Differential Pulse Oximeter Accuracy, Occult Hypoxemia Prevalence, and Clinical Outcomes by Patient Race/Ethnicity

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PREFACE

The VA Evidence Synthesis Program (ESP) was established in 2007 to conduct timely, rigorous, and independent systematic reviews to support VA clinicians, program leadership, and policymakers improve the health of Veterans. ESP reviews have been used to develop evidence-informed clinical policies, practice guidelines, and performance measures; to guide implementation of programs and services that improve Veterans' health and wellbeing; and to set the direction of research to close important evidence gaps. Four ESP Centers are located across the US. Centers are led by recognized experts in evidence synthesis, often with roles as practicing VA clinicians. The Coordinating Center, located in Portland, Oregon, manages program operations, ensures methodological consistency and quality of products, engages with stakeholders, and addresses urgent evidence synthesis needs.

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Operational Partners

Operational partners are system-level stakeholders who help ensure relevance of the review topic to the VA, contribute to the development of and approve final project scope and timeframe for completion, provide feedback on the draft report, and provide consultation on strategies for dissemination of the report to the field and relevant groups.

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Disclosures

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The findings and conclusions in this document are those of the author(s) who are responsible for its contents and do not necessarily represent the views of the Department of Veterans Affairs or the United States government. Therefore, no statement in this article should be construed as an official position of the Department of Veterans Affairs. The final research questions, methodology, and/or conclusions may not necessarily represent the views of contributing operational and content experts. No investigators have affiliations or financial involvement (*eg*, employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties) that conflict with material presented in the report.

Executive Summary

KEY FINDINGS

- Pulse oximeters likely overestimate Black patients' blood oxygen saturation level (*moderate strength of evidence*), though recent studies in contemporary hospital and health system settings suggest that modern pulse oximeters possess some degree of bias and considerable imprecision regardless of patient race/ethnicity.
- Occult hypoxemia is likely more common among Black patients compared with White patients (*moderate strength of evidence*). Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients may also experience occult hypoxemia more frequently than White patients (*low strength of evidence*).
- Evidence is insufficient to draw conclusions about clinical outcomes attributable to race/ethnicity biases in occult hypoxemia, but available studies provide suggestive evidence that Black patients with undetected hypoxemia could experience poorer treatment delivery and clinical outcomes than White patients with undetected hypoxemia.
- Clinicians should be aware of the risk for occult hypoxemia in patients with darker skin pigmentation. Evidence from hospital and health system settings relevant to the VA also suggests that the amount of bias in pulse oximeter readings could vary substantially from patient to patient regardless of their race/ethnicity.

Pulse oximeters are used in many clinical settings and provide a rapid and noninvasive means of measuring oxygen saturation. Despite this utility, pulse oximeters may over- or underestimate a patient's arterial oxygen saturation (SaO_2). Overestimating oxygen saturation is especially concerning when pulse oximeter readings of peripheral oxygen saturation (SpO_2) indicate a normal blood oxygen level while a patient is actually in a hypoxemic state—a situation known as *occult hypoxemia*. Potential clinical impacts of occult or undetected hypoxemia include delayed or inadequate treatment, premature treatment de-escalation or discharge, and ultimately, greater morbidity and mortality.

Inaccurate pulse oximeter readings can occur for a variety of reasons, including severe anemia, excessive blood carbon monoxide levels, impaired circulation (hypoperfusion), and patient movement. Because pulse oximeters rely on the transmission of light through the skin to estimate SaO_2, skin pigmentation level may also influence pulse oximeter accuracy. Differences in pulse oximeter accuracy by patient race/ethnicity have been observed in clinical settings for several decades, but the COVID-19 pandemic has heightened concern that pulse oximeters may routinely be less accurate in patients with darker skin pigmentation.

The COVID-19 pandemic has also drawn attention to whether racial or ethnic minority patients are at greater risk of occult hypoxemia due to pulse oximeter inaccuracy. A widely discussed retrospective study published in late 2020 analyzed nearly 50,000 paired SpO_2–SaO_2 measurements, finding that the prevalence of occult hypoxemia was over 3 times greater among Black or African American ("Black") patients compared with White patients (11.4% versus 3.4%). Additional studies reporting occult hypoxemia prevalence by patient race or ethnicity have since been published. Most utilize large health system databases and also report data on pulse oximeter accuracy, which goes some way to addressing the sparsity of accuracy data in racial and ethnic minority patients in the pre-COVID-19 literature.

The aim of the present review was to provide an up-to-date synthesis of evidence on racial and ethnic disparities in the accuracy of pulse oximeters, the prevalence of occult hypoxemia, and clinical outcomes associated with occult hypoxemia. This review was developed in response to a request from the Veterans Health Administration (VHA) National Hospital Medicine Program and Office of Specialty Care Services.

CURRENT REVIEW

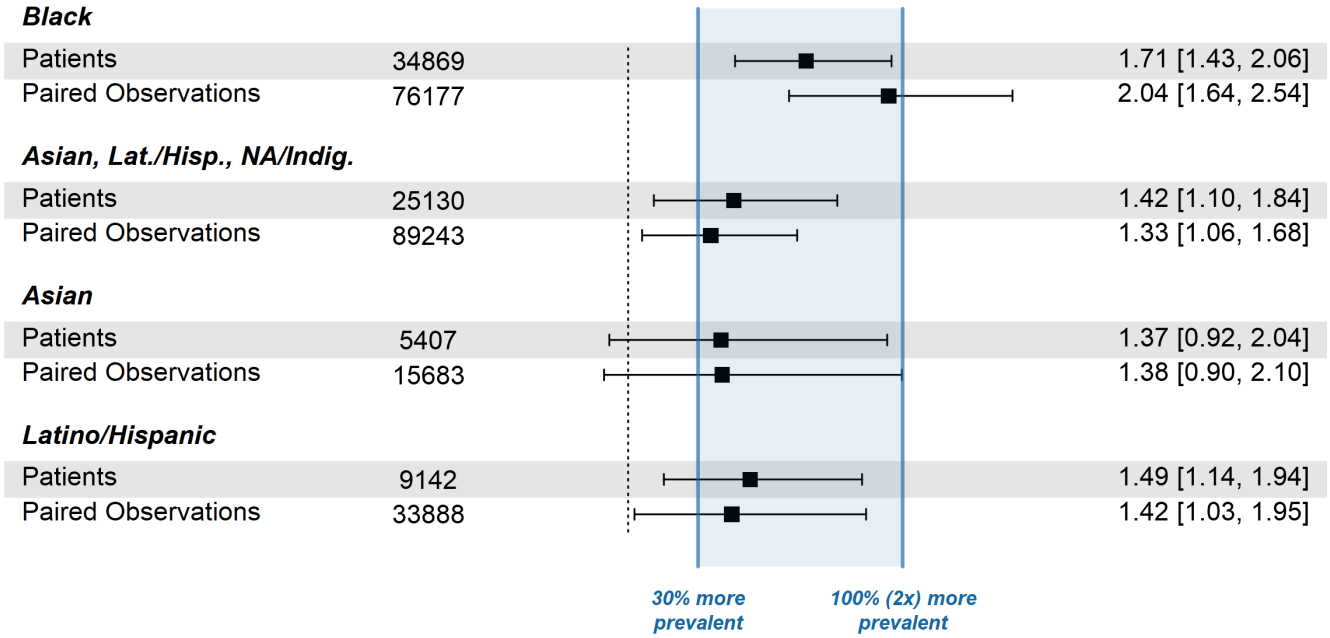
Thirty-four primary studies and 1 existing systematic review and meta-analysis on pulse oximeter accuracy met eligibility criteria. Eighteen studies were included in the identified systematic review, which together provided 21,269 paired oximetry observations from 3,176 patients. We located 4 recent observational studies that reported pulse oximeter accuracy data in sufficient detail for meta-analyses; together these studies contribute 241,680 new paired observations in 102,841 patients. We also identified 11 observational studies that reported occult hypoxemia prevalence and 4 studies that examined the association between occult hypoxemia and clinical outcomes by patient race/ethnicity. Most newly identified studies used data from patients receiving acute care in academic or community hospitals or health systems.

In Black patients, pulse oximeters appear to overestimate blood oxygen saturation by an average of 1.5% compared with CO-oximetry in arterial blood (pooled mean bias = 1.54, 95% CI [0.99, 2.10]), based on 37,562 paired observations in 14,626 patients. Mean bias among Black patients was considerably larger than among White patients (0.62, 95% CI [-0.08, 1.32]; N_{Obs} = 154,286) or patients identifying as Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity (0.31, 95% CI [0.09, 0.54]; N_{Obs} = 71,101). Precision of pulse oximeter readings was comparable across race/ethnicity groups, with pooled standard deviations (SDs) from 1.61 to 1.98.

In recent studies that contribute most available oximetry data, mean bias was larger in all race/ethnicity groups compared with earlier evidence. The most substantial increase from older studies was among Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (from 0.31% to 1.41%). Precision estimates were comparable across groups but considerably larger than in earlier studies (pooled SDs from 4.30 to 5.23), indicating greater variability in bias between patients. The calculated accuracy root mean square error (A_{RMS}) for all accuracy data was 1.64 for Black patients, 0.78 for White patients, and 0.75 for Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients. A_{RMS} values in newly identified studies were 2.57, 1.83, and 2.03, respectively.

The pooled prevalence of occult hypoxemia was highest among Black patients (11.4%, 95% CI [4.6, 25.5]; N = 34,869) and Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (9.7%, 95% CI [3.2, 26.1]; N = 25,130), compared with White patients (6.5%, 95% CI [2.8, 14.2]; N = 109,286). Corresponding prevalence ratios (PRs) are shown in the figure below. Compared with White patients, the prevalence of occult hypoxemia was 71% greater among Black patients (pooled PR = 1.71, 95% CI [1.43, 2.06]) and 42% greater among Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (pooled PR = 1.42, 95% CI [1.10, 1.84]). For Black patients, an even larger disparity was apparent at the observation level (pooled PR = 2.04, 95% CI [1.64, 2.54]; N_{Obs} = 76,177). Similarly, in several studies that reported odds of occult hypoxemia adjusted for potential confounders, Black patients had twice the odds of occult hypoxemia compared with White patients (95% CI [1.15, 3.41]; N = 8,410).

Occult Hypoxemia Prevalence Ratios by Patient Race/Ethnicity



Notes. All prevalence ratios use White patients as the reference group, and the dashed line corresponds to a prevalence ratio of 1.0 (no difference in prevalence compared with White patients). *N* indicates the number of patients in the race/ethnicity group shown and does not include the number of White patients comprising the reference group. Patients reported as *Other race/ethnicity* are included in the group *Asian, Lat./Hisp., NA/Indig* (Asian, Latino or Hispanic, Native American or Indigenous).

One recent study used approximately 30,000 paired SpO_2–SaO_2 observations from patients treated in VHA surgical and general (non-intensive) care settings, and may provide the most applicable evidence to the VHA setting. The study found larger bias and worse precision in Black VHA patients compared with White patients, and reported occult hypoxemia prevalences that were among the highest of any included study: 19.6% for Black patients, 16.2% for Hispanic or Latino patients, and 15.6% for White patients. The difference in likelihood of occult hypoxemia between Black and White patients remained after controlling for patient sex, age, and comorbidities ($p < .001$). Black patients also had a higher likelihood of occult hypoxemia at a second oximetry reading than White patients, even when patients in both groups did not show occult hypoxemia on their first oximetry reading taken the same day (*ie*, Black patients' probability of hypoxemia was more varied among readings than that of White patients).

Finally, we found few studies examining the association between occult hypoxemia (or differential pulse oximeter accuracy) and clinical outcomes by patient race/ethnicity, and evidence was insufficient to make firm conclusions about this relationship. Nonetheless, there does appear to be some signal that Black patients with undetected hypoxemia could experience poorer treatment delivery and clinical outcomes compared with White patients with undetected hypoxemia.

Re-assessing oxygen saturation in arterial blood more routinely, particularly in patients that show signs or symptoms of arterial hypoxemia, has been suggested as one step to reduce the risk of occult hypoxemia and subsequent harms. Another approach suggested to mitigate this risk is to raise the

oxygen saturation range to 94–98%, though this may increase risk of hyperoxemia. Applying a skin-tone-based correction factor to readings from currently available pulse oximeters has also been discussed, but such adjustments have a controversial history and may have limited efficacy because the accuracy and reliability of pulse oximetry readings is influenced by a number of factors that cannot be accounted for in a single correction factor. A broader recommendation has been to revise guidelines for pulse oximeter validation studies, in particular to require enrolling more patients with darker skin pigmentation, testing oximeters under real-world health care conditions, and incorporating perfusion into validation requirements. At the same time, it has been acknowledged that addressing biases in pulse oximeter readings and in the care that follows from those readings requires fundamental advancements in the technologies used for routine, noninvasive oxygen saturation monitoring.

