Pulse Oximetry Accuracy in Children with Dark Skin Tones: Relevance to Acute Lower Respiratory Infection Care in Low- and Middle-Income Countries.

Shubhada Hooli[1*], Tim Colbourn[2], Manish I. Shah[3], Kristy Murray[4], Anna Mandalakas[5], and Eric D. McCollum[6,7]

1. Division of Emergency Medicine, Department of Pediatrics, Baylor College of Medicine, Houston, TX, United States
2. Institute for Global Health, University College London, London, United Kingdom
3. Department of Emergency Medicine, Stanford University School of Medicine, Palo Alto, CA, United States
4. Division of Tropical Medicine, Department of Pediatrics, Baylor College of Medicine, Houston, TX, United States
5. Global Tuberculosis Program, Department of Pediatrics, Baylor College of Medicine, Houston, TX, United States
6. Global Program in Pediatric Respiratory Sciences, Eudowood Division of Pediatric Respiratory Sciences, Department of Pediatrics, School of Medicine, Johns Hopkins University, Baltimore, MD, United States
7. Health Systems Program, Department of International Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, United States

6621 Fannin St Suite A210 MS: BCM 320 Houston, TX 77030

hooli@bcm.edu, +1-727-505-9525

Key Words: pulse oximetry, respiratory infections, pediatrics

Abstract: 181 Text: 1840 Table: 1

Acute lower respiratory infections (ALRI) are the leading post-neonatal cause of death in children under 5 years old. There is a high prevalence of pediatric ALRI-related hypoxemia in low- and middle-income countries. The World Health Organization defines clinically meaningful hypoxemia in children as a SpO_2 (peripheral oxygen saturation) < 90%. Multiple studies put this convention into question and found SpO_2 of 90-92% to be associated with child ALRI mortality. There is an evolving body of evidence that suggests that pulse oximeters, systematically, over-estimate oxygen saturation in individuals with dark skin tones. We conducted a narrative review of pediatric studies evaluating pulse oximeter accuracy in children without COVID-19. Four studies, one prospective, examined pulse oximeter accuracy in children of varying ages with dark skin tones. All studies had limitations that affect their generalizability. There is evidence that certain pulse oximeters may over-estimate oxygen saturation in children with dark skin tones. Further prospective research is urgently needed to identify affected populations and clinical implications. Despite recognized challenges, we strongly urge continued and expanded use of pulse oximetry as its use will save lives.

Globally acute lower respiratory infections (ALRI), including pneumonia and bronchiolitis, remain the number one cause of death of children under 5 years old outside of the neonatal period[1]. Hypoxemia is a well-recognized risk factor for ALRI mortality[2] that informs clinical care of severely ill patients. Pulse oximeters are portable devices that non-invasively measure the peripheral arterial oxyhemoglobin saturation (SpO_2), or blood oxygen levels. Although their use is associated with reduced child pneumonia related hospital mortality[3], they are inconsistently available or used within clinics and hospitals in low- and middle-income countries (LMICs).[4-6] A growing body of evidence suggests that pulse oximeter reported oxygen saturation (SpO_2) may not precisely equate to measured arterial hemoglobin oxygen saturation (SaO_2), the reference standard, with potential implications on patient outcomes. We aim to conduct a narrative review on pulse oximeter accuracy in children with dark skin tones and discuss the potential relevance in ALRI care in LMICs.

Role of Pulse Oximetry in Pediatric ALRI Care in LMICs

Though pulse oximeters have not been adopted as a universal component of high quality ALRI care delivery, evidence on hypoxemia burden and the impact of oximetry on care provision and mortality indicates they should be.[3] A sub analysis reported in a recent metanalysis of studies exploring hypoxemia incidence in children with ALRI in LMICs estimates up to 23% of children with ALRI presenting to clinics were hypoxemic.[7] Hypoxemia, with a SpO_2 <90%, is associated with an over 5-fold increase odds for ALRI-related mortality in children under 5.[2] Studies from Malawi and Bangladesh suggest that a significant number of hypoxemic children would not have been referred to the hospital if clinicians relied exclusively on clinical signs for medical decision making in the absence of pulse oximetry.[8,9]

Multiple studies report 'moderate' hypoxemia, defined as a SpO_2 of 90-92% or 90-93%, predicts pediatric ALRI-related mortality independent of severity of work of breathing, moderate or severe malnutrition, or tachypnea.[2, 9-12] Anemia, poor pulmonary reserve or chronic lung disease, altered affinity between hemoglobin and oxygen due to fever or acidosis, mild malnutrition, or other host or environmental factors could be unmeasured contributors to this association. The association between 'moderate' hypoxemia and death could also in part be explained by systematic over-estimation of SaO_2 by pulse oximeter measured SpO_2 in children with dark skin tones.

