BMJ Global Health

# Measuring oxygen access: lessons from health facility assessments in Lagos, Nigeria

Hamish R Graham ,[1,2] Omotayo E Olojede,[2] Ayobami A Bakare,[3,4] Agnese Iuliano,[5] Oyaniyi Olatunde,[2] Adamu Isah,[6] Adams Osebi,[6] Tahlil Ahmed,[7] Obioma C Uchendu,[3,8] Rochelle Burgess ,[5] Eric McCollum,[9] Tim Colbourn ,[5] Carina King ,[5,10] Adegoke G Falade,[2,11] INSPIRING Project Consortium

**To cite:** Graham HR, Olojede OE, Bakare AA, *et al*. Measuring oxygen access: lessons from health facility assessments in Lagos, Nigeria. *BMJ Global Health* 2021;**6**:e006069. doi:10.1136/bmjgh-2021-006069

**Handling editor** Seye Abimbola

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bmjgh-2021-006069).

Received 21 April 2021
Accepted 24 June 2021



For numbered affiliations see end of article.

**Correspondence to**
Dr Hamish R Graham;
hamish.graham@rch.org.au

## ABSTRACT

The COVID-19 pandemic has highlighted global oxygen system deficiencies and revealed gaps in how we understand and measure 'oxygen access'. We present a case study on oxygen access from 58 health facilities in Lagos state, Nigeria. We found large differences in oxygen access between facilities (primary vs secondary, government vs private) and describe three key domains to consider when measuring oxygen access: availability, cost, use. Of 58 facilities surveyed, 8 (14%) of facilities had a functional pulse oximeter. Oximeters (N=27) were typically located in outpatient clinics (12/27, 44%), paediatric ward (6/27, 22%) or operating theatre (4/27, 15%). 34/58 (59%) facilities had a functional source of oxygen available on the day of inspection, of which 31 (91%) facilities had it available in a single ward area, typically the operating theatre or maternity ward. Oxygen services were free to patients at primary health centres, when available, but expensive in hospitals and private facilities, with the median cost for 2 days oxygen 13 000 (US$36) and 27 500 (US$77) Naira, respectively. We obtained limited data on the cost of oxygen services to facilities. Pulse oximetry use was low in secondary care facilities (32%, 21/65 patients had $SpO_2$ documented) and negligible in private facilities (2%, 3/177) and primary health centres (<1%, 2/608). We were unable to determine the proportion of hypoxaemic patients who received oxygen therapy with available data. However, triangulation of existing data suggested that no facilities were equipped to meet minimum oxygen demands. We highlight the importance of a multifaceted approach to measuring oxygen access that assesses access at the point-of-care and ideally at the patient-level. We propose standard metrics to report oxygen access and describe how these can be integrated into routine health information systems and existing health facility assessment tools.

## Summary box

- Oxygen access is poorly understood and the most commonly used metrics (eg, presence of an oxygen source) do not correlate well with actual access to patients.
- Pulse oximetry use is a critical indicator for the quality of oxygen services and may be a reasonable reflection of oxygen coverage to patients with hypoxaemia.
- Oxygen, and pulse oximeter, availability must be assessed at the point-of-care in all major service delivery areas, as intrafacility oxygen distribution is highly inequitable.
- Minimum functional requirements for oxygen sources must be assessed, as oxygen concentrators and cylinders may be present without being in working order.

## BACKGROUND

Oxygen therapy is an essential medicine required for stabilisation and treatment of severely ill patients with conditions such as COVID-19, pneumonia, and sepsis, and safe anaesthetic care.[1] Reliable oxygen services are therefore crucial for every health facility that cares for unwell newborns, children or adults, and every facility providing obstetric, surgical and post-operative care.

The COVID-19 pandemic has highlighted the importance of hospital oxygen systems and exacerbated existing deficiencies.[2] The pandemic has also revealed gaps in how we understand 'oxygen access' and the tools we use to measure it.[3]

In this paper, we use an illustrative case study from Nigeria to describe three domains of data required to meaningfully assess oxygen access. We aim to share lessons learnt about assessing oxygen systems in a variety of facility contexts, to provide guidance for hospital managers, health administrators, policymakers, funders and supporting non-governmental organisations.

### What do we mean by 'oxygen access'?

Access to medicines from a health systems perspective involves medication availability,

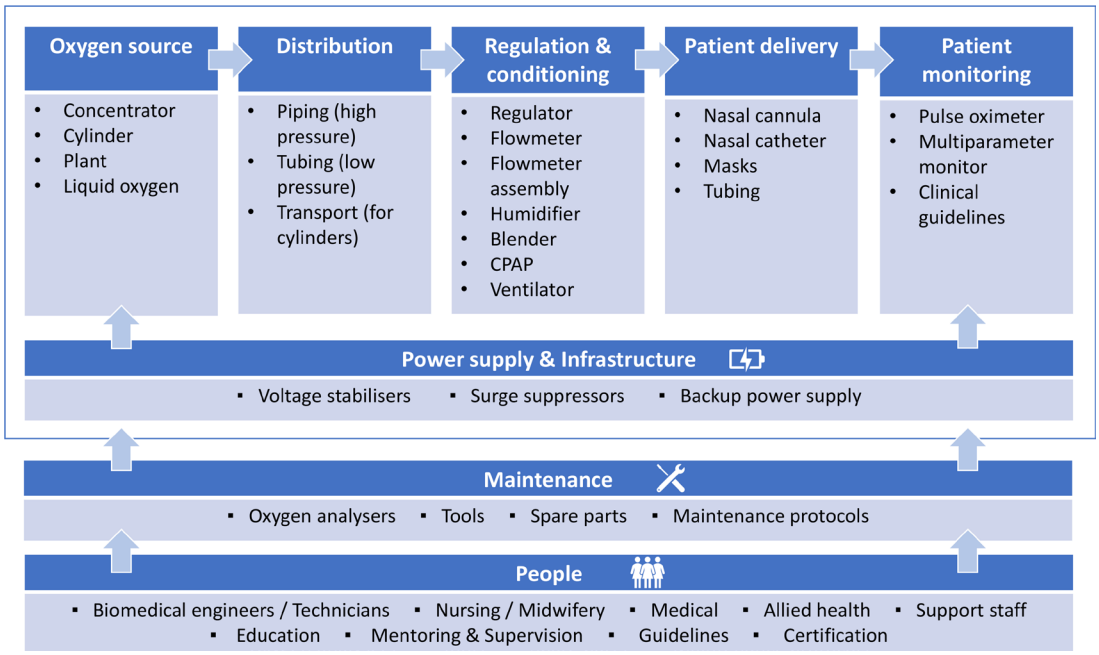


**Figure 1** Hospital oxygen systems require key components, including people, maintenance systems, infrastructure and a range of medical devices and supplies (adapted from WHO, UNICEF[5]). CPAP, continuous positive airway Pressure.

affordability, quality and rational use.[4] This means that oxygen access requires quality oxygen therapy to be available and affordable to those who need it, when they need it and used in a safe and rational way.

While these four core domains apply to all essential medicines, oxygen systems are somewhat unique. Medical oxygen must achieve high quality standards—including being ≥82% in purity.[5] For medical oxygen to be safely administered, delivery devices must be appropriate for the particular patient and indication (eg, nasal cannula, mask with reservoir bag) and guided by the clinical situation and blood oxygen measurements (eg, $SpO_2$, peripheral oxygen saturation from a pulse oximeter). Medical oxygen must be continually available at points-of-care throughout health facilities—from emergency departments, to wards and operating theatres. Achieving this depends on a range of medical technologies and devices (eg, oxygen concentrators, cylinders), people (eg, technicians, nurses/midwives, doctors, administrators) and broader infrastructure and logistic systems (eg, power supply, maintenance and repair tools and systems) (figure 1).

Current widely used facility survey tools, including the Service Provision Assessment (SPA) and Service Availability and Readiness Assessment (SARA), focus on the binary question of 'is oxygen equipment available?'. This approach neglects many of these other important dimensions, as well as whether the equipment is functional, what clinical areas it serves, whether healthcare workers (HCWs) can recognise who requires oxygen therapy or if patients can afford it. As such, this binary approach is a poor reflection of whether patients who need oxygen are actually getting it.[6]

## CASE STUDY: INSPIRING PROJECT, LAGOS, NIGERIA

Nigeria is a populous lower-middle income country in West Africa with high child (2019: under-five mortality rate 117.2 per 1000 live births) and maternal mortality ratios (2017: 770 per 100 000 live births).[7] Lagos is the most populous state, located in the south-west on the Gulf of Guinea. The Lagos population live in urban/peri-urban environments and have lower child mortality rates (50 per 1000 live births) and poverty levels (1.1% live in severe poverty) compared with Nigeria as a whole.[8]

Recent studies in Nigeria have shown major deficiencies in existing hospital oxygen systems and highlighted the importance of oxygen in improving pneumonia case management and preventing deaths.[6 9–13] To better understand the current oxygen capacity and needs of health facilities in Lagos, we surveyed 58 health facilities in Ikorodu local government area (LGA), with an emphasis on paediatric care. We included all government primary health centres (PHCs, n=28), all secondary healthcare facilities (SHFs, n=3) and a random sample of private primary care facilities (n=27/148) (figure 2). There are no tertiary care facilities in Ikorodu LGA.