CONCLUSIONS

Pulse oximeters likely overestimate Black patients' blood oxygen saturation level, increasing the risk for unrecognized or occult hypoxemia. Occult hypoxemia occurs to some degree in all races/ethnicities but is likely more common among Black patients compared with White patients. Findings of this review underscore that clinicians should be aware of the risk of occult hypoxemia in patients with darker skin pigmentation. Moreover, while pulse oximeter readings are on average fairly similar to arterial oxygen saturation levels, evidence from hospital and health system settings relevant to the VA suggests that the amount of bias could vary substantially from patient to patient regardless of their race/ethnicity. This finding implies that incorporating conventional race or ethnicity-based correction factors into pulse oximeters would not eliminate disparities in occult hypoxemia risk. Although proposed changes to clinical practice to accommodate bias and imprecision in pulse oximeters may help to mitigate harms in the near-term, advancements in noninvasive oximeter technology are needed. As the largest integrated health system in the United States, the VHA is uniquely positioned to cultivate innovations in oximeter technology.

Main Report

Evidence Synthesis Program

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ABBREVIATIONS TABLE

aHR	Adjusted hazard ratio
aOR	Adjusted odds ratio
A_{RMS}	Accuracy root mean square error
CI	Confidence interval
FDA	US Food and Drug Administration
IQR	Interquartile range
k	Number of studies
PI	Prediction interval
PR	Prevalence ratio
N	Number of patients
N_{Obs}	Number of paired observations
SaO_2	Arterial oxygen saturation
SD	Standard deviation
SpO_2	Peripheral oxygen saturation measured by pulse oximetry
VHA	Veterans Health Administration

BACKGROUND

Pulse oximeters are used in many clinical settings and provide a rapid and noninvasive means of measuring oxygen saturation. Despite this utility, pulse oximeters may over- or underestimate a patient's arterial oxygen saturation (SaO_2). Overestimating oxygen saturation is especially concerning when pulse oximeter readings of peripheral oxygen saturation (SpO_2) indicate a normal blood oxygen level while a patient is actually in a hypoxemic state—a situation known as *occult hypoxemia*. Potential clinical impacts of occult or undetected hypoxemia include delayed or inadequate treatment, premature treatment de-escalation or discharge, and ultimately, greater morbidity and mortality.[1,2]

Inaccurate pulse oximeter readings can occur for a variety of reasons, including severe anemia, excessive blood carbon monoxide levels, impaired circulation (hypoperfusion), and patient movement.[3,4] Because pulse oximeters rely on the transmission of light through the skin to estimate SaO_2, skin pigmentation level may also influence pulse oximeter accuracy. Differences in pulse oximeter accuracy by patient race/ethnicity have been observed in clinical settings for several decades, but the COVID-19 pandemic has heightened concern that pulse oximeters may routinely be less accurate in patients with darker skin pigmentation. In the United States, the Food and Drug Administration (FDA) regulates pulse oximeter accuracy and recommends that pulse oximeter performance be within 3% of CO-oximetry in arterial blood (as assessed with accuracy root mean square error, or A_{RMS}).[5] A recent synthesis of pulse oximeter accuracy studies published prior to mid-2021 by Shi et al[6] reported a somewhat larger pulse oximeter A_{RMS} among Black or African American ("Black") patients compared with White patients (2.3% versus 1.6%).

The COVID-19 pandemic has also drawn attention to whether racial or ethnic minority patients are at greater risk of occult hypoxemia due to pulse oximeter inaccuracy. A widely discussed retrospective study[7] published in late 2020 analyzed nearly 50,000 paired SpO_2–SaO_2 measurements, finding that the prevalence of occult hypoxemia was over 3 times greater among Black patients compared with White patients (11.4% versus 3.4%). In late 2022, the FDA convened a public meeting of its Anesthesiology and Respiratory Therapy Devices Panel in response to ongoing concerns about racial biases in pulse oximeter accuracy and unrecognized hypoxemia. Guidance on the use and interpretation of pulse oximeters was subsequently updated and emphasizes that pulse oximeter readings are *estimates* of oxygen saturation that provide "more utility for trends over time instead of absolute thresholds" at the individual patient level.[8]

A number of studies of racial or ethnic disparities in occult hypoxemia prevalence have been recently published. Most utilize large health system databases and also report data on pulse oximeter accuracy, which goes some way to addressing the sparsity of accuracy data in racial and ethnic minority patients in the pre-COVID-19 literature reviewed by Shi et al. The aim of the present review was to provide an up-to-date synthesis of evidence on racial and ethnic disparities in the accuracy of pulse oximeters, the prevalence of occult hypoxemia, and clinical outcomes associated with occult hypoxemia. This review was developed in response to a request from the Veterans Health Administration (VHA) National Hospital Medicine Program and Office of Specialty Care Services.

METHODS

REGISTRATION AND REVIEW

A preregistered protocol for this review can be found on the PROSPERO register of systematic reviews (CRD42023402152). A draft version of this report was reviewed by external peer reviewers; their comments and author responses are located in the Appendix.

KEY QUESTIONS AND ELIGIBILITY CRITERIA

The following key questions were the focus of this review:

Key Question 1	Does pulse oximeter accuracy differ by patient race/ethnicity?
Key Question 2	Does the prevalence or risk of occult hypoxemia differ by patient race/ethnicity?
Key Question 2b	If present, are racial/ethnic disparities in occult hypoxemia associated with differences in treatment delivery or harms?

Eligible studies must have been conducted among adults in inpatient or outpatient healthcare settings. Accuracy studies were required to report paired SpO_2–SaO_2 readings measured within 10 minutes of one another. Studies reporting occult hypoxemia prevalence were required to define occult hypoxemia as, at minimum, arterial oxygen saturation ≤ 88% despite a pulse oximeter reading > 88%. Stricter criteria (*eg*, pulse oximeter reading > 92%) were permitted. Studies that induced hypoxemia in a controlled setting were ineligible. We considered evidence on clinical outcomes (treatment delivery or harms) of occult hypoxemia only when studies reported within-group comparisons by occult hypoxemia status. For example, we included studies that examined whether there was a relationship between occult hypoxemia and in-hospital mortality by comparing patients of the same race or ethnicity with and without occult hypoxemia (then examined whether this relationship differed across race/ethnicity groups), but we did not include studies that investigated whether in-hospital mortality differed by patient race or ethnicity in general.

SEARCHING AND SCREENING

A research librarian searched Ovid MEDLINE, CINAHL, Scopus, the Cochrane Database of Systematic Reviews, and AHRQ and HSR&D databases for relevant studies published through February 2023 (see Appendix for complete search strategies). Additional citations were identified by hand-searching reference lists. English-language titles, abstracts, and full-text articles were independently reviewed by 2 investigators, and disagreements were resolved by consensus.

DATA ABSTRACTION AND RISK OF BIAS ASSESSMENT

Participant characteristics, study methodological details, and outcome data were abstracted from all included studies. The internal validity (risk of bias) of included studies was rated using tools appropriate to each study type: the ROBIS[9] tool for systematic reviews, the QUADAS-2[10] tool for studies providing accuracy data, and the QUIPS[11] tool for studies of occult hypoxemia prevalence or occult hypoxemia as a risk factor for downstream clinical outcomes. Potential biases in prevalence estimates were captured in the *prognostic factor measurement* domain of the QUIPS tool; we supplemented criteria for this domain with biases specific to prevalence assessment.[12] Risk of bias rating and data abstraction were first completed by 1 investigator then checked by another, and disagreements were resolved by consensus. See Appendix for complete risk of bias ratings.

SYNTHESIS

When 3 or more sufficiently comparable studies were available, study findings were pooled using random-effects meta-analysis. We identified a well-conducted systematic review and meta-analysis of pulse oximeter accuracy by Shi et al,[6] which synthesized accuracy data available through mid-2021. To expedite the present review, we took the approach of updating this review with the most recent evidence available. This involved pooling mean bias and precision data from studies published since the end search date of the review (replicating the methods used by Shi et al), then synthesizing the pooled estimates from new evidence with those reported in the existing review. Each of these steps is described in detail below. To harmonize risk of bias ratings, we also re-assessed risk of bias of studies included in the existing systematic review using the approach described above.

For newly identified studies, we first adjusted reported standard deviations (SDs) for each race/ethnicity group in each study using the formula shown below.[13] The purpose of this adjustment, which was also implemented by Shi et al, was to produce more conservative estimates of precision that account for repeated observations of the same patient. The number of paired oximetry measurements per patient was calculated by dividing the total number of oximetry measurements by the number of patients (*eg*, in a group of 50 patients in which 500 paired measurements were collected, the approximate number of measurements per patient would be 500/50 = 10 measurements).

$$Adjusted\ SD = \sqrt{Reported\ SD^2 \times \left(\frac{Total\ Measurements - 1}{Total\ Measurements - Measurements\ per\ Patient}\right)}$$

We also replicated the use of hierarchical random-effects models, cluster-robust confidence intervals, and degrees of freedom calculated using the Satterwaithe approximation. These approaches better account for dependency among estimates; that is, when estimates from the same study are more similar than they would be if they were from a different study and patient sample. The final stage of analysis of mean bias and precision data was to synthesize pooled estimates reported by Shi et al with those from new studies. We implemented the recommendation of Tang et al[14] for updating a meta-analysis with new results based on comparable methods, which was to use a fixed-effect model to synthesize the final pooled estimates (*ie*, a pooled estimate corresponding to all evidence prior to September 2021 from Shi et al, and a pooled estimate of evidence from September 2021 through February 2023).

To synthesize occult hypoxemia prevalence estimates, we used meta-analytic generalized random-effects logistic models or hierarchical approximations when dependent prevalence estimates were available. Prevalence estimates were transformed using the standard logit transformation for analysis, and back-transformed for interpretation and reporting. To facilitate comparison of occult hypoxemia prevalences between race/ethnicity groups, we also calculated and synthesized prevalence ratios (PRs). Conventional random-effects models were used to pool PRs[i] as well as adjusted odds ratios (aORs) of occult hypoxemia by race/ethnicity group. Models incorporated the Knapp-Hartung adjustment to

[i] We chose standard random-effects models over more complex options (*eg*, log-binomial models) for prevalence ratios because: 1) overall, occult hypoxemia was fairly rare, and therefore logarithms of prevalence ratios and odds ratios would be expected to have similar analytic properties; 2) no studies reported zero occult hypoxemia events, meaning we were not required to use continuity corrections to carry out standard random-effects modeling (analysis in "one step" using log-binomial or similar models would be preferable in such a scenario); and 3) the standard approach was more compatible with methods to account for dependency in reported estimates.

better account for uncertainty in heterogeneity estimation,[15,16] and when necessary, we used methods for handling dependent data comparable to those described above.

For all analyses, heterogeneity was estimated using (restricted) maximum-likelihood estimation and is presented as 95% prediction intervals (PIs). Prediction intervals describe the likeliest range of true effects (*eg*, true occult hypoxemia prevalence) across studies and provide an estimate of the magnitude and direction of effects that would be found in future studies similar to those included in a synthesis.[17] All meta-analyses were conducted using the *metafor*[18] package for R (R Foundation for Statistical Computing, Vienna, Austria). When fewer than 3 comparable studies were available for a given outcome—or studies were judged to be too disparate in methodological or participant characteristics—we described evidence narratively.