Pulse Oximetry Accuracy in Adults with Dark Skin Tones

Pulse oximeters calculate a SpO_2 using proprietary algorithms that interpret changes in light diffusion as it passes through the nail, tissues, and skin of the measurement location, which is usually a finger or toe. Movement, moderate-severe anemia, nail polish, dirt, ambient light, and digit thickness can affect pulse oximeter accuracy.[13] Manufacturers report SpO_2 accuracy within +/- 2% of the reference SaO_2. Triggered by discordance between pulse oximeter measured hypoxemia and clinical outcomes during the COVID-19 pandemic, several retrospective studies conducted in adults report that US Food and Drug Administration (FDA) approved pulse oximeters may systematically produce SpO_2 results that over-estimate SaO_2 in Black patients.[14-17]

Although the WHO defines hypoxemia as a SpO_2 <90%, studies that assess SpO_2 over-estimation of SaO_2 define occult hypoxemia as a SaO_2 <88% when the SpO_2 is >92%, however this is less stringent than FDA accuracy requirements. The first large retrospective study of adults reported an occult hypoxemia prevalence of 11.4% (95% CI 7.6-15.2%) in Black patients

compared to 3.6% (95% CI 2.5-4.6%) in White patients.[16] The study paired SpO_2 and SaO_2 measurements collected up to 10 minutes apart even though these indices change minute to minute, severely limiting the strength of these findings. A subsequent, retrospective study simultaneously paired SpO_2-SaO_2 measurements demonstrated a more modest occult hypoxemia prevalence of 6.2% (95% CI 5.1-7.6%) amongst Black adults and a 3.6% prevalence (95% CI 3.4–3.8%) amongst White adults.[14] This study uniquely identified associations between occult hypoxemia and longer hospital stays in surgical patients (2.5 days) and increased odds for mortality amongst surgical [adjusted odds ratio (aOR) of 2.96, 95% CI 1.20-7.28] and intensive care unit (aOR 1.36, 95% CI 1.03-1.80) patients.[14] A recent meta-analysis reported that measured SpO_2 over-estimates SaO_2 by 1.1% in people with darker skin pigmentation.[17] Based on limitations in existing studies, the FDA highlighted the need to further explore if this over-estimation occurs in people with dark skin tones and exacerbates racial health disparities.[18] In contrast, a meta-analysis of 32 studies reported an acceptable pooled mean SpO_2-SaO_2 difference of (1.52%; 95% CI 0.95 to 2.09%) amongst electronic medical record (EMR) reported Black/African American patients, and the overall root mean squared error was <4%, also within acceptable limits, amongst all racial groups.[17] Notably, studies have not attempted to distinguish if different pulse oximeter manufacturers or probe types are more accurate than others.

Pulse Oximetry Accuracy in Children with Dark Skin Tones

We searched PubMed using these search terms: “pediatric, pulse oximeter, accuracy, bias.” We included only non-COVID 19 specific studies, to assure this narrative review is generalizable, that compared SpO_2 to arterial blood gas SaO_2. Pediatric studies examining pulse oximeter performance with respect to dark skin tones are sparse, mostly retrospective, and also

inconsistent (Table 1).[19–22] An exception was a single prospective study in infants with cyanotic congenital heart disease that classified skin hue using the Munsell Soil Color chart, an unvalidated means of skin tone classification.[21] It found no skin tone differences in pulse oximetry performance,[21] but these patients had cyanotic congenital heart disease and pulse oximeters are known to be inaccurate at a SpO_2 <80%.[18] The first large retrospective pediatric study in patients hospitalized in intensive care units [N=1061 (17.2% Black), 9023 SpO_2-SaO_2 pairs] reported Black children had a 2.16 adjusted odds (aOR) of occult hypoxemia (defined as a SaO_2 <88% with a SpO_2 ≥92%) compared to White children.[20] Notably SpO_2-SaO_2 measurements were paired within 10 minutes, rather than concurrently, and the authors did not extrapolate the effect on clinical outcomes. Another retrospective study in children undergoing cardiac catheterization reported an unadjusted difference between SpO_2 and SaO_2 of 2.58 (95% CI 2.15-3.00) in Black children compared with that of 0.89 (95% CI 0.64-1.15) in White patients.[19] And finally a retrospective study in preterm neonates under 32 weeks gestational age reported that there was no difference in the frequency of occult hypoxemia in Black vs White neonates.[22] No study to date has attempted to prospectively investigate the impact of skin tone on pulse oximeter performance or if discrepant matched SpO_2-SaO_2 measurements impact clinical outcomes in pediatric patients.

