing-to-inefficiency-163753 [Accessed 1 Mar 2024].
37 IHME. South Africa | Institute for Health Metrics and Evaluation, Available: https://www.healthdata.org/research-analysis/health-by-location/profiles/south-africa [Accessed 1 Mar 2024].
38 Ministerio de Sanidad. Informe anual del sistema nacional de salud 2022. Ministerio de Sanidade; 2023. Available: https://www.sanidad.gob.es/estadEstudios/estadisticas/sisInfSanSNS/tablasEstadisticas/InfAnualSNS2022/INFORME_ANUAL_2022.pdf [Accessed 23 Mar 2024].
39 OECD/European Observatory on Health Systems and Policies. Spain country health profile 2023 state of health in the eu. OECD Publishing; 2023. Available: https://eurohealthobservatory.who.int/publications/m/spain-country-health-profile-2023
40 IHME. Spain | Institute for Health Metrics and Evaluation, Available: https://www.healthdata.org/research-analysis/health-by-location/profiles/spain [Accessed 1 Mar 2024].
41 CSN. Informes al Parlamento - Publications, Available: https://www.csn.es/en/centro-de-documentacion?_20_folderId=13529&_20_viewEntries=1&_20_viewFolders=1&_20_struts_action=%2Fdocument_library%2Fview&_20_action=browseFolder&p_p_id=20&p_p_lifecycle=0&_20_entryStart=0&_20_entryEnd=30&_20_folderStart=0&_20_folderEnd=100 [Accessed 27 Jan 2024].
42 Ministerio de Sanidad. Catálogo Nacional de Hospitales 2023 (Actualizado a 31 de diciembre de 2022), 2023. Available: https://www.sanidad.gob.es/ciudadanos/prestaciones/centrosServiciosSNS/hospitales/docs/CNH_2023.pdf [Accessed 27 Jan 2024].
43 INE. Instituto Nacional de Estatistica: Projecções da População 2017- 2050, 2024. Available: https://ine.gov.mz/censo-2017/-/document_library/pfpz/view/92163 [Accessed 27 Jan 2024].
44 Instituto Nacional de Estadistica. INE. INEbase / Demography and population /Population figures and Demographic Censuses / Population Continuous Statistics / Latest data, Available: https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736177095&menu=ultiDatos&idp=1254735572981 [Accessed 27 Jan 2024].
45 Stats SA. Statistics South Africa | Census Dissemination, 2024. Available: https://census.statssa.gov.za/#/ [Accessed 27 Jan 2024].
46 Ministerio de Sanidad. Indicadores del año 2022. Plan para la prevención y control de la tuberculosis en España, 2022. Available: https://www.sanidad.gob.es/profesionales/saludPublica/prevPromocion/PlanTuberculosis/docs/Resumen_PlanTB2022_SEPTIEMBRE_2023.pdf
47 Patel M. Re-inventing the future of the radiological research footprint in South Africa. *SA J Radiol* 2018;22:1665.
48 Makgopa S, Madiba S. Tuberculosis Knowledge and Delayed Health Care Seeking Among New Diagnosed Tuberculosis Patients in Primary Health Facilities in an Urban District, South Africa. *Health Serv Insights* 2021;14:11786329211054035.
49 Jenkins HE, Ayuk S, Puma D, *et al*. Geographic accessibility to health facilities predicts uptake of community-based tuberculosis screening in an urban setting. *Int J Infect Dis* 2022;120:125–31.
50 Valls Martínez MDC, Grasso MS, Montero J-M. Regional well-being inequalities arising from healthcare expenditure public policies in Spain. *Front Public Health* 2022;10:953827.
51 Maru DS-R, Schwarz R, Jason A, *et al*. Turning a blind eye: the mobilization of radiology services in resource-poor regions. *Global Health* 2010;6:18.
52 Hinrichs-Krapels S, Tombo L, Boulding H, *et al*. n.d. Barriers and facilitators for the provision of radiology services in Zimbabwe: A qualitative study based on staff experiences and observations. *PLOS Glob Public Health*3:e0001796.
53 Fernandes Q, Augusto O, Machai H, *et al*. n.d. Scrutinizing human resources for health availability and distribution in Mozambique between 2016 and 2020: a subnational descriptive longitudinal study. *Hum Resour Health*21:33.
54 Radiation UNSC on the E of A. Sources, effects and risks of ionizing radiation, united nations scientific committee on the effects of atomic radiation (unscear) 2020/2021 report. Volume I. United Nations, 2022. Available: https://www.un-ilibrary.org/content/books/9789210010030
55 WHO operational handbook on tuberculosis: module 5: management of tuberculosis in children and adolescents, Available: https://www.who.int/publications-detail-redirect/9789240046832 [Accessed 23 Mar 2023].
56 Palmer M, Seddon JA, van der Zalm MM, *et al*. Optimising computer aided detection to identify intra-thoracic tuberculosis on chest x-ray in South African children. *PLOS Glob Public Health* 2023;3:e0001799.
57 Qin ZZ, Ahmed S, Sarker MS, *et al*. Tuberculosis detection from chest x-rays for triaging in a high tuberculosis-burden setting: an evaluation of five artificial intelligence algorithms. *Lancet Digit Health* 2021;3:e543–54.
58 Hwang EJ, Jeong WG, David PM, *et al*. AI for Detection of Tuberculosis: Implications for Global Health. *Radiol Artif Intell* 2024;6:e230327.
59 Tzelios C, Nathavitharana RR. Can AI technologies close the diagnostic gap in tuberculosis? *Lancet Digit Health* 2021;3:e535–6.
60 Ambroggio L, Sucharew H, Rattan MS, *et al*. Lung Ultrasonography: A Viable Alternative to Chest Radiography in Children with Suspected Pneumonia? *J Pediatr* 2016;176:93–8.
61 Bosch-Marcet J, Serres-Créixams X, Zuasnabar-Cotro A, *et al*. Comparison of ultrasound with plain radiography and CT for the detection of mediastinal lymphadenopathy in children with tuberculosis. *Pediatr Radiol* 2004;34:895–900.
62 Bigio J, Kohli M, Klinton JS, *et al*. Diagnostic accuracy of point-of-care ultrasound for pulmonary tuberculosis: A systematic review. *PLoS ONE* 2021;16:e0251236.
63 Ministry of Health - INVEAT Plan, Available: https://www.sanidad.gob.es/profesionales/prestacionesSanitarias/PlanINVEAT/home.htm [Accessed 6 Feb 2024].