For the purposes of synthesizing and reporting findings, the consensus reached among investigators was that the following categorizations best balanced data availability with variation in race/ethnicity groups reported across studies: Patients described as Black or African American ("Black"), patients described as White or Caucasian ("White"), and patients described as Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity. Where possible, we disaggregated findings for the latter group by specific race or ethnicity identities. Studies also varied in whether prevalence of occult hypoxemia was reported by patients or by paired observations. We synthesized each type of prevalence estimate separately. Finally, for consistency with existing literature on pulse oximeter accuracy, we also report A_{RMS} values calculated from pooled mean bias and precision results. It is important to note, however, that interpretation of A_{RMS} is not straightforward: A value between 2–3%, for example, equates to roughly 66% of SpO_2 readings being within 2–3% of corresponding SaO_2 readings and 95% being within 4–6% of SaO_2 readings.[8]

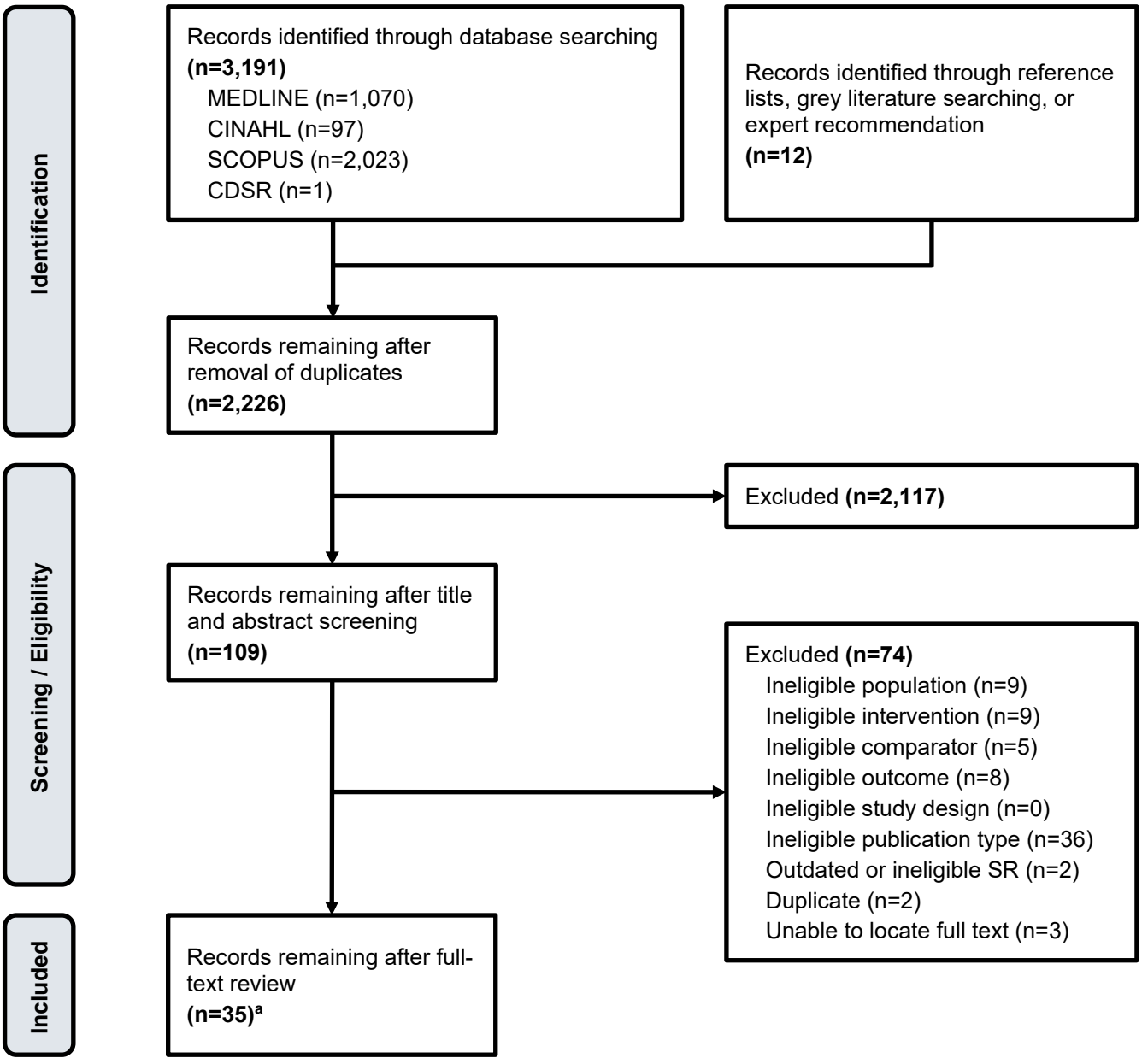
Strength of Evidence

After synthesizing available evidence, we rated the strength of evidence for each outcome based on the methodology and risk of bias of available studies, the consistency and certainty of findings, and the directness of outcomes (whether reported outcomes are relevant to patients and providers). We used the following general algorithm: *high strength* evidence consisted of multiple, large studies with consistent and precise findings at low risk of bias, and clinically relevant outcomes; *moderate strength* evidence consisted of multiple studies with consistent and precise findings at low to moderate risk of bias, and clinically relevant outcomes; *low strength* evidence consisted of a single study, or multiple small studies, with moderate to high risk of bias, inconsistent or imprecise findings, and/or outcomes with limited clinical relevance; and *insufficient* evidence consisted of a single study with moderate or high risk of bias, or no available studies. Conclusions using *likely* (*eg*, "Pulse oximeters likely overestimate Black patients' blood oxygen saturation level") are based on moderate strength evidence, while those using *may* are based on low strength evidence.

RESULTS

LITERATURE FLOW DIAGRAM

The literature flow diagram summarizes the results of the study selection process. A full list of excluded studies is provided in the Appendix.



Notes. [a]34 primary studies and 1 systematic review.

Abbreviations. CDSR=Cochrane Database of Systematic Reviews; CINAHL=Cumulative Index to Nursing and Allied Health Literature; SR=systematic review.

OVERVIEW OF INCLUDED STUDIES

Our search identified 109 potentially relevant articles after deduplication and title and abstract screening. Of these, 34 primary studies and 1 existing systematic review and meta-analysis[6] on pulse oximeter accuracy met eligibility criteria. Eighteen studies[19-36] were included in the identified systematic review, which together provided 21,269 paired observations from 3,176 patients. These studies were published between 1985 and 2021 and varied considerably in setting and patient characteristics (details of all included studies are provided in the Appendix). We found 2 additional accuracy studies published in the 1980s[37,38] but did not include these in formal syntheses because they used pulse oximeters that are no longer commercially available.

We located 4 recent observational studies[3,4,39,40] that reported pulse oximeter accuracy data in sufficient detail for meta-analyses; together these studies contribute 241,680 new paired observations in 102,841 patients. Four other accuracy studies[36,41-43] did not provide adequate outcome data or information about race/ethnicity groups to be included in formal syntheses. The 4 studies contributing accuracy data noted above also reported occult hypoxemia prevalence; in total, we included 11 observational studies[1-4,7,35,39,40,44-46] that reported occult hypoxemia prevalence and 4 studies[1,2,39,46] that examined the association between occult hypoxemia and clinical outcomes by patient race/ethnicity. Most newly identified studies used data from patients receiving acute care in academic or community hospitals or health systems. One study was limited to patients undergoing anesthesia[4] and 2 studies included surgical inpatients.[2,40] Patient race/ethnicity was generally self-reported.

MAIN FINDINGS

Pulse Oximeter Accuracy

Pooled mean bias and precision findings by race/ethnicity groups are shown in the Table below. In Black patients, pulse oximeters appear to overestimate blood oxygen saturation by an average of 1.5% compared with CO-oximetry in arterial blood (pooled mean bias = 1.54, 95% CI [0.99, 2.10]), based on 37,562 paired observations in 14,626 patients. Mean bias among Black patients was considerably larger than among White patients (0.62, 95% CI [-0.08, 1.32]; N_{Obs} = 154,286) or patients identifying as Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity (0.31, 95% CI [0.09, 0.54]; N_{Obs} = 71,101). Precision of pulse oximeter readings was comparable across race/ethnicity groups, with pooled SDs ranging from 1.61 to 1.98.[ii] In recent studies that contribute most available oximetry data, mean bias was larger in all race/ethnicity groups compared with earlier evidence. The most substantial increase from older studies was among Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (from 0.31% to 1.41%). Precision estimates were comparable across groups but considerably larger than in earlier studies (pooled SDs from 4.30 to 5.23), indicating greater variability in bias between patients.

The calculated A_{RMS} for all accuracy data was 1.64 for Black patients, 0.78 for White patients, and 0.75 for Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients. A_{RMS} values in newly identified studies were much larger: 2.57, 1.83, and 2.03, respectively.

[ii] Shi et al also pooled studies that reported accuracy by patient pigmentation level (high pigmentation, medium pigmentation, or low pigmentation). Pooled mean bias was largest among patients with high pigmentation (1.11, 95% CI [0.29, 1.93]). Pooled SDs were similar across pigmentation levels and comparable to findings in race/ethnicity groups (1.47 to 1.52).

Table. Pulse Oximeter Accuracy, Occult Hypoxemia Prevalence, and Clinical Outcomes by Patient Race/Ethnicity

Patients Described as Black or African American				
Accuracy	**Patients**	**Paired Obs.**	**Mean Bias [95% CI]**	**Precision [95% CI]**
Shi 2022 Review (*k* = 9)	459	5,753	1.52 [0.95, 2.09]	1.68 [1.32, 2.14]
Recent Studies (*k* = 4)	14,167	31,809	1.96 [-0.57, 4.50]	5.23 [1.50, 18.28]
Updated Estimate (*k* = 13)	14,626	37,562	1.54 [0.99, 2.10]	1.75 [1.38, 2.22]
Occult Hypoxemia Prevalence			**% [95% CI]**	**[95% PI]**
Patients (*k* = 5)	34,869		11.4 [4.6, 25.5]	[1.2, 58.1]
Paired Observations (*k* = 11)		76,177	6.9 [3.9, 11.9]	[0.9, 36.9]
Clinical Outcomes				
Eligibility Recognition (*k* = 1)	928		aHR: 0.71 [0.63, 0.80] (ref: White)	
Treatment Delay (*k* = 1)	681		Median (IQR): 7.0 h (1.9–20.8)	
Length of Stay (*k* = 1)	26,032		Difference: -3.0 d (*p* = .00)	
In-hospital Mortality (*k* = 1)	26,032		Difference: +5.9% (*p* < .001)	
Patients Described as Asian, Latino or Hispanic, Native American or Indigenous, or Other				
Accuracy	**Patients**	**Paired Obs.**	**Mean Bias [95% CI]**	**Precision [95% CI]**
Shi 2022 Review (*k* = 3)	522	2,646	0.31 [0.09, 0.53]	1.55 [0.53, 4.53]
Recent Studies (*k* = 3)	23,001	68,455	1.41 [-2.65, 5.47]	4.30 [0.63, 29.17]
Updated Estimate (*k* = 6)	23,523	71,101	0.31 [0.09, 0.54]	1.98 [0.78, 5.04]
Occult Hypoxemia Prevalence			**% [95% CI]**	**[95% PI]**
Patients (*k* = 5)	25,130		9.7 [3.2, 26.1]	[0.6, 66.6]
Paired Observations (*k* = 6)		89,243	5.3 [2.0, 13.0]	[0.4, 42.8]
Clinical Outcomes				
Eligibility Recognition (*k* = 1)	Asian: 25; Hispanic: 445		aHR: 0.97 [0.62, 1.50]; 0.77 [0.66, 0.89] (ref: White)	
Treatment Delay (*k* = 1)	Asian: 21; Hispanic: 323		Median (IQR): 7.7 h (3.5–13.6); 5.0 h (1.2–15.8)	
Length of Stay (*k* = 1)	Asian: 1,919; Hispanic: 2,397		Difference: +0.5 d (*p* = .02); +0.8 d (*p* < .01)	
In-hospital Mortality (*k* = 1)	Asian: 1,919; Hispanic: 2,397		Difference: +5.6% (*p* = .13); +4.6% (*p* = .06)	
Patients Described as White or Caucasian				
Accuracy	**Patients**	**Paired Obs.**	**Mean Bias [95% CI]**	**Precision [95% CI]**
Shi 2022 Review (*k* = 13)	2,195	12,870	0.55 [-0.21, 1.31]	1.55 [1.32, 1.83]
Recent Studies (*k* = 4)	65,673	141,416	1.01 [-0.78, 2.79]	4.63 [1.89, 11.37]
Updated Estimate (*k* = 17)	67,868	154,286	0.62 [-0.08, 1.32]	1.61 [1.37, 1.89]
Occult Hypoxemia Prevalence			**% [95% CI]**	**[95% PI]**
Patients (*k* = 5)	109,286		6.5 [2.8, 14.2]	[0.8, 36.8]
Paired Observations (*k* = 11)		337,976	3.3 [1.8, 5.9]	[0.4, 22.0]
Clinical Outcomes				
Treatment Delay (*k* = 1)	427		Median (IQR): 5.3 h (1.4–15.2)	
Length of Stay (*k* = 1)	57,623		Difference: -0.5 d (*p* < .01)	
In-hospital Mortality (*k* = 1)	57,623		Difference: +11.1% (*p* < .001)	

Abbreviations. aHR=adjusted hazard ratio; CI=confidence interval; d=day; h=hour; IQR=interquartile range; k=number of studies; PI=prediction interval.