Table 1: Pediatric Pulse Oximetry Racial and Dark Skin Tone Bias Studies (excluded COVID19 related)				
Author	Ruppel[19]	Andrist[20]	Vesoulis[22]	Foglia[21]
Population	1-17 years old undergoing cardiac catheterization; frequently with CHD*	Children 17 years old or younger hospitalized in an intensive care unit	Neonates < 32 weeks gestational age <1500 grams	Infants with CHD* and baseline SpO_2 < 90%
Design	Retrospective Cross-sectional EMR^ 2016-2021	Retrospective Cross-sectional EMR^ 2015-2020	Retrospective Cross-sectional EMR^ 2012-2019	Prospective Cross-sectional 2013-2015
Sample Size	774 patients (26% Black)	9023 measurements from 1061 patients (17.2% Black)	4387 measurements from 294 patients (42% Black)	36 infants (39% with dark skin tone)
Occult Hypoxemia Definition	SaO_2 < 88% and $SpO_2 \geq$ 92% collected within 1 minute	SaO_2 < 88% and $SpO_2 \geq$ 92% collected within 10 minutes	SaO_2 <85% and $SpO_2 \geq$ 90% collected within 1 minute	Did not report occult hypoxemia; collected simultaneously
Gas Sample Collection Site	Descending aorta, femoral artery, or systemic ventricle	Not documented	Not documented, likely included umbilical artery	Not documented
Occult Hypoxemia Frequency	5% (7/139) in Black and 1% (4/407) in White patients.	9.6% (95% CI 6.3-14.5%) in Black and 5.8% (95% CI 4.6-7.3%) in White patients.	9.2% in Black and 7.7% (p=0.08) in White patients.	Did not report occult hypoxemia
Pulse Oximeter Bias	2.58 (95% CI 2.15-3.00) in Black vs 0.89 (95% CI 0.64-1.15) White Children	3.5 (5.0) in White vs 4.3 (5.0) in Black patients (P<0.001)	1.73 in Black vs 0.72 in White infants p<0.01	Masimo Radical 7: 1.6 (4.8) in Dark vs 0.2 (3.8) in Fair infants Nellcor Oximax: 5.4 (5.1) in Dark vs 3.0 (5.0) in Fair infants

*CHD: congenital heart disease, ^EMR: electronic medical record

Challenges in Interpreting Existing Studies

Although compelling, retrospective studies characterizing differences in paired SpO_2 and SaO_2 measurements have limited generalizability. First, pulse oximeters may save continuous SpO_2 measurements, but few record plethysmography waveforms to confirm measurement accuracy making it difficult to confirm if EMR extracted SpO_2 measurements were accurate. Second, the time stamp of an ABG may not be precise, limiting the ability to truly pair SpO_2-SaO_2 measurements. Many studies paired measurements collected within 5-10 minutes, which could account for the apparent discrepancies. Third, most published studies relied on race data

extracted from the EMR; however there may be discordance between patient reported and EMR documented race.[23] Finally, the hypothesis of studies assessing SpO_2 over-estimation of SaO_2 is that skin tone, not the social construct of race, affects pulse oximeter accuracy. Race may not accurately reflect a subject's skin tone and skin tone may differ in different areas of the body. To test the hypothesis that pulse oximeter accuracy is affected by patient skin tone, subject skin tone must be measured, including at the site of measurement, and SpO_2-SaO_2 measurements must be near simultaneously paired.