Trained data collectors conducted facility visits between January and August 2020, collecting data from observation, equipment testing and staff surveys using a standardised form, input directly onto tablet computers using CommCare (Dimagi, Cambridge, Massachusetts, USA). We used Handi+ and UltraMax02 oxygen analysers (Maxtec, Salt Lake City, Utah, USA) to test oxygen purity and ProSim SPOT Light (Fluke Corporation, Everett, Washington, USA) to test pulse oximeter function. We cleaned and analysed data using Stata V.15 (StataCorp)

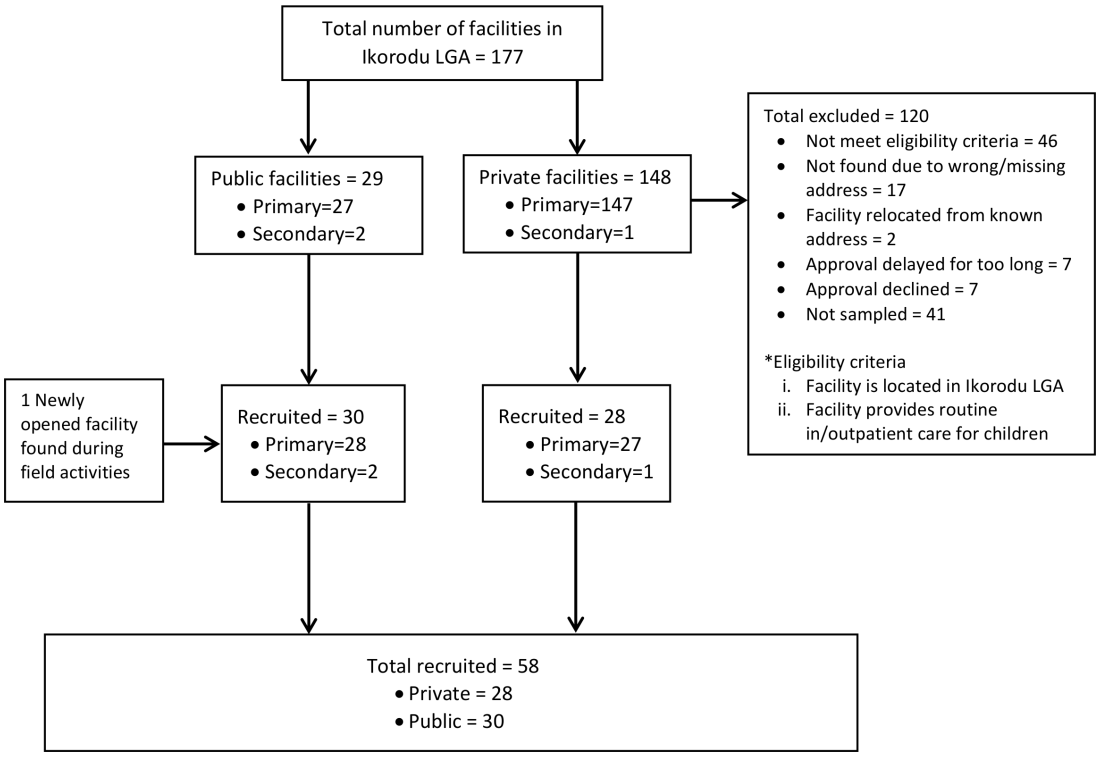


**Figure 2** Flow diagram showing selection of 58 health facilities in Lagos, Nigeria. Initial identification of facilities conducted in November 2019. We randomly assigned numbers to private facilities then screened and selected until reaching the prespecified target number for enrolment. LGA, local government area.

and report data descriptively under three broad domains: availability, use, cost (figure 3).

### Patient and public involvement

This study was conducted to inform the 'Integrated Sustainable childhood Pneumonia and Infectious disease Reduction in Nigeria' (INSPIRING) programme, implemented by Save the Children to improve child health in Jigawa and Lagos states. INSPIRING involved civil society representatives in co-design activities, including a co-design workshop in April 2019 involving representatives from civil society, local and national government and professional organisations, together with Save the Children, GSK and evaluation partners. Selection of the facilities was conducted in partnership with the Ikorodu local government. Community perspectives were sought during the situational analysis but did not contribute substantively to this study.

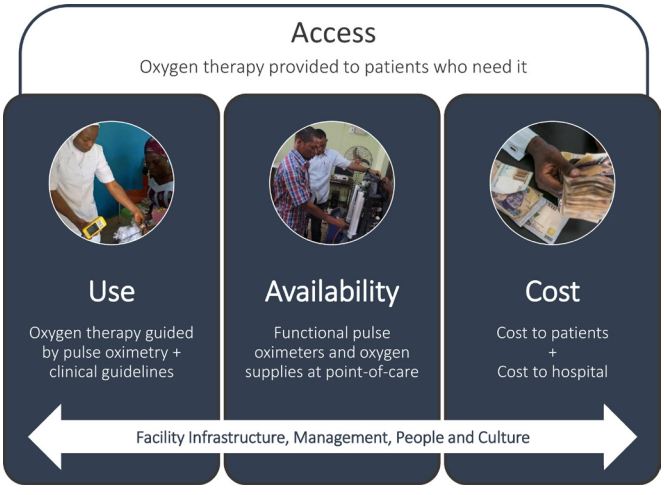


**Figure 3** Three domains of data on the quality of 'oxygen access'.

### Availability: pulse oximetry

Pulse oximeters enable HCWs to accurately and non-invasively measure blood oxygen levels and guide oxygen treatment decisions.[14] Given that clinical signs of hypoxaemia (low blood oxygen level) lack both sensitivity and specificity, pulse oximeters are now a global standard of care for hypoxaemia management and regarded as a 'priority medical device' by WHO.[15 16]

#### Is a pulse oximeter present?

We located pulse oximeters in all three SHFs—exclusively located in the paediatric wards; none of the government PHCs and 56% (15/27) of the private primary care facilities. In the private facilities, oximeters were typically located in outpatient clinics (12/27, 44%), paediatric ward (6/27, 22%) or operating theatre (4/27, 15%) (table 1). The two government hospitals were the only facilities that had paediatric oximetry probes available.

#### Is the pulse oximeter functional?

We tested 27 oximeters in 22 ward areas, including 4 desktop, 5 handheld and 18 fingertip oximeters (table 1, detail in online supplemental appendix). Models varied widely, half (14/27, 52%) had visible CE markings,

**Table 1** Oxygen access summary data for secondary and primary health facilities in Ikorodu LGA, Lagos, Nigeria

| Characteristic | Hospital | Government PHC | Private facility | Overall |
|---|---|---|---|---|
| Facilities surveyed (% of total in Ikorodu LGA) | 3/3 (100%) | 28/28 (100%) | 27/147 (18%) | 58/179 (32%) |
| Oxygen source | | | | |
| Facilities with ANY oxygen source | 3/3 (100%) | 12/28 (43%) | 27/27 (100%) | 42/58 (72%) |
| None | 0 | 16 (57%) | 0 | 16 (28%) |
| Cylinder only | 0 | 4 (14%) | 6 (22%) | 10 (17%) |
| Concentrator only | 1 (33%) | 2 (7%) | 5 (19%) | 8 (14%) |
| Both | 2 (67%) | 6 (21%) | 16 (59%) | 24 (41%) |
| Facilities with functional oxygen source* | 3/3 (100%) | 9/28 (32%) | 22/27 (81%) | 34/58 (59%) |
| Cylinder location | N=14 | N=17 | N=51 | N=82 |
| Theatre | 0 | 0 | 21 | 21 |
| Emergency/triage | 0 | 0 | 10 | 10 |
| Adult/general ward | 0 | 0 | 1 | 1 |
| Paediatric/neonatal | 2 | 0 | 0 | 2 |
| Outpatient/clinic | 0 | 2 | 4 | 6 |
| Delivery suite | 0 | 11 | 5 | 16 |
| ICU | 12 | 0 | 0 | 12 |
| Store | 0 | 4 | 10 | 14 |
| Other | 0 | 0 | 0 | 0 |
| Concentrator location | N=3 | N=11 | N=28 | N=42 |
| Theatre | 0 | 0 | 16 | 16 |
| Emergency/triage | 0 | 1 | 3 | 4 |
| Adult/general ward | 0 | 0 | 4 | 4 |
| Paediatric/neonatal | 3 | 0 | 0 | 3 |
| Outpatient/clinic | 0 | 0 | 1 | 1 |
| Delivery suite | 0 | 8 | 3 | 11 |
| ICU | 0 | 0 | 0 | 0 |
| Store | 0 | 2 | 1 | 3 |
| Other | 0 | 0 | 0 | 0 |
| Pulse oximeter | | | | |
| Facilities with ANY pulse oximeter | 3/3 (100%) | 0/28 (0%) | 15/27 (56%) | 18/58 (31%) |
| Facilities with functional pulse oximeter† | 1/3 (33%) | 0/28 (0%) | 7/27 (26%) | 8/58 (14%) |
| Oximeter location | N=6 | N=0 | N=21 | N=27 |
| Theatre | 0 | 0 | 4 | 4 |
| Emergency/triage | 0 | 0 | 1 | 1 |
| Adult/general ward | 0 | 0 | 2 | 2 |
| Paediatric/neonatal | 6 | 0 | 0 | 6 |
| Outpatient/clinic | 0 | 0 | 12 | 12 |
| Delivery suite | 0 | 0 | 1 | 1 |
| ICU | 0 | 0 | 0 | 0 |
| Store | 0 | 0 | 0 | 0 |
| Other | 0 | 0 | 1 | 1 |
| Oximeter type | | | | |
| Table top | 0 | 0 | 4 | 4 |
| Hand held | 3 | 0 | 2 | 5 |
| Finger tip | 3 | 0 | 15 | 18 |