Although available studies of pulse oximeter accuracy generally use observational designs, we judged newly identified studies to be at moderate or low overall risk of biased findings. The most common concerns were unclear detail about the pulse oximeter or CO-oximeter devices used, lack of reporting on blinding (*ie*, whether pulse oximeter results were read without knowledge of SaO_2), and limitations arising from use of health record data, including unclear detail about patient characteristics. Shi et al found that excluding studies with high risk of bias did not substantively alter conclusions. No newly identified studies included in syntheses were rated at high risk of bias.

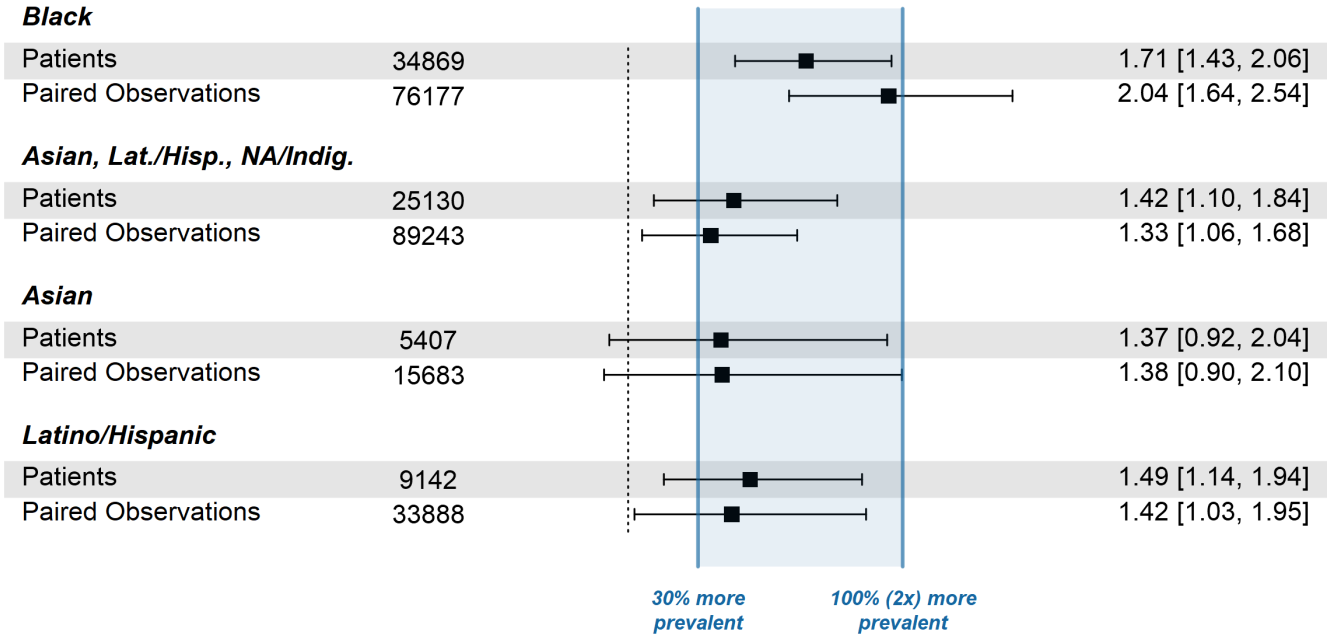
Evidence on differential pulse oximeter accuracy by patient race/ethnicity from studies published prior to mid-2021 was rated as low or very low strength (certainty) by Shi et al. Despite pooled mean bias and SD values being larger in recent studies, the substantial increase in available data and consistent magnitude of findings led us to increase the strength of evidence supporting the finding that pulse oximeters overestimate SaO_2 in Black patients to moderate. Although there were comparable increases in the amount of data available for other race/ethnicity groups, there was also much greater variability in paired readings. Given this, we did not upgrade the strength of evidence supporting the conclusion that pulse oximeters *do not* overestimate SaO_2 to a clinically important degree among Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (from low certainty). The same conclusion was upgraded to low strength or certainty (from very low certainty) for White patients because of the substantial increase in the number of observations contributing to pooled estimates.

Occult Hypoxemia Prevalence

Occult hypoxemia prevalence by race/ethnicity groups is shown in the Table above. The pooled prevalence of occult hypoxemia was highest among Black patients (11.4%, 95% CI [4.6, 25.5]; N = 34,869) and Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (9.7%, 95% CI [3.2, 26.1]; N = 25,130), compared with White patients (6.5%, 95% CI [2.8, 14.2]; N = 109,286). Corresponding prevalence ratios (PRs) are shown in the Figure below. Compared with White patients, the prevalence of occult hypoxemia was 71% greater among Black patients (pooled PR = 1.71, 95% CI [1.43, 2.06]) and 42% greater among Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients (pooled PR = 1.42, 95% CI [1.10, 1.84]). For Black patients, an even larger disparity was apparent at the observation level (pooled PR = 2.04, 95% CI [1.64, 2.54]).

Four studies[2,4,35,44] reported odds of occult hypoxemia adjusted for potential confounders (in most cases, patient demographics, comorbidities, and therapeutic variables such as use of vasopressors). When results were pooled, Black patients had twice the odds of experiencing occult hypoxemia compared with White patients (aOR = 1.99, 95% CI [1.15, 3.41]; N = 8,410). Reported odds ratios from all studies were similar in magnitude and consistent in direction. Three[2,4,44] of the 4 studies also included Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients, whose odds of hypoxemia were not significantly greater than those of White participants (aOR = 1.36, 95% CI [0.82, 2.25]; N = 20,536). Most odds ratios in this population were consistent in direction but differed in magnitude. Prevalence ratios and odds ratios followed similar patterns in each group.

Figure. Occult Hypoxemia Prevalence Ratios by Patient Race/Ethnicity



Notes. All prevalence ratios use White patients as the reference group, and the dashed line corresponds to a prevalence ratio of 1.0 (no difference in prevalence compared with White patients). *N* indicates the number of patients in the race/ethnicity group shown and does not include the number of White patients comprising the reference group. Patients reported as *Other race/ethnicity* are included in the group *Asian, Lat./Hisp., NA/Indig* (Asian, Latino or Hispanic, Native American or Indigenous).

Most studies providing data on occult hypoxemia prevalence were rated at moderate risk of biased findings for the same reasons as accuracy studies (given the use of accuracy data to define the occult hypoxemia outcome). One study[35] reporting odds of occult hypoxemia adjusted only for patient sex and measured SpO_2, compared with the other available studies which controlled for a more comprehensive set of potential confounders. Considering both prevalence and associational findings together, occult hypoxemia is likely more common among Black patients than among White patients (moderate strength of evidence). Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients may also experience occult hypoxemia more frequently than White patients, but the inconsistency of findings across studies and sparse data for some subgroups led us to rate evidence supporting this conclusion as low strength.

One recent study[40] used approximately 30,000 paired SpO_2–SaO_2 observations from patients treated in VHA surgical and general (non-intensive) care settings between 2013 and 2019. The study found larger bias and worse precision in Black VHA patients compared with White patients, and reported prevalences of occult hypoxemia (defined as SaO_2 less than 88% despite SpO_2 of 92% or greater) that were among the highest of any included study: 19.6% for Black patients, 16.2% for Hispanic or Latino patients, and 15.6% for White patients. The difference in likelihood of occult hypoxemia between Black patients and White patients remained after controlling for patient sex, age, and comorbidities ($p < .001$). Investigators also analyzed whether SpO_2 and SaO_2 values were consistent across pairs of patient measurements taken the same day. Black patients had a higher likelihood of occult hypoxemia

at a second oximetry reading than White patients, even when patients in both groups did not show occult hypoxemia on their first oximetry reading taken the same day (*ie*, Black patients' probability of occult hypoxemia was more variable among measurement instances than that of White patients). Data used in the study were drawn from the Corporate Data Warehouse, and in our appraisal, reasonable efforts were made to generate a dataset representative of the general VHA patient population and to limit selection biases that could reduce the generalizability of study findings.

Clinical Outcomes

We found few studies that examined the association between occult hypoxemia (or differential pulse oximeter accuracy) and clinical outcomes by patient race/ethnicity, and evidence was considered insufficient to make firm conclusions about this relationship. Nonetheless, there does appear to be some signal that Black patients with undetected hypoxemia could experience poorer treatment delivery and clinical outcomes than White patients with undetected hypoxemia.

One multicenter study[46] in 215 US hospitals and 315 intensive care units reported length of stay and in-hospital mortality by whether patients experienced occult or "hidden" hypoxemia (defined as SaO_2 less than 88% despite SpO_2 of 88% or greater in observations separated by no longer than 10 minutes). For Black patients ($N = 26{,}032$), occult hypoxemia was associated with significantly shorter length of stay compared with Black patients without occult hypoxemia (-3.0 days, $p < .01$). Length of stay for White patients ($N = 57{,}623$) with occult hypoxemia was also significantly shorter than White patients without occult hypoxemia, but by only 0.5 days on average ($p < .01$). Length of stay was significantly longer for Asian ($N = 1{,}919$) and Hispanic ($N = 2{,}397$) patients with occult hypoxemia, but by less than 1 day on average compared with patients without occult hypoxemia. In-hospital mortality was more common in patients experiencing occult hypoxemia regardless of race or ethnicity, with the largest difference among White patients (11.1% greater than White patients without occult hypoxemia, $p < .001$). Length of stay comparisons were unadjusted, while mortality comparisons were adjusted for patient age, sex, and Sequential Organ Failure Assessment (SOFA) score.

A second study,[2] which used health record data from 26,603 patients in intensive care or undergoing surgery at 3 US academic medical centers, reported that occult hypoxemia was associated with fewer hospital-free days and greater in-hospital mortality after adjusting for patient age, sex, comorbidities, setting (intensive care unit or surgery), and acuity. Neither outcome significantly differed by patient race or ethnicity, though Black, Asian, or American Indian patients together made up a relatively small proportion of the patient sample (2,110 versus 24,493 White patients). Only simultaneously collected SpO_2–SaO_2 readings were used in the study, and occult hypoxemia was defined as SaO_2 less than 88% despite SpO_2 of 92% or greater.

A smaller study[1] in patients evaluated in the emergency department or hospitalized for COVID-19 in the Johns Hopkins Health System ($N = 1{,}903$) examined whether patients predicted to have an SaO_2 of 94% or less prior to a measured SpO_2 of 94% or less (*ie*, an unrecognized hypoxemic state) experienced delayed recognition of treatment eligibility or delayed treatment initiation. Failure to recognize eligibility or delayed recognition of eligibility was significantly more likely among both Black patients (adjusted hazard ratio [aHR] = 0.71, 95% CI [0.63, 0.80]) and Hispanic or Latino patients (aHR = 0.77, 95% CI [0.66, 0.89]) with unrecognized hypoxemia compared with White patients with unrecognized hypoxemia. Analyses were adjusted for patient demographics, comorbidities, acuity, and laboratory values (*eg*, hemoglobin). In the subset of patients eventually recognized as treatment eligible, the median delay to eligibility recognition was about 2 hours longer

for Black patients and Asian patients compared with Hispanic or Latino and White patients (see Table above; $p = .01$ for Black patients versus White patients).

A final observational study[39] used a causal inference methodology to assess whether differential bias in pulse oximeter measurements led to poorer COVID-19 treatment and health services outcomes for Black patients in a large California integrated health system. Compared with White patients, overestimation of SaO_2 among Black patients (N = 1,699) was associated with a significantly lower likelihood of hospital admission (-3.1%, 95% CI [-3.4, -2.8]), initiation of treatment with dexamethasone (-3.1%, 95% CI [-3.4, -2.7]), delivery of supplemental oxygen (-4.5%, 95% CI [-4.9, -4.2]), and post-discharge return to the hospital (-1.2%, 95% CI [-1.9, -0.5]). Overestimation of SaO_2 was predicted to result in a 37-minute delay in dexamethasone initiation (95% CI [20.1, 54.3]) and a 279-minute delay in supplemental oxygen initiation (95% CI [181.0, 376.0]). Results were adjusted for patient age, sex, common comorbidities, and homelessness and insured statuses.

DISCUSSION

Based on a large body of evidence, pulse oximeters likely overestimate Black patients' blood oxygen saturation level. Most available oximetry data is from recent studies conducted in contemporary hospital and health system settings and using modern pulse oximeters. In these studies, pulse oximeters also appear to have the largest bias and greatest imprecision among Black patients, though some degree of bias and considerable imprecision is evident regardless of patient race/ethnicity. Occult hypoxemia is likely more common among Black patients compared with White patients. Asian, Latino or Hispanic, Native American or Indigenous, or other or mixed race/ethnicity patients may also experience occult hypoxemia more frequently than White patients, but evidence in these groups is less certain. Studies examining differences in clinical outcomes associated with occult hypoxemia or biases in pulse oximeter accuracy are methodologically inconsistent but provide suggestive evidence that Black patients with undetected hypoxemia could experience poorer treatment delivery and clinical outcomes than White patients with undetected hypoxemia.