All of the aforementioned SpO_2 accuracy studies were conducted in high-income contexts, and it is notable that 90% of children who succumb to ALRI live in LMICs.[24] Pulse oximeters effectively designed for LMICs should be less expensive, more portable, run on batteries, have reusable probes, withstand environments with more heat and dust, and still perform accurately.[25-27] Pulse oximeters that don't meet these specifications may not perform well in LMIC environments. To date, no published studies have evaluated if the measured SpO_2 of pulse oximeters designed for LMICs is within regulatory standard accuracy (+/- 2%) of SaO_2 in children or when used clinically. Additionally, it is unclear how SpO_2 relative to SaO_2 may differ between different types of pulse oximeter probes and manufacturers. The COVID-19 pandemic brought a rush of respiratory care supplies, including pulse oximeters, into LMICs. As the pandemic subsides these pulse oximeters presumably are being integrated into child ALRI care pathways, but it is critical that this is done judiciously. A large inaccuracy in pulse oximeters more commonly used in LMICs, particularly if healthcare workers inappropriately use hypoxemia as the sole clinical indication for hospital referral or escalation of hospital based care, could result in delayed ALRI treatment of children.

Conclusions

Pulse oximeters, based on limited low quality data, may be inaccurate in children with dark skin tones like what has been reported in adult populations. While other explanations are plausible, an over-estimation of SaO_2 may be contributing to the association between a SpO_2 of 90-93% and ALRI mortality in children living in LMICs.[2, 9-12] Given the different types of oxygen saturation probes available and manufacturer specific light wavelength interpretation algorithms, some oximeters are likely to be more inaccurate and biased than others. We need to understand the full magnitude and clinical implications of these inaccuracies, determine if they are across all or specific manufacturers of pulse oximeters and probes, define affected populations, and determine how other co-morbidities that affect systemic oxygen carrying capacity affect device accuracy. If a discrepancy truly exists, we must understand how it impacts individual patient outcomes in order to thoughtfully address this bias at a population level. These questions must be answered systematically and through collaborative multi-country research with studies in LMICs. To date no published studies have occurred outside of high income countries. In order to reduce further ALRI deaths it is critical that studies occur in LMICs as these countries have the greatest population of children with dark skin tones and bear the greatest child ALRI mortality burden.

Despite recognized challenges, we strongly urge continued and expanded use of pulse oximetry in child ALRI care as its use will save lives.[28] This is particularly important as the WHO Integrated Management of Childhood Illness guidance, when implemented without pulse oximetry, may not identify all hypoxemic or children at risk for ALRI related mortality as needing hospital referral. With this knowledge in hand, in the interim, health systems should continue to integrate pulse oximetry into child ALRI care while emphasizing to clinicians that

hypoxemia is one of several clinical findings associated with mortality. Pulse oximeters should be used alongside other clinical information. Clinicians should interpret SpO_2 measurements conservatively by weighing the risk profile of patients (i.e., age, immune and nutritional status, vaccination history, co-morbidities) alongside existing hypoxemia evidence when deciding on patient management. Children with an overall clinical picture suggestive of severe pneumonia, even if their SpO_2 seems normal, should still be referred to care. Further, it is critically important that health systems continue to allocate resources to support incorporation of pulse-oximeters in LMICs.

Tim Colbourn t.colbourn@ucl.ac.uk
Institute for Global Health, University College London

Manish Shah mshah5@stanford.edu
Department of Emergency Medicine, Stanford University School of Medicine

Kristy Murray kmurray@bcm.edu
Division of Tropical Medicine, Department of Pediatrics, Baylor College of Medicine

Anna Mandalakas anna.mandalakas@bcm.edu
Global Tuberculosis Program, Department of Pediatrics, Baylor College of Medicine

Eric D. McCollum ericdmccollum@gmail.com
Global Program in Pediatric Respiratory Sciences, Eudowood Division of Pediatric Respiratory Sciences, Department of Pediatrics, School of Medicine, Johns Hopkins University

1. Troeger CE, Khalil IA, Blacker BF, Biehl MH, Albertson SB, Zimsen SRM, Rao PC, Abate D, Admasie A, Ahmadi A, Ahmed MLCB, Akal CG, Alahdab F, Alam N, Alene KA, et al., 2020. Quantifying risks and interventions that have affected the burden of lower respiratory infections among children younger than 5 years: an analysis for the Global Burden of Disease Study 2017. *The Lancet Infectious Diseases 20*: 60–79