Continued

**Table 1** Continued

| Characteristic | Hospital | Government PHC | Private facility | Overall |
|---|---|---|---|---|
| Technician capacity‡ | | | | |
| Facilities with technician | 3/3 (100%) | 0 | 2/27 (7%) | 5/58 (9%) |
| Biomedical engineer | 3/3 (100%) | 0 | 1/27 (4%) | 4/58 (7%) |
| Other technician | 3/3 (100%) | 0 | 2/27 (7%) | 5/58 (9%) |
| Training on oxygen systems | 2/3 (67%) | 0 | 0 | 2/58 (3%) |
| Routine maintenance plan | 1/3 (33%) | 0 | 2/27 (7%) | 3/58 (5%) |
| Concentrator maintenance | 1/3 (33%) | 0 | 2/27 (7%) | 3/58 (5%) |
| Spare parts | 0 | 0 | 1/27 (4%) | 1/58 (2%) |
| Repair | 0 | 0 | 0 | 0 |
| Cylinder maintenance | 0 | 0 | 1/27 (4%) | 1/58 (2%) |
| Spare parts | 0 | 0 | 1/27 (4%) | 1/58 (2%) |
| Repair | 0 | 0 | 0 | 0 |
| Oximeter maintenance | 0 | 0 | 0 | 0 |
| Spare parts | 0 | 0 | 0 | 0 |
| Repair | 0 | 0 | 0 | 0 |
| Oxygen costs, Naira§ | | | | |
| Concentrator purchase, median (IQR) | N/A | N/A | 160 000 (100 000–275 000)<br>US$446 (279–766) | |
| Cylinder refill per $m^3$, median (IQR) | 900<br>US$3 | 450<br>US$1 | 640 (291–882)<br>US$2 (1–2) | 640 (250–1470)<br>US$2 (1–4) |
| Pulse oximeter price, median (IQR) | N/A | N/A | 93 500 (7000–180 000)<br>US$260 (19–501) | |

Multiple cylinders, concentrators and pulse oximeters could be included for each facility.
*Oxygen source function included assessment of cylinder regulator apparatus and measurement of concentrator gas concentration using an oxygen analyser.
†Pulse oximeter functionality included testing with Fluke simulator.
‡Technician data from 27/28 facilities.
§Limited financial data on pulse oximeter or oxygen concentrator procurement costs (4/58, 7%), cylinder refill costs (7/58, 12%), cylinder cost data from a single SHF and PHC. US$1: 359 Naira. Maximum volume of a large oxygen cylinder is typically 3.4 or 7.0 $m^3$ (G-type and H-type).
IQR, interquartile range, 25th–75th centiles; LGA, local government area; PHC, primary health centre; SHF, secondary healthcare facility; Spare parts, in stock or ordered in past 12 months.

indicating conformity with European regulatory standards. Twenty-two of 27 (81%) oximeters turned on, and 19/27 (70%) provided an $SpO_2$ reading. Testing with the Fluke device revealed that 13/19 (68%) were within ±2% of the correct $SpO_2$ for a simulated healthy person (one read falsely low, five gave no reading). However, only 9/19 (47%) were within ±3% for a simulated sick person (two read falsely high, eight gave no reading). Overall, one-third (9/27) of oximeters were demonstrably functional, including 3/4 (75%) desktop, 1/5 (20%) handheld and 5/18 fingertip (28%) devices—all at private primary care facilities.

## Availability: oxygen supplies

### Is an oxygen source present?

We found all SHFs (3/3) and private facilities (27/27), and half of PHCs (12/28, 43%), had an oxygen source in the facility (table 1). Similar numbers of facilities used oxygen cylinders and oxygen concentrators (34 vs 32), and many facilities had both (24/58, 41%; table 1). No facilities had a bulk liquid oxygen tank or oxygen plant.

Most oxygen cylinders (49/82, 60%) and concentrators (27/42, 64%) were in the operating theatre, intensive care unit or delivery room (online supplemental appendix). Seven facilities had cylinders in store for distribution to wards on demand.

### Is the oxygen source functional?

We visually inspected and tested 42 oxygen concentrators in 36 ward areas; 11 could not be fully tested due to power failure (n=10) or active clinical use (n=1). Models varied greatly and one-third (26/42, 62%) had visible CE markings. We found 5/42 (12%) were functional at the time of inspection (table 1, online supplemental appendix). All used main power as the primary power source, but only 4/42 (10%) used a voltage stabiliser to protect the device from power fluctuations.

Table 2 Estimated cost of a 3-day admission or stabilisation care at government PHC, for a child under 5 years of age with severe pneumonia

| | Median cost (IQR) in Naira and USD* | | | |
|---|---|---|---|---|
| Item | Hospital | Government PHC | Private facility | Overall |
| Admission fee | 1500 (0–5000)<br>US$4 (0–14) | N/A | 10 000 (5000–10 000)<br>US$28 (14–28) | 0 (0–7250)<br>US$0 (0–20) |
| Daily bed fee | 0 (0–1500)<br>US$0 (0–4) | N/A | 2000 (1000–2000)<br>US$6 (3–6) | 0 (0–2000)<br>US$0 (0–6) |
| Antibiotics | No data | 300 (280–300)<br>US$1 (1–1) | 1000 (600–1500)<br>US$3 (2–4) | 400 (300–1000)<br>US$1 (1–3) |
| IV and fluids | No data | 200 (200–200)<br>US$1 (1–1) | 1000 (600–1000)<br>US$3 (2–3) | 550 (200–1000)<br>US$2 (1–3) |
| Oxygen | 13 000 (6000–20 000)<br>US$36 (17–56) | 0 (0–0)<br>US$0 (0–0) | 27 500 (3500–96 000)<br>US$77 (10–267) | 3500 (0–36 000)<br>US$10 (0–100) |
| Total† | 18 500 (7500–29 500)<br>US$52 (21–82) | 150 (0–425)<br>US$0 (0–1) | 45 550 (20 250–109 375)<br>US$127 (56–305) | 15 250 (400–53 000)<br>US$42 (1–148) |

Based on 3 days in hospital, full course of antibiotics and supportive care, 2 days of oxygen therapy.
*US$1: 359 Naira (rate 31 January 2020).
†Restricted to 34 facilities that had data on oxygen and admission costs.
IQR, interquartile range (25th and 75th centiles); PHC, primary health centre .

We visually inspected 82 oxygen cylinders in 43 ward areas, finding 53/82 (65%) cylinders had a regulator apparatus available (or manifold connection for piped supply) making them ready for use (table 1, online supplemental appendix). We did not obtain reliable data on leaks, oxygen purity or pressure.

Overall, 34/58 (59%) facilities had a functional source of oxygen available on the day of inspection, of which 31 (91%) had it available in a single ward area (11 exclusively in the operating theatre, 10 delivery suite, 5 emergency, 2 clinic room, 1 ward, 2 store) (table 1, online supplemental appendix). We did not evaluate the presence of appropriate oxygen delivery devices.

### What is the technical capacity for oxygen provision?

Five facilities (9%), including all three SHFs, had onsite biomedical engineers or technicians; but only two of these facilities had staff who had been trained on oxygen equipment (table 1). Three facilities (5%) had routine maintenance schedules for medical equipment and reported performing oxygen concentrator and/or cylinder maintenance in the past 6 months. One facility reported procurement of concentrator and cylinder spare parts in the past year. We did not evaluate technician skills or knowledge.

## Cost of oxygen

### What is the cost of oxygen services to patients?

We obtained patient oxygen cost data from 39/58 (67%) facilities, which variously billed for oxygen using hourly or daily rates, or per admission, cylinder or episode of use. When available, oxygen was typically free to patients at PHCs, but expensive in SHFs and private facilities. The median cost for 2 days oxygen was 13 000 Naira (US$36) and 27 500 Naira (US$77), respectively, accounting for two-thirds of the cost of a 3-day admission for a child with severe pneumonia (table 2). This is consistent with previous findings of high out-of-pocket costs for oxygen services in Nigeria[6] and reflective of Nigeria's relatively high out-of-pocket health expenditure (2018: 77% of total health expenditure).[17]

### What is the cost of providing oxygen services to facilities?

We found no facilities that included oxygen-related items in their budgets, and few could provide information on pulse oximeter, oxygen concentrator or cylinder costs. Limited data from seven facilities suggested median oximeter purchase cost was 93 500 Naira (US$260), range 7000–180 000 (US$19–500); concentrator purchase cost was 160 000 Naira (US$446), range 80 000–350 000 (US$223–975); and cylinder refill cost was 640 Naira per cubic metre (~US$2), range 250–1470 (US$1–4) (online supplemental appendix).