Re-assessing oxygen saturation in arterial blood more routinely—particularly for patients who show signs or symptoms of arterial hypoxemia—has been proposed as one step to reduce the risk of occult hypoxemia and subsequent harms arising from biases in pulse oximeter readings.[40] Another approach suggested to mitigate this risk is to raise the oxygen saturation range from 92–96% to 94–98%, though this may increase risk of hyperoxemia.[44] Applying a skin-tone-based correction factor to readings from currently available pulse oximeters has also been discussed,[47] but such adjustments have a controversial history[48-50] and may have limited efficacy because the accuracy and reliability of pulse oximetry readings is influenced by a number of factors that cannot be accounted for in a single correction factor.[47,49] A broader recommendation has been to revise guidelines for pulse oximeter validation studies, in particular to require enrolling more patients with darker skin pigmentation, testing oximeters under real-world health care conditions, and incorporating perfusion into validation requirements.[44,51]

As noted earlier, the systematic review by Shi et al[6] identified some studies that reported pulse oximeter accuracy by skin pigmentation level rather than race or ethnicity. We focused on the latter because most available accuracy data is from recent studies that report their results by race/ethnicity (likely due to the use of patient health record data). A concern with the use of race/ethnicity in accuracy studies is that it may introduce spurious variation across studies and lead to unexpected or clinically counterintuitive findings, given that individuals with a wide range of skin pigmentation levels may identify with the same race/ethnicity.

For instance, groups made up of patients identified as Black through health record data may, in one hypothetical study, be composed of individuals who on average have lighter skin pigmentation compared with a Black patient group in a different study. Variation in sample composition could be caused by many factors, including geographic or other contextual differences between the studies, or may simply be due to chance. In the former study, pulse oximeter bias in the Black patient group may be smaller and closer to levels observed among White patients, while in the latter study, bias in the Black patient group may be more substantial. Underlying differences in sample composition by skin pigmentation level, therefore, resulted in inconsistent evidence about the same race/ethnicity group. Moreover, findings from any single study (*eg*, the first study, in which bias was similar across groups) could be inappropriately generalized because they do not account for the composition of patient groups relative to skin pigmentation level. Given these considerations, use of objective skin pigmentation

metrics when determining the accuracy of pulse oximeters has been proposed.[51] Extending this recommendation to prospective research on disparities in occult hypoxemia is likely warranted.

Finally, it has been acknowledged that addressing biases in pulse oximeter readings and in the care that follows from those readings requires fundamental advancements in the technologies used for routine oxygen saturation monitoring. Fawzy et al[1] state:

> "Although increased awareness of the limitations of pulse oximetry may mitigate some of the adverse effects…the race and ethnicity-based discrepancy of pulse oximetry exposes a fundamental flaw in the acquisition rather than interpretation of data, although all the aforementioned biases are associated with systematic underdiagnosis of disease or withholding of therapies for racial and ethnic minority groups."

Improving pulse oximeter technology is an active research area. A small validation study[52] published earlier this year, for example, tested an investigational noninvasive oximeter that uses green rather than the conventional red light, is designed to target superficial skin layers to increase sensitivity to tissue hypoxia, and implements patient-specific skin tone calibration (rather than a pre-programmed correction factor). The study enrolled equal proportions of patients with fair skin, brown skin, and dark skin. Oxygen saturation readings from the novel oximeter were more highly correlated with blood-based oximetry ($r = 0.76$) than pulse oximeter readings ($r = 0.47$), and the novel oximeter was also able to accurately assess oxygen levels in cases in which the pulse oximeter failed, including a patient with very high skin pigmentation.

Limitations

Incorporating an existing review of pulse oximeter accuracy meant that we could not exclude studies with limited relevance to modern clinical practice among Veterans (*ie*, studies that used older pulse oximeter technologies or pediatric samples). Observations from these studies make up a small proportion of available accuracy data, so it is unlikely this limitation impacts the validity of the review's findings. We also used sequential data abstraction and risk of bias assessment rather than a fully independent (blinded) process.

CONCLUSIONS

Pulse oximeters likely overestimate Black patients' blood oxygen saturation level, increasing the risk for unrecognized or occult hypoxemia. Occult hypoxemia occurs to some degree in all races/ethnicities but is likely more common among Black patients compared with White patients. Findings of this review underscore that clinicians should be aware of the risk of occult hypoxemia in patients with darker skin pigmentation. Moreover, while pulse oximeter readings are on average fairly similar to arterial oxygen saturation levels, evidence from hospital and health system settings relevant to the VA suggests that the amount of bias could vary substantially from patient to patient regardless of their race/ethnicity. This finding implies that incorporating conventional race or ethnicity-based correction factors into pulse oximeters would not eliminate disparities in occult hypoxemia risk. Although proposed changes to clinical practice to accommodate bias and imprecision in pulse oximeters may help to mitigate harms in the near-term, advancements in noninvasive oximeter technology are needed. As the largest integrated health system in the United States, the VHA is uniquely positioned to cultivate innovations in oximeter technology.

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51. Okunlola OE, Lipnick MS, Batchelder PB, Bernstein M, Feiner JR, Bickler PE. Pulse oximeter performance, racial inequity, and the work ahead. *Respiratory Care*. 2022;67(2):252-257. doi:https://dx.doi.org/10.4187/respcare.09795
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Appendix

SEARCH STRATEGIES

SYSTEMATIC REVIEWS

Search Date: 2/23/2023		Search Statement	Results
MEDLINE **Origination to 2/23/2023**	1	exp Oximetry/ or exp Photoplethysmography/ or (oximet* or PPG or photoplethysmography or ((saturation adj1 (oxygen or oxyhemoglobin or oxyhaemoglobin)) or (blood adj1 (gas or oxygen or arterial)) or PtcO2 or TcPCO2 or SpO2 or %SpO2 or Sp O2)).ti,ab,kf.	126417
	2	Skin Pigmentation/ or exp Ethnicity/ or Minority Groups/ or (((cutaneous or skin) adj3 (color* or colour* or pigment* or tone* or type)) or race or racial or ethnic* or ((minorit* or biracial or multiracial or african* or afro-american* or asian* or asiatic or black* or caucasian* or hispanic* or indian* or indigenous or latin* or native* or nonwhite* or (pacific adj3 islander*) or white) adj2 (patient* or participant* or adult*)) or ((persons or people) adj3 (color or colour))).ti,ab,kf.	433474
	3	((over?estimat* or under?estimat* or detect* or classify* or rule in or rule out or identif*) adj3 (hypox* or occult)).ti,ab,kf.	7296
	4	(accura* or inaccura* or agreement or precision or evaluat* or reliab* or bias or concordance or performance or validat* or error* or fail* or discrepanc* or disparit* or vary or varied or varies or variab* or sensitivity or specificity or over?estimat* or under?estimat* or detect* or classify* or rule in or rule out or identif*).ti,ab,kf.	13177197
	5	exp Pediatrics/ or (pediatric* or paediatric* or neonat* or infant* or hyperbaric or wearable).ti,ab,kw.	1150414
	6	2 or 3	1150414
	7	1 AND 4 AND 6	1362
	8	7 not 5	1119
	9	(systematic review.ti. or meta-analysis.pt. or meta-analysis.ti. or systematic literature review.ti. or this systematic review.tw. or pooling project.tw. or (systematic review.ti,ab. and review.pt.) or meta synthesis.ti. or meta-analy*.ti. or integrative review.tw. or integrative research review.tw. or rapid review.tw. or umbrella review.tw. or consensus development conference.pt. or practice guideline.pt. or drug class reviews.ti. or ("cochrane database of systematic reviews" or acp journal club or health technology assessment winchester england or evidence report technology assessment summary or "jbi database of systematic reviews and implementation reports").jn. or (clinical guideline and management).tw. or ((evidence based.ti. or evidence-based medicine/ or best practice*.ti. or evidence synthesis.ti,ab.) and (((review.pt. or diseases category/ or behavior.mp.) and behavior mechanisms/) or therapeutics/ or evaluation studies.pt. or validation studies.pt. or guideline.pt. or pmcbook.mp.)) or (((systematic or systematically).tw. or critical.ti,ab. or study selection.tw. or ((predetermined or inclusion) and criteri*).tw. or exclusion criteri*.tw. or main outcome measures.tw. or standard of care.tw. or standards of care.tw.) and ((survey or	572025

Search Date: 2/23/2023		Search Statement	Results
		surveys).ti,ab. or overview*.tw. or review.ti,ab. or reviews.ti,ab. or search*.tw. or handsearch.tw. or analysis.ti. or critique.ti,ab. or appraisal.tw. or (reduction.tw. and (risk/ or risk.tw.) and (death or recurrence).mp.)) and ((literature or articles or publications or publication or bibliography or bibliographies or published).ti,ab. or pooled data.tw. or unpublished.tw. or citation.tw. or citations.tw. or database.ti,ab. or internet.ti,ab. or textbooks.ti,ab. or references.tw. or scales.tw. or papers.tw. or datasets.tw. or trials.ti,ab. or meta-analy*.tw. or (clinical and studies).ti,ab. or treatment outcome/ or treatment outcome.tw. or pmcbook.mp.))) not (letter or newspaper article).pt.	
	10	8 and 9	42
	11	limit 9 to english language	41
	12	limit 10 to last 7 years	26
Cochrane Database of Systematic Reviews **2005 to February 22, 2023**	1	MeSH descriptor: [Oximetry] explode all trees	1169
	2	MeSH descriptor: [Photoplethysmography] this term only	107
	3	(oximet* or PPG or photoplethysmography or ((saturation adj1 (oxygen or oxyhemoglobin or oxyhaemoglobin)) or (blood adj1 (gas or oxygen or arterial)) or PtcO2 or TcPCO2 or SpO2 or %SpO2 or Sp O2)):ti,ab,kw	12798
	4	{OR #1-#3}	12956
	5	MeSH descriptor: [Skin Pigmentation] this term only	374
	6	MeSH descriptor: [Ethnicity] explode all trees	2978
	7	MeSH descriptor: [Minority Groups] this term only	513
	8	(((cutaneous or skin) NEAR/3 (color* or colour* or pigment* or tone* or type)) or race or racial or ethnic* or ((minorit* or biracial or multiracial or african* or afro-american* or asian* or asiatic or black* or caucasian* or hispanic* or indian* or indigenous or latin* or native* or nonwhite* or (pacific adj3 islander*) or white) NEAR/2 (patient* or participant* or adult*)) or ((persons or people) NEAR/3 (color or colour))):ti,ab,kw	34578
	9	{OR #5-#7}	3640
	10	((over?estimat* or under?estimat* or detect* or classify* or rule in or rule out or identif*) NEAR/3 (hypox* or occult)):ti,ab,kw	4076
	11	(accura* or inaccura* or agreement or precision or evaluat* or reliab* or bias or concordance or performance or validat* or error* or fail* or discrepanc* or disparit* or vary or varied or varies or variab* or sensitivity or specificity or over?estimat* or under?estimat* or detect* or classify* or rule in or rule out or identif*):ti,ab,kw	994866
	12	MeSH descriptor: [Pediatrics] explode all trees	918
	13	(pediatric* or paediatric* or neonat* or infant* or hyperbaric or wearable):ti,ab,kw	118779
	14	#12 OR #13	118792
	15	#9 OR #10	7713
	16	#4 AND #11 AND #15	378
	17	#16 NOT #14	309

Search Date: 2/23/2023		Search Statement	Results
	18	limit to last 7 years	1
		Total	1
		Total after deduplication	1