2. Lazzerini M, Sonego M, Pellegrin MC., 2015. Hypoxaemia as a Mortality Risk Factor in Acute Lower Respiratory Infections in Children in Low and Middle-Income Countries: Systematic Review and Meta-Analysis. *PLOS ONE 10*: e0136166

3. Hooli S, King C, McCollum ED, Colbourn T, Lufesi N, Mwansambo C, Gregory CJ, Thamthitiwat S, Cutland C, Madhi SA, Nunes MC, Gessner BD, Hazir T, Mathew JL, Addo-Yobo E, et al., 2023. In-hospital mortality risk stratification in children aged under 5 years with pneumonia with or without pulse oximetry: A secondary analysis of the Pneumonia REsearch Partnership to Assess WHO REcommendations (PREPARE) dataset. *Int J Infect Dis 129*: 240–250

4. Ginsburg AS, Van Cleve WC, Thompson MIW, English M., 2012. Oxygen and pulse oximetry in childhood pneumonia: a survey of healthcare providers in resource-limited settings. *J Trop Pediatr 58*: 389–393

5. Simkovich SM, Underhill LJ, Kirby MA, Crocker ME, Goodman D, McCracken JP, Thompson LM, Diaz-Artiga A, Castañaza-Gonzalez A, Garg SS, Balakrishnan K, Thangavel G, Rosa G, Peel JL, Clasen TF, et al., 2022. Resources and Geographic Access to Care for Severe Pediatric Pneumonia in Four Resource-limited Settings. *Am J Respir Crit Care Med 205*: 183–197

6. Enoch AJ, English M, Clinical Information Network, McGivern G, Shepperd S., 2019. Variability in the use of pulse oximeters with children in Kenyan hospitals: A mixed-methods analysis. *PLoS Med 16*: e1002987

7. Rahman AE, Hossain AT, Nair H, Chisti MJ, Dockrell D, Arifeen SE, Campbell H., 2022. Prevalence of hypoxaemia in children with pneumonia in low-income and middle-income countries: a systematic review and meta-analysis. *The Lancet Global Health 10*: e348–e359

8. McCollum ED, King C, Deula R, Zadutsa B, Mankhambo L, Nambiar B, Makwenda C, Masache G, Lufesi N, Mwansambo C, Costello A, Colbourn T., 2016. Pulse oximetry for children with pneumonia treated as outpatients in rural Malawi. *Bull World Health Organ 94*: 893–902

9. McCollum ED, Ahmed S, Roy AD, Islam AA, Schuh HB, King C, Hooli S, Quaiyum MA, Ginsburg AS, Checkley W, Baqui AH, Colbourn T., 2023. Risk and accuracy of outpatient-identified hypoxaemia for death among suspected child pneumonia cases in rural Bangladesh: a multifacility prospective cohort study. *Lancet Respir Med*: S2213-2600(23)00098-X

10. Hooli S, King C, Zadutsa B, Nambiar B, Makwenda C, Masache G, Lufesi N, Mwansambo C, Malla L, Costello A, Colbourn T, McCollum ED., 2020. The Epidemiology of Hypoxemic Pneumonia among Young Infants in Malawi. *Am J Trop Med Hyg 102*: 676–683

11. Hooli S, Colbourn T, Lufesi N, Costello A, Nambiar B, Thammasitboon S, Makwenda C, Mwansambo C, McCollum ED, King C., 2016. Predicting Hospitalised Paediatric Pneumonia Mortality Risk: An External Validation of RISC and mRISC, and Local Tool Development (RISC-Malawi) from Malawi. *PLOS ONE 11*: e0168126

12. Gallagher KE, Knoll MD, Prosperi C, Baggett HC, Brooks WA, Feikin DR, Hammitt LL, Howie SRC, Kotloff KL, Levine OS, Madhi SA, Murdoch DR, O'Brien KL, Thea DM, Awori JO, et al., 2020. The Predictive Performance of a Pneumonia Severity Score in Human Immunodeficiency Virus-negative Children Presenting to Hospital in 7 Low- and Middle-income Countries. *Clin Infect Dis 70*: 1050–1057

13. Fouzas S, Priftis KN, Anthracopoulos MB., 2011. Pulse Oximetry in Pediatric Practice. *Pediatrics 128*: 740–752

14. Henry NR, Hanson AC, Schulte PJ, Warner NS, Manento MN, Weister TJ, Warner MA., 2022. Disparities in Hypoxemia Detection by Pulse Oximetry Across Self-Identified Racial Groups and Associations With Clinical Outcomes*. *Critical Care Medicine 50*: 204–211