## Clinical use of oxygen

In addition to having pulse oximeters and oxygen supplies available, rational use of oxygen also requires trained and motivated HCWs who regularly perform pulse oximetry and provide oxygen therapy according to clinical guidelines.[10 18]

### What is the capacity of healthcare workers to provide oxygen therapy?

We conducted knowledge and skills tests for 169 HCWs in 56 of the 58 facilities (online supplemental appendix). Participants included doctors, nurses, midwives, health assistants,and community health extension workers with varying levels of experience (median 12 years).

One-quarter (40/169, 24%) of HCWs reported training on oxygen, and one-third of these had been trained in the past 5 years (online supplemental appendix). Most HCWs (97/169, 57%) reported experience using oxygen

**Box 1 Summary of lessons learnt on assessing oxygen access**

**Lessons learnt: oxygen use**

- Measuring the proportion of hypoxaemic patients receiving oxygen therapy is the single most important indicator for evaluating patient access—but is only interpretable with reliable pulse oximetry data to define the denominator.
- Pulse oximetry coverage (ie, the proportion of patients who receive pulse oximetry and have $SpO_2$ documented) is a critical indicator of the quality of oxygen services. Given that pulse oximetry is essential to identifying who requires oxygen and routine pulse oximetry is rare without oxygen supplies, pulse oximetry coverage may be a reasonable proxy for patient oxygen access.
- The presence of a pulse oximeter correlates poorly with actual use. If clinical data on oximetry use is unavailable, reported device use may be an acceptable proxy.

**Lessons learnt: pulse oximetry availability**

- Pulse oximeter presence must be assessed in all major service delivery areas—including availability of appropriate oximeter devices and probes for patient populations being served (eg, neonatal and paediatric care).
- Simple functional testing of oximeters can be done by applying to your own finger. More detailed testing requires specialised equipment calibrated to particular oximeters and may be most useful to technicians managing large numbers of oximeters.
- Some low-cost oximeters, particularly fingertip devices, are not suitable for children or unwell populations with low perfusion and/or dark or thick skin.
- Assessments of healthcare worker knowledge and skills are useful in the context of planning and conducting training—but are a poor reflection of actual oxygen practices. Oxygen practices are largely determined by individual motivators (intrinsic and extrinsic), attitudes and behaviour of peers and seniors, and the culture of the work environment.[18]

**Lessons learnt: oxygen availability**

- Oxygen availability must be assessed at the point-of-care and include all major service delivery areas. Hospital-wide summary data on the availability of oxygen equipment can be very misleading, as intrafacility oxygen distribution is highly inequitable (eg, skewed towards anaesthetic care).
- Minimum functional requirements for oxygen sources must be assessed, as many oxygen concentrators and cylinders may be present without being in working order. For oxygen concentrators, this should include assessment of oxygen purity using an oxygen analyser. For oxygen cylinders, this should include assessment of whether it is currently full or empty and whether it is fitted with a regulator and pressure gauge at point of use.
- These basic assessments can be carried out by trained non-experts, but more detailed equipment data requires greater technical expertise.
- Efforts to improve hospital oxygen systems must involve hospital technicians and seek to understand existing capacities and restraints without blame. Hospital technicians have valuable skills, experience and understanding of hospital equipment systems, but are too frequently neglected by clinical and administrative decision-makers.

**Lessons learnt: oxygen cost**

- Oxygen costs can be prohibitive to patients and exacerbate existing inequities. Understanding cost structures and variation between facilities could help construct more efficient, equitable oxygen systems.
- Many facilities do not keep clear records of their current oxygen expenditure, making it difficult to demonstrate financially advantageous alternatives. Further, reliable cost data may be difficult to obtain without high levels of trust. Assistance to health managers in understanding and forecasting whole-of-system costs for oxygen could improve oxygen system efficiency and sustainability.

therapy, though only 13 (8%) had administered oxygen in the prior 2 weeks. Experience with oxygen therapy was low in government primary care facilities (2/96, 2%, had used in previous 2 weeks), despite regularly seeing children who required resuscitation (10/96, 10%, had resuscitated a child in the previous 2 weeks).

Knowledge test results showed generally low appreciation of the fundamentals of oxygen therapy, with many respondents lacking the confidence to answer questions—particularly in government primary care facilities (online supplemental appendix). For example, 22% (37/169) of HCWs could identify the core functions of pulse oximetry (ie, heart rate and $SpO_2$) and 28% (48/169) recognised that a child with an $SpO_2$ of 87% warranted oxygen therapy.

### Is pulse oximetry a routine practice?

Audit of routine case notes for children presenting with acute illness to outpatients in a subsample of 12 participating clinics (April–September 2020) showed that pulse oximetry use was low in secondary care facilities (32%, 21/65 patients had $SpO_2$ documented) and negligible in private facilities (2%, 3/177) and PHCs (<1%, 2/608).

Among all participating facilities, 17/27 (63%) of the oximeters had not been used in the previous day and only five (19%) had been used ≥10 times (online supplemental appendix). Thus, despite 31% of facilities having an oximeter, routine use was rare.

### Is oxygen therapy provided to all patients who need it?

The capacity to deliver oxygen services does not tell us whether the patients who need oxygen are actually getting it. The clearest metric to measure actual oxygen access to patients is the proportion of patients with hypoxaemia (typically defined as $SpO_2$ <90%) who are provided with oxygen therapy. We were unable to obtain this data via clinical audit as pulse oximetry coverage was too low and hypoxaemia cannot be accurately determined using clinical signs alone.[9] Alternative approaches to measuring oxygen access to patients are using cross-sectional hypoxaemia and oxygen therapy surveys,[19] crude counts of patients who receive oxygen or relying on HCW recall about oxygen supply stock-outs.[20] These approaches are problematic and provide a poor indication of whether oxygen is actually reaching those who need it.[10]

**Table 3** Summary of most useful indicators of oxygen access

| Domain | Indicator | Potential sources |
|---|---|---|
| Use | ► ***Proportion of patients with hypoxaemia receiving oxygen therapy.***<br>► ***Proportion of acutely unwell patients screened using pulse oximetry.***<br>*Additional considerations:*<br>*- presence of oxygen clinical guideline, including routine pulse oximetry*<br>*- rational use (oxygen provision with vs without indication)*<br>*- flow rates and duration of therapy (useful for quantification of oxygen need and quality improvement)*<br>*- equity between populations (hospital department, age, sex, ethnic background, socioeconomic status)*<br>*- training and skills of healthcare workers* | Clinical audit, routine health information system, HCW survey |
| Availability | ► ***Proportion of wards with functional oxygen source and delivery devices.***<br>► ***Proportion of wards with functional pulse oximeter and probes.***<br>*Additional considerations:*<br>*- pulse oximeter and oxygen source presence and function (including oxygen purity testing for oxygen concentrators)*<br>*- delivery devices (cannula, mask, CPAP, flowmeter assembly, etc)*<br>*- maintenance personnel (local capacity and access to expert help)*<br>*- equipment inventory and preventive maintenance schedules*<br>*- spare parts: access and cost* | Physical inspection+device testing, technician survey |
| Cost | ► ***Daily cost of oxygen therapy to patients***<br>► ***Annual expenditure on oxygen equipment and maintenance/repairs.***<br>*Additional considerations:*<br>*- equity and non-payment action (hospital department, age, poor)*<br>*- whole of life cycle (capital and operating costs): oxygen source; refill cost; spare parts and maintenance; power; consumables.* | Patient accounts and general finance ledger, administrator survey |

CPAP, continuous positive airway pressure ; HCWs, healthcare workers

.

Triangulating the data from the 58 health facilities shows clear gaps between need and access with the vast majority of facilities and ward areas lacking a functional oxygen supply and/or pulse oximetry capacity (online supplemental appendix). At best, 10 facilities had oxygen supply adequate to provide minimum services to at least one ward area but only the two government hospital paediatric wards had both oxygen supplies and routine pulse oximetry. Without routine pulse oximetry, the other facilities are likely to miss up to 50% of patients with hypoxaemia even with adequate oxygen supplies.[9]

## IMPLICATIONS

The COVID-19 pandemic has illuminated the need to better measure access to oxygen therapy and stimulated activity to respond.[3 21] As part of a comprehensive response to the pandemic,[22] the WHO has released guidance on oxygen-related biomedical equipment, including how to conduct facility surveys[23] and technical specifications.[5 24 25]

Many other governmental and non-governmental organisations are also working to document oxygen access capacity and needs in health facilities globally—including large-scale facility surveys[26 27]—and provide practical tools to improve access (eg, UNICEF online repository at https://bit.ly/OxygenResources).[21] However, if these efforts count oxygen equipment without assessing actual oxygen availability and patient access, they will overestimate the capacity of current oxygen systems and condemn patients to substandard care—particularly those in smaller and more remote facilities.

We tested strategies to obtain more meaningful data on oxygen access, identifying lessons learnt that can help HCWs, hospital managers, health administrators, policymakers and funders who wish to better understand and respond to the oxygen access crisis (box 1). We included a wide variety of healthcare facilities in Lagos state, Nigeria, and while our specific findings reflect this urban Nigerian environment, the broader lessons about measuring oxygen access are highly generalisable. We focused on oxygen access metrics that would be most widely applicable and broadly feasible but recognise that some readers will also want additional detail on specific populations (eg, neonates), services (eg, continuous positive airway pressure (CPAP)) or supply systems (eg, cylinder distribution).