PRIMARY STUDIES

Search Date: 2/23/2023		Search Statement	Results
MEDLINE **Origination to 2/23/2023**	1	exp Oximetry/ or exp Photoplethysmography/ or (oximet* or PPG or photoplethysmography or ((saturation adj1 (oxygen or oxyhemoglobin or oxyhaemoglobin)) or (blood adj1 (gas or oxygen or arterial)) or PtcO2 or TcPCO2 or SpO2 or %SpO2 or Sp O2)).ti,ab,kf.	126556
	2	exp Skin Pigmentation/ or exp Ethnicity/ or exp Minority Groups/ or (((cutaneous or skin) adj3 (color* or colour* or pigment* or tone* or type)) or race or racial or ethnic* or ((minorit* or biracial or multiracial or african* or afro-american* or asian* or asiatic or black* or caucasian* or hispanic* or indian* or indigenous or latin* or native* or nonwhite* or (pacific adj3 islander*) or white) adj2 (patient* or participant* or adult*)) or ((persons or people) adj3 (color or colour))).ti,ab,kf.	434193
	3	((over?estimat* or under?estimat* or detect* or classify* or rule in or rule out or identif*) adj3 (hypox* or occult)).ti,ab,kf.	7300
	4	(accura* or inaccura* or agreement or precision or evaluat* or reliab* or bias or concordance or performance or validat* or error* or fail* or discrepanc* or disparit* or vary or varied or varies or variab* or sensitivity or specificity or over?estimat* or under?estimat* or detect* or classify* or rule in or rule out or identif*).ti,ab,kf.	13196427
	5	exp Pediatrics/ or (pediatric* or paediatric* or neonat* or infant* or hyperbaric or wearable).ti,ab,kw.	1151790
	6	2 OR 3	441424
	7	1 AND 4 AND 6	1364
	8	7 NOT 5	1120
	9	limit 8 to English language	1070
CINAHL **Origination to 2/23/2023**	1	((MH "Oximetry+") OR (MH "Oximeters+")) OR TI (oximet* OR photoplethysmography OR PPG OR ((saturation adj1 (oxygen OR oxyhemoglobin OR oxy haemoglobin)) OR (blood adj1 (gas OR oxygen OR arterial)) OR PtcO2 OR TcPCO2 OR SpO2 OR %SpO2 OR Sp O2) OR AB (oximet* OR photoplethysmography OR PPG OR ((saturation adj1 (oxygen OR oxyhemoglobin OR oxy haemoglobin)) OR (blood adj1 (gas OR oxygen OR arterial)) OR PtcO2 OR TcPCO2 OR SpO2 OR %SpO2 OR Sp O2)	10,601
	2	((MH "Skin Pigmentation") OR (MH "Ethnic Groups+") OR (MH "Minority Groups")) OR TI (((cutaneous OR skin) adj3 (color* OR colour* OR pigment* OR tone* OR type*)) OR ethnic* OR race OR racial OR ((minorit* or biracial or multiracial or african* or afro-american* or asian* or asiatic or black* or caucasian* or hispanic* or indian* or indigenous or latin* or native* or	249,307

Search Date: 2/23/2023		Search Statement	Results
		nonwhite* or (pacific adj3 islander*) or white) adj2 (patient* or participant* or adult*)) OR ((people OR persons) adj3 (color OR colour))) OR AB (((cutaneous OR skin) adj3 (color* OR colour* OR pigment* OR tone* OR type*)) OR ethnic* OR race OR racial OR ((minorit* or biracial or multiracial or african* or afro-american* or asian* or asiatic or black* or caucasian* or hispanic* or indian* or indigenous or latin* or native* or nonwhite* or (pacific adj3 islander*) or white) adj2 (patient* or participant* or adult*)) OR ((people OR persons) adj3 (color OR colour)))	
	3	((overestimat* or over-estimat* OR underestimat* OR under-estimat* OR detect* or classify* or rule in or rule out or identif*)) adj3 (hypox* or occult))	0
	4	TI ((accura* or inaccura* or agreement or precision or evaluat* or reliab* or bias or concordance or performance or validat* or error* or fail* or discrepanc* or disparit* or vary or varied or varies or variab* or sensitivity or specificity or overestimat* or over-estimat* or underestimat* or under-estimat* or detect* or classify* or rule in or rule out or identif*)) OR AB ((accura* or inaccura* or agreement or precision or evaluat* or reliab* or bias or concordance or performance or validat* or error* or fail* or discrepanc* or disparit* or vary or varied or varies or variab* or sensitivity or specificity or overestimat* or over-estimat* or underestimat* or under-estimat* or detect* or classify* or rule in or rule out or identif*))	2487269
	5	(MH "Pediatrics+") OR TI ((pediatric* or paediatric* or neonat* or infant* or hyperbaric or wearable)) OR AB ((pediatric* or paediatric* or neonat* or infant* or hyperbaric or wearable))	349837
	6	S2 OR S3	249307
	7	S1 AND S4 AND S6	121
	8	S7 NOT S5	97
	9	limit 8 to English language	97
Scopus **Origination to 2/23/2023**	1	TITLE-ABS-KEY (oximet* OR ppg OR photoplethysmography OR (saturation W/1 (oxygen OR oxyhemoglobin OR oxyhaemoglobin)) OR (blood W/1 (gas OR oxygen OR arterial)) OR ptco2 OR tcpco2 OR spo2 OR %spo2 OR "sp o2")	249433
	2	TITLE-ABS-KEY (((cutaneous OR skin) W/3 (color* OR colour* OR pigment* OR tone* OR type)) OR race OR racial OR ethnic* OR ((minorit* OR biracial OR multiracial OR african* OR afro-american* OR asian* OR asiatic OR black* OR caucasian* OR hispanic* OR indian* OR indigenous OR latin* OR native* OR nonwhite* OR (pacific W/3 islander*) OR white) W/2 (patient* OR participant* OR adult*)) OR ((persons OR people) W/3 (color OR colour)))	874035
	3	TITLE-ABS-KEY ((over?estimat* OR under?estimat* OR detect* OR classify* OR "rule in" OR "rule out" OR identif*) W/3 (hypox* OR occult))	10188
	4	TITLE-ABS-KEY (accura* OR inaccura* OR agreement OR precision OR evaluat* OR reliab* OR bias OR concordance OR performance OR validat* OR error* OR fail* OR discrepanc*	36072897

Search Date: 2/23/2023		Search Statement	Results
		OR disparit* OR vary OR varied OR varies OR variab* OR sensitivity OR specificity OR over?estimat* OR under?estimat* OR detect* OR classify* OR "rule in" OR "rule out" OR identif*)	
	5	TITLE-ABS-KEY (pediatric* OR paediatric* OR neonat* OR infant* OR hyperbaric OR wearable)	2260722
	6	2 OR 3	884101
	7	1 AND 4 AND 6	2691
	8	7 NOT 5	2162
	9	limit 8 to English language	2023
		Total	3190
		Total after deduplication	2226

STUDIES EXCLUDED DURING FULL-TEXT SCREENING

Citation	Exclude Reason
Occult Hypoxemia Is More Common in Black Patients than in White Patients About to Undergo ECMO for Respiratory Failure. *Critical Care Alert.* 2022;30(3):1-3.	Ineligible publication type
Impact of Skin Color on Spo2 Detection of Hypoxemia. In. Vol 43. Alisa Veijo, California: American Association of Critical-Care Nurses; 2023:80-80.	Ineligible publication type
Adams A, Cho HJ. Ensuring Progress Toward Racial Equity in Pulse Oximetry. *JAMA Internal Medicine.* 2022;182(12):1329.	Ineligible publication type
Anonymous. Racial Bias in Pulse Oximetry Measurement. *The New England journal of medicine.* 2021;385(26):2496.	Ineligible publication type
Arefin MS, Dumont AP, Patil CA. Monte Carlo based Simulations of Racial bias in Pulse Oximetry. Paper presented at: Progress in Biomedical Optics and Imaging - Proceedings of SPIE2022.	Ineligible publication type
Baek HJ, Shin J, Cho J. The Effect of Optical Crosstalk on Accuracy of Reflectance-Type Pulse Oximeter for Mobile Healthcare. *Journal of healthcare engineering.* 2018;2018:3521738.	Ineligible comparator
Balmaceda J, D Gerber E, J Arnold M, A Williams D, Snyder K, M Pandya S. RACIAL BIAS IN PULSE OXIMETRY IN ACUTE HYPOXEMIC RESPIRATORY FAILURE. *CHEST.* 2022;162(4):A1168-A1168.	Ineligible publication type
Barker SJ, Wilson WC. Racial effects on Masimo pulse oximetry: a laboratory study. *Journal of clinical monitoring and computing.* 2022.	Ineligible population
Bickler P, Tremper KK. The pulse oximeter is amazing, but not perfect. *Anesthesiology.* 2022;136(5):670-671.	Ineligible publication type
Bota GW, Rowe BH. Continuous monitoring of oxygen saturation in prehospital patients with severe illness: The problem of unrecognized hypoxemia. *Journal of Emergency Medicine.* 1995;13(3):305-311.	Ineligible intervention
Brownscombe JJ, Loane H, Honan B. COVID-19 highlights the need for action on pulse oximeter accuracy in people with dark skin. *Medical Journal of Australia.* 2022;216(10):539.	Ineligible publication type
Bunch D. Pulse Oximeters May Overestimate Blood Oxygen Levels in Ethnic Groups. *AARC Newsroom.* 2022:8-8.	Unable to locate full text
Burnett GW, Stannard B, Wax DB, et al. Self-reported Race/Ethnicity and Occult Hypoxemia: Reply. *Anesthesiology.* 2022;137(3):371-372.	Ineligible publication type
Cabanas AM, Fuentes-Guajardo M, Latorre K, Leon D, Martin-Escudero P. Skin Pigmentation Influence on Pulse Oximetry Accuracy: A Systematic Review and Bibliometric Analysis. *Sensors (Basel, Switzerland).* 2022;22(9).	Outdated or ineligible systematic review
Cahan C, Decker MJ, Hoekje PL, et al. Agreement between noninvasive oximetric values for oxygen saturation. *CHEST.* 1990;97(4):814-819.	Ineligible outcome
Crooks C, West J, Card T, Shaw D, Simmonds M, Fogarty A. Reply to: Inaccuracy of pulse oximetry in darker-skinned patients is unchanged across 32 years. *The European respiratory journal.* 2022;59(6).	Ineligible publication type
Crooks CJ, West J, Morling JR, et al. Pulse oximeter measurement error of oxygen saturation in patients with SARS-CoV-2 infection stratified by smoking status. *European Respiratory Journal.* 2022;60(5).	Ineligible outcome
Dabbous A, Bijjani A, Nader T, Dahdah S, Tarraf S, Baraka A. Incidence of postoperative hypoxemia as detected by pulse oximetry. *Middle East journal of anaesthesiology.* 1992;11(4):321-329.	Unable to locate full text

Citation	Exclude Reason
Ebmeier SJ, Barker M, Bacon M, et al. A Two Centre Observational Study of Simultaneous Pulse Oximetry and Arterial Oxygen Saturation Recordings in Intensive Care Unit Patients. *Anaesthesia and Intensive Care.* 2018;46(3):297-303.	Duplicate
Emery JR. Skin pigmentation as an influence on the accuracy of pulse oximetry. *Journal of Perinatology.* 1987;7(4):329-330.	Ineligible population
Feiner JR, Severinghaus JW, Bickler PE. Dark skin decreases the accuracy of pulse oximeters at low oxygen saturation: the effects of oximeter probe type and gender. *Anesthesia and analgesia.* 2007;105(6 Suppl):S18-S23.	Ineligible population
Ferrari M, Quaresima V. Racial discrepancies in oximetry: where do we stand? The gold standard choice. *Anaesthesia.* 2022;77(4):492-492.	Ineligible publication type
Ferrari M, Quaresima V, Scholkmann F. Pulse oximetry, racial bias and statistical bias: further improvements of pulse oximetry are necessary. *Annals of intensive care.* 2022;12(1):19.	Ineligible publication type
Gokhale SG, Daggubati V, Alexandrakis G. Innovative technology to eliminate the racial bias in non-invasive, point-of-care (POC) haemoglobin and pulse oximetry measurements. *BMJ Innovations.* 2022.	Ineligible intervention
Gottlieb ER, Ziegler J, Rush B. Ensuring Progress Toward Racial Equity in Pulse Oximetry-Reply. *JAMA Internal Medicine.* 2022;182(12):1329-1330.	Ineligible publication type
Gottlieb ER, Ziegler J, Morley K, Rush B, Celi LA. Assessment of Racial and Ethnic Differences in Oxygen Supplementation Among Patients in the Intensive Care Unit. *JAMA Internal Medicine.* 2022;182(8):849-858.	Ineligible outcome
Gadrey SM, Mohanty P, Haughey SP, et al. Overt and Occult Hypoxemia in Patients Hospitalized With COVID-19. *Critical care explorations.* 2023;5(1):e0825.	Ineligible intervention
Harlan EA, Colon Hidalgo D, Valley TS. Addressing racial bias in pulse oximetry. *Chest Physician.* 2022;17(8):18-18.	Ineligible publication type
Hassan EA, Mohamed SN, Hamouda EH, Ahmed NT. Clinical evaluation for the pharyngeal oxygen saturation measurements in shocked patients. *BMC Nursing.* 2022;21(1).	Ineligible comparator
Hess D. Detection and monitoring of hypoxemia and oxygen therapy. Paper presented at: Respiratory Care2000.	Unable to locate full text
Hobensack M, Phan NM. Racial Bias in Pulse Oximetry: Sjoding M, Dickson R, Iwashyna T, et al. N Engl J Med. 2020;383(25):2477-2478. doi:10.1056/NEJMc2029240. *Journal of Emergency Medicine (0736-4679).* 2021;60(2):262-263.	Duplicate
Holder AL, Wong A-KI. The Big Consequences of Small Discrepancies: Why Racial Differences in Pulse Oximetry Errors Matter. *Critical Care Medicine.* 2022;50(2):335-337.	Ineligible publication type
Hunasikatti M. Racial bias in accuracy of pulse oximetry and its impact on assessments of hypopnea and T90 in clinical studies. *Journal of clinical sleep medicine : JCSM : official publication of the American Academy of Sleep Medicine.* 2021;17(5):1145.	Ineligible publication type
Jacobs JW, Abels E. The potential for unnecessary medical interventions due to inaccurate pulse oximetry measurements. *Heart & lung : the journal of critical care.* 2022.	Ineligible publication type
Jouffroy R, Jost D, Prunet B. Prehospital pulse oximetry: a red flag for early detection of silent hypoxemia in COVID-19 patients. *Critical care (London, England).* 2020;24(1):313.	Ineligible outcome