15. Valbuena VSM, Seelye S, Sjoding MW, Valley TS, Dickson RP, Gay SE, Claar D, Prescott HC, Iwashyna TJ., 2022. Racial bias and reproducibility in pulse oximetry among medical and surgical inpatients in general care in the Veterans Health Administration 2013-19: multicenter, retrospective cohort study. *BMJ 378*: e069775

16. Sjoding MW, Dickson RP, Iwashyna TJ, Gay SE, Valley TS., 2020. Racial Bias in Pulse Oximetry Measurement. *N Engl J Med 383*: 2477–2478

17. Shi C, Goodall M, Dumville J, Hill J, Norman G, Hamer O, Clegg A, Watkins CL, Georgiou G, Hodkinson A, Lightbody CE, Dark P, Cullum N., 2022. The accuracy of pulse oximetry in measuring oxygen saturation by levels of skin pigmentation: a systematic review and meta-analysis. *BMC Med 20*: 267

18. Health C for D and R., 2021. Pulse Oximeter Accuracy and Limitations: FDA Safety Communication. *FDA*

19. Ruppel H, Makeneni S, Faerber JA, Lane-Fall MB, Foglia EE, O'Byrne ML, Bonafide CP., 2023. Evaluating the Accuracy of Pulse Oximetry in Children According to Race. *JAMA Pediatrics*

20. Andrist E, Nuppnau M, Barbaro RP, Valley TS, Sjoding MW., 2022. Association of Race With Pulse Oximetry Accuracy in Hospitalized Children. *JAMA Network Open 5*: e224584

21. Foglia EE, Whyte RK, Chaudhary A, Mott A, Chen J, Propert KJ, Schmidt B., 2017. The Effect of Skin Pigmentation on the Accuracy of Pulse Oximetry in Infants with Hypoxemia. *The Journal of Pediatrics 182*: 375-377.e2

22. Vesoulis Z, Tims A, Lodhi H, Lalos N, Whitehead H., 2022. Racial discrepancy in pulse oximeter accuracy in preterm infants. *J Perinatol 42*: 79–85

23. Polubriaginof FCG, Ryan P, Salmasian H, Shapiro AW, Perotte A, Safford MM, Hripcsak G, Smith S, Tatonetti NP, Vawdrey DK., 2019. Challenges with quality of race and ethnicity data in observational databases. *J Am Med Inform Assoc 26*: 730–736

24. Troeger C, Forouzanfar M, Rao PC, Khalil I, Brown A, Swartz S, Fullman N, Mosser J, Thompson RL, Reiner RC, Abajobir A, Alam N, Alemayohu MA, Amare AT, Antonio CA, et al., 2017. Estimates of the global, regional, and national morbidity, mortality, and aetiologies of lower respiratory tract infections in 195 countries: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet Infectious Diseases 17*: 1133–1161

25. Hernández P, Baker K, Kallander K., 2014. Initial penumonia device short listing exercise report. *London: Malaria Consortium*

26. King C, Boyd N, Walker I, Zadutsa B, Baqui AH, Ahmed S, Islam M, Kainja E, Nambiar B, Wilson I, McCollum ED., 2018. Opportunities and barriers in paediatric pulse oximetry for

pneumonia in low-resource clinical settings: a qualitative evaluation from Malawi and Bangladesh. *BMJ Open 8*

27. Strange B, Sullivan A., 2013. Pneumonia Diagnostics: Current Outlook and Perspectives. *UNICEF Supply Division, Copenhagen, DK, Tech Rep*

28. Hooli S, King C, McCollum ED, Colbourn T, Lufesi N, Mwansambo C, Gregory CJ, Thamthitiwat S, Cutland C, Madhi SA, Nunes MC, Gessner BD, Hazir T, Mathew JL, Addo-Yobo E et al., 2023. Pneumonia REsearch Partnership to Assess WHO REcommendations (PREPARE) study group. In-hospital mortality risk stratification in children aged under 5 years with pneumonia with or without pulse oximetry: A secondary analysis of the Pneumonia REsearch Partnership to Assess WHO REcommendations (PREPARE) dataset. *Int J Infect Dis* 129: 240-250