To aid readers in adapting our approach to local context and needs, we describe three domains of oxygen access that should be considered when seeking to understand and respond to oxygen needs (figure 3, table 3, box 1).

At the centre is patients—evaluating whether patients who need oxygen actually receive it. Evaluating patient oxygen access requires clinical data on pulse oximetry

and oxygen use. Recent studies from Nigeria and Malawi have shown that without routine pulse oximetry to guide oxygen therapy, only around 20% of hypoxaemic patients receive oxygen—even if adequate oxygen supplies are available.[10 19] Given that pulse oximetry is essential to identifying who requires oxygen and routine pulse oximetry is rare without oxygen supplies,[6 18] pulse oximetry coverage (ie, the proportion of patients who receive pulse oximetry and have $SpO_2$ documented) may be a reasonable proxy for patient oxygen access.

High level metrics on pulse oximetry and oxygen use can be sourced via clinical audit but are ideally integrated into health information systems and are essential for health service planning (table 3). More detailed data, including who receives oxygen-related care, where, with what and for how long, would be desirable for hospital-level quality improvement activities and improving oxygen system efficiencies.

While measures of oxygen availability are important, existing surveys that contain this metric often fail to assess functionality of equipment or address intrahospital distribution, missing huge deficiencies in oxygen availability at the point of care.[6 13] Basic assessments of equipment functionality and distribution are not difficult and could be integrated into existing surveys such as the SPA and SARA (table 3). More detailed data on equipment types, locations and access to spare parts is useful for hospital-level decision-making and efficiency—particularly in facilities providing a wider range of respiratory support services (eg, CPAP, mechanical ventilation) across multiple service areas.

Measures of oxygen cost are important for planning purposes but were challenging to obtain in practice. We propose metrics that address oxygen costs to patients, crucial in contexts where out-of-pocket health expenditure is high, and oxygen costs to facilities/governments obtained from financial records and surveys (table 3). However, we recognise the difficulties in obtaining sensitive financial information and the limitations of relying on administrator or technician recall in the absence of reliable financial records.

Finally, our case study highlights opportunities for priority improvements in existing oxygen systems. First, pulse oximeters are low-cost devices that were grossly lacking and could substantially improve rational use of existing oxygen supplies. Second, while many devices were non-functional, support for technicians could likely rehabilitate some of these and prevent future growth of equipment graveyards (eg, Open O2 in Malawi, www.openo2.org). Third, many devices did not have CE or similar quality control markings, highlighting the ongoing challenge of inappropriate equipment donation and procurement of consumer devices for medical purposes. Fourth, the differences between government and private facilities highlight that oxygen access is fundamentally an issue of equity and efforts must include smaller, poorer and more rural facilities that care for the most at-risk populations.

## CONCLUSION

Data on oxygen access is lacking and makes efforts to improve oxygen systems for COVID-19 and beyond clumsy and inefficient. We propose three data domains to assess oxygen systems: use, availability and cost. Measuring these three domains of oxygen access will support local, regional and global efforts to provide life-saving oxygen to those in need.

**Author affiliations**
[1]Centre for International Child Health, MCRI, University of Melbourne, Royal Children's Hospital, Parkville, Victoria, Australia
[2]Department of Paediatrics, University College Hospital Ibadan, Ibadan, Oyo, Nigeria
[3]Department of Community Medicine, University College Hospital Ibadan, Ibadan, Oyo, Nigeria
[4]Institute for Global Health, Karolinska Institute, Stockholm, Sweden
[5]Institute for Global Health, University College London, London, UK
[6]Save the Children Nigeria, Abuja, FCT, Nigeria
[7]Save the Children Fund, London, UK
[8]Department of Community Medicine, University of Ibadan, Ibadan, Oyo, Nigeria
[9]Global Program in Respiratory Sciences, Eudowood Division of Pediatric Respiratory Sciences, Department of Pediatrics, Johns Hopkins School of Medicine, Baltimore, Maryland, USA
[10]Global Public Health, Karolinska Institutet, Stockholm, Sweden
[11]Department of Paediatrics, University of Ibadan, Ibadan, Oyo, Nigeria

**Twitter** Hamish R Graham @grahamhamish, Omotayo E Olojede @omotayoolojede, Adamu Isah @drIsahIsah, Rochelle Burgess @thewrittenro and Eric McCollum @tinylungsglobal

**Collaborators** INSPIRING Project Consortium: Carina King; Tim Colbourn; Rochelle Ann Burgess; Agnese Iuliano; Hamish R Graham; Eric D McCollum; Tahlil Ahmed; Samy Ahmar; Christine Cassar; Paula Valentine; Adamu Isah; Adams Osebi; Ibrahim Haruna; Abdullahi Magama; Ibrahim Seriki; Temitayo Folorunso Olowookere; Matt MacCalla; Adegoke G Falade; Ayobami Adebayo Bakare; Obioma Uchendu; Julius Salako; Funmilayo Shittu; Damola Bakare; Omotayo E Olojede.

**Contributors** CK, HRG, EM, AI, AAB, AGF and TC conceived the study and TC, CK and AGF are grant holders. CK, TC, HRG, EM, AGF, RB and AAB initiated the study design and OEO and OO led to data collection and implementation. Data analysis was conducted by HRG. The manuscript was drafted by HRG, with input from OEO, AAB and CK. All authors contributed to revisions and approved the final manuscript.

**Funding** This work was funded through the GlaxoSmithKline (GSK)-Save the Children Partnership (grant reference: 82603743). Employees of both GSK and Save the Children UK contributed to the design and oversight of the study as part of a co-design process.

**Disclaimer** Any views or opinions presented are solely those of the author/publisher and do not necessarily represent those of Save the Children UK or GSK, unless otherwise specifically stated. Sponsor: University College London (UCL).

**Competing interests** HRG, EM and CK are advisors to the Lifebox Foundation on pulse oximetry. AAB, AGF and HRG are board members for Oxygen for Life Initiative (OLI), a private non-profit that has provided services to the INSPIRING project. SA, TA, CC and PV are employed by Save the Children UK who are part of the partnership funding the research. TFO and MM are employees of and stockholders in GSK, a multinational for-profit pharmaceutical company that produces pharmaceutical products for childhood pneumonia, including a SARS-CoV-2 vaccine, and no direct financial interests in oxygen or pulse oximeter products.

**Patient consent for publication** Not required.

**Ethics approval** This study has received ethical approval from the Research Ethics Committee at: University of Ibadan (REF UI/EC/19/0551), Lagos State (REF LS/PHCB/MS/1128/VOL.V1/005), and University College London (REF 3433/005).

**Provenance and peer review** Not commissioned; externally peer reviewed.

**Data availability statement** All data relevant to the study are included in the article or uploaded as supplementary information.

**ORCID iDs**
Hamish R Graham http://orcid.org/0000-0003-2461-0463
Rochelle Burgess http://orcid.org/0000-0001-9749-7065
Tim Colbourn http://orcid.org/0000-0002-6917-6552
Carina King http://orcid.org/0000-0002-6885-6716