Citation	Exclude Reason
Keating L, Christian C, Strykowski RK, Lee C, Strek ME, Adegunsoye A. PULSE OXIMETRY INACCURATELY REFLECTS SEVERITY OF LUNG FUNCTION IMPAIRMENT ACROSS RACIAL AND DIAGNOSTIC SUBGROUPS OF INTERSTITIAL LUNG DISEASE. *CHEST.* 2022;162(4):A2618-A2619.	Ineligible publication type
Keller MD, Harrison-Smith B, Patil C, Arefin MS. Skin colour affects the accuracy of medical oxygen sensors. *Nature.* 2022;610(7932):449-451.	Ineligible publication type
Knight MJ, Subbe CP, Inada-Kim M. Racial discrepancies in oximetry: where do we stand? *Anaesthesia.* 2022;77(2):129-131.	Ineligible publication type
Lahri S. Early detection of hypoxia in covid-19. *Pan African Medical Journal.* 2020;35:1-2.	Ineligible publication type
Lee WW, Mayberry K, Crapo R, Jensen RL. The accuracy of pulse oximetry in the emergency department. *The American journal of emergency medicine.* 2000;18(4):427-431.	Ineligible outcome
Lipchak D, Chupov A. Sensorex: The Challenges for Engineering Implementation of Low-Cost Non-Invasive Pulse Oximeter Applicable to Diverse Patient Population. Paper presented at: International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices, EDM2021.	Ineligible publication type
Longcoy J, Patwari R, Hasler S, et al. Racial and Ethnic Differences in Hospital Admissions of Emergency Department COVID-19 Patients. *Medical Care.* 2022;60(6):415-422.	Ineligible intervention
Louw A, Cracco C, Cerf C, et al. Accuracy of pulse oximetry in the intensive care unit. *Intensive Care Medicine.* 2001;27(10):1606-1613.	Ineligible outcome
Melton JD, Heller MB, Kaplan R, Mohan-Klein K. Occult hypoxemia during aeromedical transport: Detection by pulse oximetry. *Prehospital and Disaster Medicine.* 1989;4(2):115-120.	Ineligible intervention
Mendelson Y, Kent JC, Shahnarian A, Welch GW, Giasi RM. Evaluation of the Datascope ACCUSAT pulse oximeter in healthy adults. *Journal of clinical monitoring.* 1988;4(1):59-63.	Ineligible outcome
Nematswerani N, Collie S, Chen T, et al. The impact of routine pulse oximetry use on outcomes in COVID-19-infected patients at increased risk of severe disease: A retrospective cohort analysis. *South African Medical Journal.* 2021;111(10):950-956.	Ineligible intervention
Noninvasive blood gas monitoring: a review for use in the adult critical care unit. Technology Subcommittee of the Working Group on Critical Care, Ontario Ministry of Health. *CMAJ : Canadian Medical Association journal = journal de l'Association medicale canadienne.* 1992;146(5):703-712.	Outdated or ineligible systematic review
Norton HL. Variation in pulse oximetry readings: melanin, not ethnicity, is the appropriate variable to use when investigating bias. *Anaesthesia.* 2022;77(3):354-355.	Ineligible intervention
Ochoa-Gutierrez V, Guerrero-Zuniga S, Reboud J, Pazmino-Betancourth M, Harvey AR, Cooper JM. Changes in Oxygenation Levels During Moderate Altitude Simulation (Hypoxia-Induced): A Pilot Study Investigating the Impact of Skin Pigmentation in Pulse Oximetry. *Advances in experimental medicine and biology.* 2022;1395:391-396.	Ineligible population
Palmer SJ. Racial bias in pulse oximetry: a significant problem in healthcare. *British Journal of Healthcare Assistants.* 2022;16(9):430-433.	Ineligible publication type

Citation	Exclude Reason
Philip KEJ, Tidswell R, McFadyen C. Racial bias in pulse oximetry: more statistical detail may help tackle the problem. *BMJ (Clinical research ed).* 2021;372:n298.	Ineligible publication type
Pierson DJ. Pulse oximetry versus arterial blood gas specimens in long-term oxygen therapy. *Lung.* 1990;168 Suppl:782-788.	Ineligible publication type
Ploen L, Pilcher J, Beckert L, Swanney M, Beasley R. An investigation into the bias of pulse oximeters. Paper presented at: Respirology2016.	Ineligible publication type
Ralston AC, Webb RK, Runciman WB. Potential errors in pulse oximetry. III: Effects of interferences, dyes, dyshaemoglobins and other pigments. *Anaesthesia.* 1991;46(4):291-295.	Ineligible publication type
Ralston AC, Webb RK, Runciman WB. Potential errors in pulse oximetry III: Effects of interference, dyes, dyshaemoglobins and other pigments. *Anaesthesia.* 1991;46(4):291-295.	Ineligible publication type
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Sjoding M, Iwashyna TJ, Valley TS. More on Racial Bias in Pulse Oximetry Measurement. Reply. *The New England journal of medicine.* 2021;384(13):1278.	Ineligible publication type
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Smyth RJ, D'Urzo AD, Slutsky AS, Galko BM, Rebuck AS. Ear oximetry during combined hypoxia and exercise. *Journal of Applied Physiology.* 1985;60(2):716-719.	Ineligible population
Stannard B, Levin MA, Lin H-M, Weiner MM. Regional cerebral oximetry is consistent across self-reported racial groups and predicts 30-day mortality in cardiac surgery: a retrospective analysis. *Journal of clinical monitoring and computing.* 2021;35(2):413-421.	Ineligible intervention
Stewart KG, Rowbottom SJ. Inaccuracy of pulse oximetry in patients with severe tricuspid regurgitation. *Anaesthesia.* 1991;46(8):668-670.	Ineligible comparator
Thrush D, Hodges MR. Accuracy of pulse oximetry during hypoxemia. *South Med J.* 1994;87(4):518-521.	Ineligible population
Tobin MJ, Jubran A. Pulse oximetry, racial bias and statistical bias. *Annals of intensive care.* 2022;12(1):2.	Ineligible publication type
Tobin MJ, Jubran A. Inaccuracy of pulse oximetry in darker-skinned patients is unchanged across 32 years. *The European respiratory journal.* 2022;59(6).	Ineligible publication type
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Citation	Exclude Reason
Todd B. Pulse Oximetry May Be Inaccurate in Patients with Darker Skin. *American Journal of Nursing.* 2021;121(4):16.	Ineligible publication type
Valbuena VSM, Merchant RM, Hough CL. Racial and Ethnic Bias in Pulse Oximetry and Clinical Outcomes. *JAMA Internal Medicine.* 2022;182(7):699-700.	Ineligible publication type
Van de Louw A, Cracco C, Cerf C, et al. Accuracy of pulse oximetry in the intensive care unit. *Intensive care medicine.* 2001;27(10):1606-1613.	Ineligible outcome
Ward E, Katz MH. Confronting the Clinical Implications of Racial and Ethnic Discrepancy in Pulse Oximetry. *JAMA Internal Medicine.* 2022;182(8):858-858.	Ineligible publication type
Zeballos RJ, Weisman IM. Reliability of noninvasive oximetry in black subjects during exercise and hypoxia. *The American review of respiratory disease.* 1991;144(6):1240-1244.	Ineligible population

RISK OF BIAS ASSESSMENTS

OBSERVATIONAL STUDIES (QUADAS)

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
Abrams 2022	Unclear Does not describe how participants were enrolled in the study.	High Used race (Black patients examined separately) as a proxy for pigmentation and method of determination was not reported.	Low Index test was conducted prior to interpretation of results from reference test.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low ABG reading was obtained 1 minute after PO reading. All patients received the same reference standard. All patients were included in analysis.	Moderate
Adler 1998	Low All adult patients requiring ABG measurement in the ER were eligible for enrollment. Included consecutive patients with vital signs and complete data on oxygen saturation measurements.	Low Used the Munsell color system and categorized patients into 3 groups.	Low Index test was conducted prior to interpretation of results from reference test.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low PO measurement was taken at the time of ABG sampling, and ABG samples were taken immediately to the lab.	Low
Bangash 2022	Low Retrospective study that included patients for whom paired measurements and ethnicity were recorded.	High Used self-reported race (Black, Asian, White, Other) as a proxy for pigmentation.	Unclear Unclear whether the index test was conducted prior to the results of the reference test being automatically entered into the HER.	Low Reference test results were automatically entered into the EHR upon analysis.	Low Included paired measurements occurring within a 20 minute time period.	Moderate
Blanchet 2023	Low Appears that all patients meeting criteria during the study period were eligible and exclusions were appropriate.	Unclear Used the Fitzpatrick scale to characterize skin color, but do not report who made the assessment and only report that 96% were light skin (types 1 and 2).	Low Index test was conducted prior to interpretation of results from reference test.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low PO values were collected simultaneously with ABG samples. Appears all patients were included in analysis.	Unclear
Bothma 1996	Low	Low	Low	Unclear	Low	Low

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
	Included consecutive patients meeting criteria and exclusions were appropriate.	Patients were selected for the study when they subjectively appeared darkly pigmented. Pigmentation was objectively quantified with a portable EEL reflectance spectrophotometer (calculated mean reflectance). They compare their mean value to that of another study that included a group of pigmented volunteers.	Index test was conducted prior to interpretation of results from reference test.	Does not state whether reference test results were interpreted without knowledge of index test results.	PO measurements occurred at the same time as blood sample, which was immediately taken for analysis. The reference standard test (CO-oximeter) was the same for all patients. Appears that all patients were included in analysis.	
Burnett 2022	Low Included all patients who received an anesthetic with at least 1 ABG sample during the time period of the study.	High Used self-reported race/ethnicity (White, Other, Hispanic/Latinx, Black, Asian) as a proxy for pigmentation.	Low Used the mean SpO2 during a 5 minute interval starting 10 min before ABG time.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low Used the mean SpO2 during a 5 minute interval starting 10 min before ABG time. The reference standard test was the same for all patients. Appear to include all data where both measurements were identified during the specified time period.	Moderate
Cecil 1988	Low The only patient selection criterion was that the patient required an ABG test. Data collection occurred consecutively as requests for blood gas analysis were received from the attending physician.	High A subjective assessment of skin pigmentation was made using a scale of I to 3 for light, medium, and dark pigment levels, respectively.	Low The PO probe was placed while the blood sample was taken.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low The PO probe was placed while the blood sample was taken and was analyzed within 15 minutes. Included all data with the exception of identified outliers.	Moderate
Chelsey 2022	Low Included all critically ill patients with paired measurements within 10 minutes of each other during the study period.	High Self-reported race/ethnicity obtained from medical record data.	Unclear Unknown whether the index test was conducted prior to the interpretation of the	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low Paired SpO2 with SaO2 measurements via ABG obtained within 10 min of each other. The 2 sites used different blood gas analyzers, but these devices	Moderate