## REFERENCES

1 Duke T, Graham SM, Cherian MN, *et al*. Oxygen is an essential medicine: a call for international action. *Int J Tuberc Lung Dis* 2010;14:1362–8.
2 Baker T, Schell CO, Petersen DB, *et al*. Essential care of critical illness must not be forgotten in the COVID-19 pandemic. *The Lancet* 2020;395:1253–4.
3 Mangipudi S, Leather A, Seedat A, *et al*. Oxygen availability in sub-Saharan African countries: a call for data to inform service delivery. *Lancet Glob Health* 2020;8:e1123–4.
4 Bigdeli M, Jacobs B, Tomson G, *et al*. Access to medicines from a health system perspective. *Health Policy Plan* 2013;28:692–704.
5 WHO, UNICEF. WHO-UNICEF technical specifications and guidance for oxygen therapy devices. Geneva World Health Organization (WHO); 2019.
6 Bakare AA, Graham H, Ayede AI, *et al*. Providing oxygen to children and newborns: a multi-faceted technical and clinical assessment of oxygen access and oxygen use in secondary-level hospitals in Southwest Nigeria. *Int Health* 2020;12:60–8.
7 WHO. WHO global health Observatory data Repository, 2021. Available: http://apps.who.int/gho/data/ [Accessed 14 Jan 2021].
8 National Bureau of Statistics (NBS), United Nations Children's Fund (UNICEF). Multiple indicator cluster survey 2016-17, survey findings report. Abuja, Nigeria National Bureau of Statistics and United Nations Children's Fund; 2017.
9 Graham H, Bakare AA, Ayede AI, *et al*. Hypoxaemia in hospitalised children and neonates: a prospective cohort study in Nigerian secondary-level hospitals. *EClinicalMedicine* 2019;16:51–63.
10 Graham HR, Bakare AA, Ayede AI, *et al*. Oxygen systems to improve clinical care and outcomes for children and neonates: a stepped-wedge cluster-randomised trial in Nigeria. *PLoS Med* 2019;16:e1002951.
11 Graham H, Bakare AA, Fashanu C, *et al*. Oxygen therapy for children: a key tool in reducing deaths from pneumonia. *Pediatr Pulmonol* 2020;55 Suppl 1:S61–4.
12 Shittu F, Agwai IC, Falade AG, *et al*. Health system challenges for improved childhood pneumonia case management in Lagos and Jigawa, Nigeria. *Pediatr Pulmonol* 2020;55 Suppl 1:1–13.
13 Fashanu C, Mekonnen T, Amedu J, *et al*. Improved oxygen systems at hospitals in three Nigerian states: an implementation research study. *Pediatr Pulmonol* 2020;55 Suppl 1:S65–77.
14 Duke T, Subhi R, Peel D, *et al*. Pulse oximetry: technology to reduce child mortality in developing countries. *Ann Trop Paediatr* 2009;29:165–75.
15 WHO. Interagency list of priority medical devices for essential interventions for reproductive, maternal, newborn and child health. Geneva, Switzerland World Health Organization (WHO), UNICEF, UNFPA; 2016.
16 WHO. Priority medical devices list for the COVID-19 response and associated technical specifications: Interim guidance 19 November. Geneva, Switzerland World Health Organization (WHO); 2020. 2020.
17 WHO. WHO global health expenditure database (GHED), 2018. Available: https://apps.who.int/nha/database [Accessed Jan 2021].
18 Graham HR, Bakare AA, Gray A, *et al*. Adoption of paediatric and neonatal pulse oximetry by 12 hospitals in Nigeria: a mixed-methods realist evaluation. *BMJ Glob Health* 2018;3:e000812.
19 Kayambankadzanja RK, Schell CO, Mbingwani I. Unmet need of essential treatments for critical illness in Malawi. *medRxiv preprint* 2021.
20 Graham H, Tosif S, Gray A, *et al*. Providing oxygen to children in hospitals: a realist review. *Bull World Health Organ* 2017;95:288–302.
21 Graham HR, Bagayana SM, Bakare AA, *et al*. Improving Hospital oxygen systems for COVID-19 in low-resource settings: lessons from the field. *Glob Health Sci Pract* 2020;8:1–5.
22 WHO. Coronavirus disease (COVID-19) technical guidance: essential resource planning, 2020. Available: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/covid-19-critical-items [Accessed 16 Apr 2020].
23 WHO. Biomedical Equipment for COVID-19 Case Management: Interim guidance - Inventory tool for facility readiness and equipment re-allocation. Geneva World Health Organization (WHO); 2020.
24 WHO. *Oxygen therapy for children*. Geneva: World Health Organization, 2016.
25 WHO. Technical Specifications for Oxygen Concentrators. In: *WHO medical device technical series*. Geneva: World Health Organization, 2015.
26 MOH-Kenya. Technical review on oxygen supply. Nairobi MOH Kenya; 2020.
27 FMOH-Ethiopia, CHAI/CHAI-Ethiopia. Summary findings of the inventory assessment for biomedical equipment for COVID-19 case management in Ethiopia. Addis Ababa Federal Ministry of Health Ethiopia, Clinton Health Access Initiative (CHAI); 2020.

# Measuring Oxygen Access: lessons from health facility assessments in Nigeria.

**Authors**: Hamish R Graham*[1,2], Omotayo E Olojede[2], Ayobami A Bakare[3,4], Agnese Iuliano[5], Oyaniyi Olatunde[2], Adamu Isah[6], Adams Osebi[6], Tahlil Ahmed[7], Rochelle Ann Burgess[5], Eric D McCollum[8], Tim Colbourn[5], Carina King[4,5], Obioma C Uchendu[2,9], Adegoke G Falade[2,10] on behalf of the INSPIRING Project Consortium**

## Supplemental material

**Supplemental table 1**: Healthcare worker knowledge and experience with oxygen, pulse oximetry and related clinical practices

**Supplemental table 2**: Results from testing of pulse oximeter in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria

**Supplemental table 3**: Results from testing of oxygen concentrators in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria

**Supplemental table 4**: Results from testing of oxygen cylinders in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria

**Supplemental table 5**: Triangulation of pulse oximetry and oxygen access to ward areas in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria



Graham HR, *et al. BMJ Global Health* 2021; 6:e006069. doi: 10.1136/bmjgh-2021-006069

**Supplemental table 1: Healthcare worker knowledge and experience with oxygen, pulse oximetry and related clinical practices**

| General characteristics | Secondary health facility | Government PHC | Private PHC | Overall |
|---|---|---|---|---|
| Facilities | N=1[1] | N=28 | N=27 | N=56 |
| Participants | 9 | 96 | 64 | 169 |
| Sex, F:M (% female) | 8:1 (89%) | 91:5 (95%) | 50:14 (78%) | 149:20 (88%) |
| Role | | | | |
| - doctor | 2 (22%) | 5 (5%) | 16 (25%) | 23 (14%) |
| - nurse/midwife | 2 (22%) | 49 (51%) | 37 (58%) | 88 (52%) |
| - other | 5 (56%) | 42 (44%) | 11 (17%) | 58 (34%) |
| Median years of work | | | | |
| - at any health facility | 7 (3-15) | 15 (6-29) | 8 (4-15) | 12 (5-25) |
| - at this facility | 1 (1-3) | 1 (1-2) | 1 (1-8) | 2 (1-3) |
| Training | | | | |
| - IMCI | 2 (22%) | 62 (65%) | 21 (33%) | 85 (50%) |
| - ICCM | 0 (0%) | 4 (4%) | 7 (11%) | 11 (7%) |
| - ETAT | 1 (11%) | 5 (5%) | 13 (20%) | 19 (11%) |
| - Oxygen | 1 (11%) | 9 (9%) | 30 (47%) | 40 (24%) |
| - Pulse oximetry | 0 (0%) | 4 (4%) | 27 (42%) | 31 (18%) |
| - CPAP | 1 (11%) | 5 (5%) | 15 (23%) | 21 (12%) |
| - Resuscitation | 4 (44%) | 27 (28%) | 35 (55%) | 66 (39%) |
| - Infection control | 4 (44%) | 41 (43%) | 40 (63%) | 85 (50%) |
| - Baby friendly initiative | 5 (56%) | 35 (36%) | 31 (48%) | 71 (42%) |
| **Child pneumonia care** | | | | |
| Ever provided | | | | |
| - antibiotic for pneumonia | 7 (78%) | 70 (73%) | 56 (88%) | 133 (79%) |
| - IV antibiotic | 6 (67%) | 39 (41%) | 57 (89%) | 102 (60%) |
| - oxygen therapy | 7 (78%) | 32 (33%) | 58 (91%) | 97 (57%) |
| - resuscitate child | 7 (78%) | 67 (70%) | 59 (92%) | 130 (79%) |
| Past 2 weeks provided | | | | |
| - antibiotic for pneumonia | 5 (56%) | 35 (36%) | 16 (25%) | 56 (33%) |
| - IV antibiotic | 4 (44%) | 8 (8%) | 11 (17%) | 23 (14%) |
| - oxygen therapy | 3 (33%) | 2 (2%) | 9 (14%) | 13 (8%) |
| - resuscitate child | 3 (33%) | 10 (10%) | 15 (23%) | 28 (17%) |
| **Oxygen knowledge** | | | | |
| Mean score (95% CI) | | | | |
| - Total score (max. 40) | 17.8 (12.1-23.5) | 6.7 (5.2-8.3) | 14.9 (13.3-16.4) | 10.4 (9.1-11.6) |
| - Yes/No (max. 20) | 10.0 (6.7-13.3) | 4.4 (3.4-5.3) | 10.9 (9.9-11.9) | 7.1 (6.3-8.0) |
| - Scenarios[2] (max. 20) | 7.8 (4.4-11.2) | 2.3 (1.6-3.1) | 4.0 (3.1-4.9) | 3.3 (2.6-3.9) |
| Sample questions<br>- Correctly identify that pulse oximeters provide heart rate, $SpO_2$ and not blood pressure or respiratory rate[3] | 3 (33%) | 7 (7%) | 27 (42%) | 37 (22%) |
| - Correctly identify that a 2-year-old child with fast breathing and $SpO_2$ of 87% should be started on oxygen | 6 (67%) | 18 (19%) | 24 (38%) | 48 (28%) |
| - Correctly identify that a small newborn baby with $SpO_2$ 99% on oxygen should have the oxygen flowrate reduced | 3 (33%) | 11 (11%) | 18 (28%) | 32 (19%) |

Notes: CI = confidence interval; CPAP – continuous positive airway pressure; ETAT – emergency triage, assessment, and treatment; ICCM – integrated community case management; IMCI = integrated management of childhood illness; IQR = inter-quartile range, 25th to 75th centiles; $SpO_2$ – peripheral oxygen saturation. (1) Two secondary health facilities did not do the knowledge test; (2) 5-option best answer scenario with pulse oximetry result displayed; (3) Composite from 4 individual true/false questions.

**Supplemental table 2: Results from testing of pulse oximeter in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria**

| Facility | Device | Type | Location | Usage (times in prior day) | Oximeter Function | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Turns on | Fluke test 1 ($SpO_2$ 95%) | Fluke test 2 ($SpO_2$ 85%) | Fit for use |
| **Secondary health facilities** | | | | | | | | |
| SHF 1 | BCI* | Handheld | Ward (child) | 10 | Y | - | - | N[3] |
| SHF 2 | BCI* | Handheld | Ward (child) | 0 | N | - | - | N |
| | Oxi-Go | Finger tip | Ward (child) | ~100 | Y | 96 | 90 | N |
| | Mindray* | Handheld | Ward (child) | 0 | Y | - | - | N[3] |
| SHF 3 | "Medi Industries" | Finger tip | Ward (child) | 2 | Y | 96 | 86 | Y |
| | "Pediatric" | Finger tip | Ward (child) | 0 | Y | 93 | NR | N |
| **Private primary care facilities** | | | | | | | | |
| PRV 1 | unknown | Finger tip | Clinic | 0 | N | - | - | N |
| | unknown* | Finger tip | Clinic | 0 | N | - | - | N |
| | Contec | Desktop | Theatre | 0 | N[1] | - | - | N[1] |
| PRV 4 | Edan* | Handheld | Clinic | 30 | Y[2] | NR | NR | ? |
| | Edan* | Desktop | Theatre | 5 | Y | 96 | 87 | Y |
| PRV 6 | Drive | Finger tip | Clinic | 50 | Y[2] | NR | NR | ? |
| | Contec* | Finger tip | Emergency | 0 | Y[2] | NR | NR | ? |
| PRV 7 | Edan* | Desktop | Theatre | 0 | Y | 96 | 88 | Y |
| PRV 8 | unknown | Finger tip | Ward (general) | 20 | Y[2] | NR | NR | ? |
| PRV 9 | unknown | Finger tip | Clinic | 0 | Y | 96 | NR | N |
| PRV 10 | Schiller* | Handheld | Other | 0 | Y | 96 | 86 | Y |
| PRV 14 | Ana Wiz* | Finger tip | Clinic | 0 | Y[2] | NR | NR | ? |
| PRV 16 | EcoMed | Finger tip | Clinic | 0 | Y | 96 | 85 | Y |
| PRV 18 | Blue Jay | Finger tip | Clinic | 0 | Y | 95 | 85 | Y |
| PRV 19 | FaceLake | Finger tip | Clinic | 4 | Y | - | - | N[3] |
| | FaceLake | Finger tip | Clinic | 0 | N | - | - | N |
| PRV 22 | Promise Technology* | Finger tip | Clinic | 5 | Y | 96 | NR | N |
| PRV 24 | "Fabrication Enterprises"* | Finger tip | Ward (general) | 3 | Y | 95 | 85 | Y |
| PRV 25 | "Medline" | Finger tip | Delivery | 0 | Y | 97 | 92 | N |
| PRV 27 | Datascope* | Desktop | Theatre | 0 | Y | 96 | 84 | Y |
| | "iHealth"* | Finger tip | Clinic | 0 | Y | 96 | 87 | Y |
| **TOTAL** | | | | | **22/27 (81%)** | **14/27 (52%)** | **9/27 (33%)** | **9/27 (33%)** |

Notes: Fluke test 1 simulate normal person, set to 95% with good perfusion. Fluke test 2 simulate sick person, set to 85% with reduced perfusion. Considered "pass" if within +/-3%. (1) unable to test due to power outage; (2) unable to test with Fluke device; (3) missing probe or other defect preventing use. NR = no result.

**Supplemental table 3: Results from testing of oxygen concentrators in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria**

| Facility | Device type | Location | Concentrator Function[1] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Turns on | Gas flow | Air | 22-49% | 50-84% | ≥85% | Fit for use |
| **Secondary health facilities** | | | | | | | | | |
| SHF 1 | "LuFaith Y007-3"* | Ward (child) | Y | Y | | ○ | | | N |
| SHF 2 | DeVilbiss* | Ward (child) | N | N | | | | | N |
| SHF 3 | unknown | Ward (child) | Y | Y | | ○ | | | N |
| **Private primary care facilities** | | | | | | | | | |
| PRV 1 | Longfe+B2+E6:M41 | Theatre | N[2] | - | | | | | N[2] |
| PRV 2 | Weinmann | Theatre | Y | N | | | | | N |
| PRV 4 | Longfei* | Theatre | Y | Y | ○ | | | | N |
| PRV 4 | Draeger* | Emergency | Y | N | | | | | N |
| PRV 4 | Longfei* | Delivery | Y | Y | ○ | | | | N |
| PRV 6 | unknown "7F-3" | Emergency | Y | Y | | | ○ | | N |
| PRV 7 | unknown | Theatre | Y | Y | ○ | | | | N |
| PRV 8 | "Leap Medical 7F-3" | Ward (general) | Y | Y[4] | | | | | ?[4] |
| PRV 10 | "Elgil LFY-I-3A-W"* | Delivery | Y | Y | ○ | | | | N |
| PRV 10 | "Globe Health 7F-3" | Ward (general) | Y | Y | | | | ○ | Y |
| PRV 12 | Philips* | Delivery | N[2] | - | | | | | N[2] |
| PRV 13 | Invacare | Emergency | Y | Y | | | | ○ | Y |
| PRV 13 | Longfei* | Theatre | N | N | | | | | N |
| PRV 14 | Microfield* | Ward (general) | N[2] | - | | | | | N[2] |
| PRV 14 | Microfield* | Ward (general) | N[3] | N | | | | | N |
| PRV 15 | Zhengzhou Olive* | Theatre | Y | Y | | | | ○ | Y |
| PRV 17 | "Shulte-Deme"* | Store | Y[2] | - | | | | | N[2] |
| PRV 18 | DeVilbiss* | Theatre | Y[2] | - | | | | | N[2] |
| PRV 19 | Microfield* | Theatre | Y[2] | - | | | | | N[2] |
| PRV 20 | "Globe Health"* | Clinic | Y | Y | ○ | | | | N |
| PRV 21 | Puritan Bennett | Theatre | N | N | | | | | N |
| PRV 22 | Philips* | Theatre | N[2] | - | | | | | N[2] |
| PRV 20 | DeVilbiss* | Theatre | N[2] | - | | | | | N[2] |
| PRV 23 | Jiangsu Folee* | Theatre | Y | Y | ○ | | | | N |
| PRV 23 | Jiangsu Folee* | Theatre | Y | Y | ○ | | | | N |
| PRV 24 | unknown* | Theatre | N | N | | | | | N |
| PRV 26 | Airsep* | Theatre | N | N | | | | | N |
| PRV 27 | Invacare | Theatre | Y | Y | ○ | | | | N |
| **Government primary health care facilities** | | | | | | | | | |
| PHC 1 | "Axiom" | Delivery | Y | N | | | | | N |
| PHC 3 | "MA-Donax"* | Delivery | N[2] | - | | | | | N[2] |
| PHC 11 | Microfield* | Delivery | N | N | | | | | N |
| PHC 14 | unknown | Delivery | Y | N | | | | | N |
| PHC 14 | unknown | Delivery | Y | Y | ○ | | | | N |
| PHC 16 | unknown | Store | Y | N | | | | | N |
| PHC 16 | unknown | Store | Y | Y | | | | ○ | Y |
| PHC 21 | Microfield* | Delivery | Y | N | | | | | N |
| PHC 21 | unknown | Emergency | Y | N | | | | | N |
| PHC 23 | "Axiom" | Delivery | Y | Y | | | | ○ | Y |
| PHC 27 | "VINS"* | Delivery | N[2] | - | | | | | N[2] |
| **TOTAL** | | **N=42** | **28 (67%)** | **17 (40%)** | **9 (21%)** | **2 (5%)** | **1 (2%)** | **5 (12%)** | **5 (12%)** |

Notes: LPM = litres per minute. (1) tested at 5LPM or specified maximum; (2) unable to fully tested due to power outage; (3) missing electrical cable and/or other essential parts; (4) unable to be tested as it was being used for a critically ill patient at the time of survey; (*) had visible Conformité Européenne CE marking indicating compliance with the Declaration of Conformity to ISO 8359.

**Supplemental table 4: Results from testing of oxygen cylinders in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria**

| Facility | Device type | Location | Number | Fit for use[1] |
|---|---|---|---|---|
| **Secondary health facilities** | | | | |
| SHF 1 | Cylinder + manifold | Various[2] | 12 | 12 |
| SHF 2 | Cylinder | Various[3] | ?[3] | ?[3] |
| SHF 3 | Cylinder | Ward (paediatric) | 2 | 2 |
| **Private primary care facilities** | | | | |
| PRV 2 | Cylinder | Delivery | 3 | 0 |
| | Cylinder | Emergency | 1 | 1 |
| PRV 3 | Cylinder | Theatre | 1 | 1 |
| PRV 4 | Cylinder | Triage | 1 | 1 |
| PRV 5 | Cylinder | Theatre | 1 | 1 |
| PRV 6 | Cylinder | Emergency | 5 | 2 |
| PRV 7 | Cylinder | Theatre | 6 | 1 |
| PRV 9 | Cylinder | Ward (adult) | 1 | 0 |
| | Cylinder | Theatre | 2 | 1 |
| PRV 10 | Cylinder | Theatre | 3 | 2 |
| | Cylinder | Clinic | 1 | 1 |
| PRV 11 | Cylinder | Store | 7 | 0 |
| | Cylinder | Emergency | 1 | 1 |
| PRV 12 | Cylinder + splitter | Delivery | 1 | 1 |
| PRV 13 | Cylinder | Emergency | 1 | 1 |
| | Cylinder | Theatre | 1 | 1 |
| PRV 16 | Cylinder | Theatre | 1 | 1 |
| PRV 17 | Cylinder | Theatre | 1 | 1 |
| PRV 18 | Cylinder | Store | 1 | 0 |
| PRV 19 | Cylinder | Emergency | 1 | 1 |
| PRV 20 | Cylinder | Theatre | 1 | 1 |
| PRV 21 | Cylinder | Clinic | 1 | 1 |
| PRV 22 | Cylinder + manifold | Theatre | 1 | 1 |
| PRV 24 | Cylinder | Clinic | 2 | 1 |
| PRV 25 | Cylinder | Store | 2 | 1 |
| PRV 26 | Cylinder | Theatre | 3 | 3 |
| PRV 27 | Cylinder | Delivery | 1 | 1 |
| **Government primary health care facilities** | | | | |
| PHC 1 | Cylinder | Delivery | 1 | 1 |
| | Cylinder | Delivery | 1 | 1 |
| PHC 2 | Cylinder | Store | 1 | 0 |
| PHC 3 | Cylinder | Store | 2 | 1 |
| PHC 11 | Cylinder | Delivery | 2 | 1 |
| PHC 14 | Cylinder | Clinic | 1 | 0 |
| | Cylinder | Delivery | 2 | 2 |
| PHC 15 | Cylinder | Delivery | 1 | 1 |
| | Cylinder | Store | 1 | 1 |
| PHC 16 | Cylinder | Delivery | 1 | 1 |
| | Cylinder | Clinic | 1 | 0 |
| PHC 20 | Cylinder | Delivery | 1 | 1 |
| PHC 23 | Cylinder + splitter | Delivery | 1 | 1 |
| PHC 26 | Cylinder | Delivery | 1 | 1 |
| **TOTAL** | **-** | **-** | **82 (100%)** | **53 (65%)** |

Notes: (1) fit for use defined as the number of cylinders with a regulator apparatus or functional outlets from manifold system. (2) Cylinders supplied outlets in 6 wards: Emergency ward, Operating Theatre, Maternity suite, General ward (M and F), and Paediatric ward. (3) Unable to complete cylinder survey at facility – cylinders were available and being used in multiple ward areas and in store, but missing exact location, quantity, and functional assessment.

**Supplemental table 5: Triangulation of pulse oximetry and oxygen access to ward areas in 58 health facilities in Ikorodu local government area, Lagos state, Nigeria**

| | Oxygen supply[1] | | | | | | | | Use[2] |
|---|---|---|---|---|---|---|---|---|---|
| **Facility** | **OPD** | **MAT** | **ED** | **GEN** | **OT** | **PED** | **ICU** | **Store** | **Oximeter** |
| **Secondary health facilities** | | | | | | | | | |
| **SHF 1** | | >2 outlets | >2 outlets | >2 outlets | >2 outlets | >2 outlets 0 concent | >2 outlets | 12-bank manifold | 0 paed* |
| **SHF 2** | cylinder[3] | cylinder[3] | cylinder[3] | cylinder[3] | cylinder[3] | cylinders[3] 0 concentr | cylinder[3] | 25 cylinder | 0 paed |
| **SHF 3** | | | | | | 2 cylinder, 0 concent | | | 1 paed |
| **Private primary care facilties** | | | | | | | | | |
| PRV 1 | | | | | 0 concent* | | | | 0 clinic, 0 OT |
| PRV 2 | | 0 cylinder no gauges | 1 cylinder | | 0 concent | | | | |
| PRV 3 | | | | | 1 cylinder | | | | |
| PRV 4 | | 0 concent | 1 cylinder, 0 concentr | | 0 concent | | | | 1 theatre, 0 clinic* |
| PRV 5 | | | | | 1 cylinder | | | | |
| PRV 6 | | | 2 cylinders, 0 concent | | | | | | 0 clinic*, 0 ED* |
| PRV 7 | | | | | 1 cylinder, 0 concent | | | | 1 OT |
| PRV 8 | | | | 1* concent | | | | | 0 ward* |
| PRV 9 | | | | 0 cylinder no reg | 1 cylinder | | | | 0 clinic* |
| PRV 10 | 1 cylinder | 0 concentr | | 1 concent | 2 cylinder | | | | 1 everwhere |
| PRV 11 | | | 1 cylinder (more in store) | | | | | | |
| PRV 12 | | 1 cylinder + splitter, 0 concent* | | | | | | | |
| PRV 13 | | | 1 cylinder, 1 concent | | 1 cylinder, 0 concent | | | | |
| PRV 14 | | | | 0 concent | | | | | 0 clinic* |
| PRV 15 | | | | | 1 concent | | | | |
| PRV 16 | | | | | 1 cylinder | | | | 1 clinic |
| PRV 17 | | | | | 1 cylinder | | | 0 concent* | |
| PRV 18 | | | | | 0 concent* | | | 0 cylinder no reg | 1 clinic |
| PRV 19 | | | 1 cylinder | | 0 concent* | | | | 0 clinic |
| PRV 20 | 0 concent | | | | 1 cylinder | | | | |
| PRV 21 | 1 cylinder | | | | 0 concent* | | | | |
| PRV 22 | | | | | 1 or more cylinder manifold, 0 concent* | | | | 0 clinic |
| PRV 23 | | | | | 0 concent | | | | |
| PRV 24 | 1 cylinder | | | | 0 concent | | | | 1 gen |
| PRV 25 | | | | | | | | 1 cylinder | 0 matern |
| PRV 26 | | | | | 3 cylinder, 0 concent | | | | |
| PRV 27 | | 1 cylinder | | | 0 concent | | | | 1 OT, 1 clinic |
| **Government primary health care facilities** | | | | | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PHC 1 | | 2 cylinder, 0 concent* | | | | | | | |
| PHC 2 | | | | | | | | 0 cylinder no regulator | |
| PHC 3 | | 0 concent* | | | | | | 1 cylinder | |
| PHC 4 | | | | | | | | | |
| PHC 5 | | | | | | | | | |
| PHC 6 | | | | | | | | | |
| PHC 7 | | | | | | | | | |
| PHC 8 | | | | | | | | | |
| PHC 9 | | | | | | | | | |
| PHC 10 | | | | | | | | | |
| PHC 11 | | 1 cylinder, 0 concent | | | | | | | |
| PHC 12 | | | | | | | | | |
| PHC 13 | | | | | | | | | |
| PHC 14 | | 2 cylinder, 0 concent | | | | | | | |
| PHC 15 | | 1 cylinder | | | | | | 1 cylinder | |
| PHC 16 | 0 cylinder no reg | 1 cylinder | | | | | | 1 concent | |
| PHC 17 | | | | | | | | | |
| PHC 18 | | | | | | | | | |
| PHC 19 | | | | | | | | | |
| PHC 20 | | 1 cylinder | | | | | | | |
| PHC 21 | | 0 concent | 0 concent | | | | | | |
| PHC 22 | | | | | | | | | |
| PHC 23 | | 1 cylinder + splitter, 1 concent | | | | | | | |
| PHC 24 | | | | | | | | | |
| PHC 25 | | | | | | | | | |
| PHC 26 | | 1 cylinder | | | | | | | |
| PHC 27 | | 0 concent* | | | | | | | |
| PHC 28 | | | | | | | | | |

Notes: * Concentrator unable to be tested due to power failure or in use (PRV 8), or pulse oximeter appeared incompatible with Fluke testing device. (1) Adequate oxygen supply for minimum expected use. Numerical values indicate functional oxygen sources located in each ward area ('0' means none of the sources present were functional), while blank cells indicate no oxygen sources in that ward area. Oxygen supply assumptions: secondary health facilities provide inpatient and outpatient services and must be able to simultaneously provide oxygen to 2 patients in each inpatient ward area with backup supply available; private facilities provide outpatient and inpatient services +/- surgical services, and must be able to provide oxygen to one patient in each inpatient ward area with backup supply available; government primary health care facilities provide outpatient and maternity services and must be able to provide oxygen to one patient with backup supply available.; (2) Ability to triage and monitor patients on oxygen with oximetry for minimum expected demand. Numerical values indicate functional oximeters located in each ward area ('0' means none of the oximeters present were functional), while blank cells indicate no oximeter in that ward area. Oxygen use assumptions: pulse oximetry must be available in every ward area that sees acutely unwell patients. (3) Unable to complete cylinder survey at facility – cylinders were available and being used in multiple ward areas and in store, but missing exact location, quantity, and functional assessment. OPD = outpatient department / clinic; MAT = maternity / birth suite; ED = emergency department; OT = operating theatre; PED = children's / neonatal ward; GEN = general / adult wards; ICU = intensive care unit. Red = not available. Orange = available but inadequate to meet needs. Green = adequate for minimum expected service need. * Device not able to be fully tested (e.g. due to power outage).