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
			reference standard results.		are regularly calibrated. Some analyses only included Black and White patient groups due to sample size, otherwise all patients appear to be included in analyses.	
Crooks 2023	Low Retrospective study that included patients admitted to a level 3 intensive treatment unit bed with COVID-19 infection during the study period.	High Race/ethnicity determined from EHR data.	Low Unknown whether the index test was conducted prior to the interpretation of the reference standard results, but ward oximetry measurements are recorded routinely electronically using NerveCentre.	Low Reference test results were automatically entered into the EHR upon analysis.	Low Used last recorded observations and blood tests prior to the time of ITU admission. Timing of these measurements relative to one another is unknown. Method of ABG measurement not recorded. All patients included in analysis although patients without ethnicity data were excluded from multivariate analysis.	Moderate
Ebmeier 2018	Low Included consecutive patients admitted to each ICU who had routine PO and ABG measurement as part of routine clinical care. Additional exclusions are appropriate.	Low The Fitzpatrick scale was used to categorize skin color at the bedside by the study investigator. The 6 numerical ratings were divided into 3 categories.	Low Index test was conducted prior to interpretation of results from reference test.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low The SpO2 value recorded was the first value displayed after the blood entered the syringe for the ABG sample. ABG analysis was the same for all patients. A small number of patients were excluded (2 opted out of the study and 8 had measurements taken within 2 hours of ICU admission).	Low
Escourrou 1990	Unclear No information provided on selection of patients.	High States only that 5 patients were "moderately pigmented but not Black;" no information was provided on how this judgment was made.	Unclear Oximeters used continuously display saturation. ABG was measured at rest and exercise and analyzed immediately; it is unclear whether continuous PO measurements were observed with	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Unclear The time between ABG and PO measurement is not reported. ABG was sampled and analyzed the same for all patients. A satisfactory pulse output could not be obtained in 5 patients who were excluded. In 3 patients the transcutaneous value	Moderate

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
			knowledge of the results of the initial ABG test.		was not obtained at exercise due to poor signal.	
Fawzy 2022	Low	High	Unclear	Unclear	Low	Moderate
	Retrospective study that included patients for whom specified data were available during the study period.	Used self-reported race/ethnicity (Asian, Black/African American, White and Hispanic or non-Hispanic).	Retrospective data and timing/conduct of measurements is unknown.	Retrospective data and timing/conduct of measurements is unknown.	SaO2 and Sp02 readings occurred within 10 minutes of each other. All ABG samples were analyzed via CO-oximetry using an ABL brand device. Flow diagrams shows reasons for exclusion of patients from each analysis and exclusions are appropriate.	
Gabrielczyk 1988	Unclear	High	Low	Unclear	Low	Moderate
	No information provided on selection of patients.	Only report that 4 patients had "racially pigmented skin."	Index test was conducted prior to interpretation of results from reference test.	Does not state whether reference test results were interpreted without knowledge of index test results.	Blood was drawn after the PO reading was obtained. All patients had ABG measurement done with the same CO-oximeter. Measurement pairs from all patients were included in analysis.	
Harskamp 2021	Low	Low	Low	Low	Low	Low
	Enrolled consecutive adult patients admitted to the ICU with a catheter for ABG samples. Exclusions listed are appropriate.	Used the Fitzpatrick classification scale, as assessed by the site investigator. Considered Fitzpatrick type IV-VI to be dark skin type, in accordance with FDA guidance.	PO readings were blinded for SaO2.	The intensive care personnel analyzing blood samples were blind to PO readings.	PO readings were done directly (within 10 minutes) after blood sample was taken. The same equipment was used to analyze all blood samples. Included all valid SpO2 measurements.	
Henry 2022	Low	High	Low	Unclear	Low	Moderate
	Retrospective study that included adults meeting criteria from 4 self-identified racial groups with paired measurements.	Four self-identified racial groups.	There were zero minutes of separation between tests so the results from the blood sample would not have been analyzed before the PO reading was taken.	Does not state whether reference test results were interpreted without knowledge of index test results.	PO readings and blood samples were done simultaneously (*ie*, zero minutes of separation). Method of blood gas analysis not reported. Appear to include all patients in analysis.	

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
Hinkelbein (2007) acrylic	Low	High	Low	Unclear	Low	Moderate
	All adult ICU patients meeting criteria (mechanically ventilated, Caucasian patients with white skin color, plethysmographic waveform was of poor quality, other factors that can affect PO readings) with an arterial line within the study period who agreed to participate were included. Excluded non-White patients (n=2) due to "possible severe interference with the measurement."	Do not report how determination of skin color/race was made for inclusion in study and white patients may have represented a range of skin pigmentation.	PO readings were taken before blood sample.	Does not state whether reference test results were interpreted without knowledge of index test results.	Blood sample was taken directly after PO readings. Same device type was used for all ABG measurements. All study patients were included in analysis.	
Hinkelbein 2007 (nail polish)	Low	High	Low	Unclear	Low	Moderate
	All ICU patients meeting criteria (mechanically ventilated, 5 fingers without nail polish, Caucasian patients with white skin color, plethysmographic waveform was of poor quality, other factors that can affect PO readings) within the study period who agreed to participate were included. Excluded non-White patients (n=2).	Do not report how determination of skin color/race was made for inclusion in study and White patients may have represented a range of skin pigmentation.	Blood sample was drawn at the same time as PO readings.	Does not state whether reference test results were interpreted without knowledge of index test results.	Blood sample was taken at the time of PO readings. Same device type was used for all ABG measurements. All study patients were included in analysis.	
Jubran 1990	Unclear	High	Low	Unclear	Unclear	Moderate
	Unclear whether consecutive patients meeting criteria were included.	The skin of each of the Black patients was inspected by one of the investigators and subjectively graded as light, moderately dark, or very dark.	Each PO reading was taken at the same time as the paired blood sample.	Does not state whether reference test results were interpreted without knowledge of index test results. Since the index test values were set a priori according to the study protocol, investigators would have been aware of these	Blood sample was taken when each target PO reading was reached. Arterial oxygen saturation was measured with a CO-oximeter for all patients. It is unclear whether all patients were included in analysis.	

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
				values, but the publication does not report who analyzed the blood samples.		
Lee 1993	Unclear Unclear whether consecutive patients meeting criteria were included.	High Made note of the patient's race (Chinese, Malay, Indian) but it was not reported how this was determined.	Low SpO2 reading was taken when blood sample was drawn.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low SpO2 reading was taken when blood sample was drawn. All SaO2 readings were done with the same blood gas analyzer device type. Appears that jaundiced patients were excluded from analysis looking at effect of race.	Moderate
McGovern 1996	Unclear Patients were recruited from another study; details are not provided.	High Reports that all included subjects were White but does not report how this was determined or whether there was variation in skin color within the group.	Low Blood samples were evaluated after the exercise test.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low Arterial blood was collected at baseline and at each workload. SpO2 and SaO2 were recorded in the last 15s of each 1 min exercise period. All blood samples were analyzed with the same CO-oximeter. Measurements were obtained in all patients and data from each patient was included in the analysis.	Moderate
Muñoz 2008	Low Included all patients under assessment for long-term oxygen therapy at an outpatient center who had both measurements taken during the study period who met criteria. Excluded patients with factors that could affect measurements and exclusions are appropriate.	High All patients were Caucasian; do not report how race determination was made or whether there was variation in skin color/pigmentation within this group.	Low States that SaO2 and SpO2 were obtained simultaneously.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low States that SaO2 and SpO2 were obtained simultaneously. ABG was analyzed with the same CO-oximeter for all patients. All patients meeting criteria included in analysis.	Moderate
Nguyen 2022	Low Included all consecutive patients admitted to the	High Examine the effect of ethnic group, but do not	Low	Unclear Does not state whether reference test results were	Low SpO2 was measured continuously but the	Moderate

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
	ICU for acute respiratory failure (COVID-19 and non-COVID-19) during 2 different time periods who met criteria. Exclusion criteria included factors known to affect PO readings and exclusions are appropriate.	explain how this was determined; report % Black patients in table.	SpO2 reading was taken when ABG was performed.	interpreted without knowledge of index test results.	measurement was recorded at the time the ABG was performed. SaO2 was measured by the same type of blood gas analyzer device for all readings. All included patients included in analysis.	
Pilcher 2020	Low Patients 16 or older who were to have an ABG measurement as part of routine clinical care in hospital wards and outpatient clinics were recruited. Exclusions appear appropriate.	Low Based on modified Fitzpatrick scale with patient skin color classified as either: Light (Type I to Type II), Medium (Type III to Type IV) or Dark (Type V to Type VI).	Low SpO2 reading was taken when blood was drawn for ABG.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low The SpO2 value recorded was the first value on the oximeter when blood was first observed to enter the collection vial. Models of ABG analyzers appear to have varied. Excluded measurement paired with ABG samples identified to be venous or unusable. Participants in which there was a reported concern with oximeter accuracy were not excluded from analyses. Analyzed all participants that were included.	Low
Ries 1985	Unclear Included pulmonary patients referred to the laboratory for clinical exercise testing. Unclear if the study group represents all referred patients during a time period. Does not note any exclusions.	High Report skin pigmentation for a subset of participants. Skin pigmentation was assessed using a semiquantitative scale of light (1) to dark (4). Do not describe how this judgment was made or by whom.	Low Ear oximetry readings were recorded by a separate observer simultaneously with each arterial blood sample.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	High Ear oximetry readings were recorded simultaneously with each arterial blood sample. Blood samples were analyzed using 2 different blood gas analyzers that were regularly calibrated as well as by CO-oximeter. Skin pigment data was only collected for the subset of patients who were tested with both oximeter types.	High
Ries 1989	Unclear Included patients referred to the laboratory for evaluation of arterial blood gas changes during	High Skin color quantified by the Munsell color system. The 5YR hue chart was used as it	Low SpO2 readings and withdrawal of blood	Unclear Does not state whether reference test results were interpreted without	Low Readings from the ear oximeters were taken simultaneously with the withdrawal of each arterial	Moderate

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
	exercise. Unclear if the study group represents all referred patients during a time period. Does not note any exclusions.	corresponded most closely to the range of skin colors. A technician selected the tile from the hue chart which best matched the skin at the probe placement site. However, the 4 lightest colors were each considered their own group while the darker colors were grouped together in a single group (range of skin colors was not evenly distributed across the groups).	sample occurred simultaneously.	knowledge of index test results.	blood sample. All blood samples were analyzed with a blood gas analyzer that was regularly calibrated and each sample was checked with a CO-oximeter. Appears measurements from all patients are included but not all patients have measurements for both oximeters.	
Seitz 2022	Low Retrospective study that included all patients meeting criteria with paired measurements and race documented as Black or White during the study period. Excluded patients with COVID-19. Patients with other values for race were not included due to an inadequate number of patients for comparison.	High Race (Black or White) was used as a surrogate for skin pigmentation.	Low SpO2 values were directly transferred from the bedside monitor into the institutional data warehouse every 1 minute.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Low Measurements occurred within 10 minutes of each other and the SpO2 value closest in time was used. SaO2 measurement were done using the same CO-oximeter. All patients included in study were included in analysis.	Moderate
Sjoding 2020	Unclear Retrospective study; does not clearly describe how patients were selected for inclusion.	High Race (non-Hispanic Black or non-Hispanic White) was used as a surrogate for skin pigmentation.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Low Measurements occurred within 10 minutes of each other. SaO2 was directly measured by CO-oximetry for all patients. Appear to include all study patients in analysis.	Moderate
Sudat 2022	Low Appear to include all patients meeting their criteria during the study period. Excluded patients	High Race (Black or White) was used as a	Unclear Retrospective data and timing/conduct of	Unclear Retrospective data and timing/conduct of	Low Paired each SaO2 measurement with the nearest recorded SpO2 for the same person, truncated	Moderate

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
	who were not non-Hispanic Black or non-Hispanic white. Second cohort included ED patients with COVID-19. Excluded visits with no documented SpO2.	surrogate for skin pigmentation.	measurements is unknown.	measurements is unknown.	at ± 10m from the earlier of the ABG specimen time or result time. No information provided on ABG measurement. Appear to include all patients meeting their criteria in the respective cohort analyses.	
Valbuena 2022 ECMO	Low Retrospective study including adult patients with ARDS or COVID-19 on ECMO for respiratory failure during the study period. Included patients with relevant data (blood gas samples had to meet certain criteria for timing).	High Race/ethnicity was used as a surrogate for skin pigmentation.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Low No data on the timing of measurements were available. No information provided on SaO2 measurement. For hypoxemia analyses, only included race/ethnicity categories that met their calculated sample size threshold.	Moderate
Valbuena 2022 VHA	Low Retrospective study including all SpO2 and SaO2 data available for hospital stays, with some exclusions for indicators of critical illness (to capture a general hospital sample, not ICU). Valid records in the database require core identifiers, including race and ethnic origin, to be present.	High Race (Black, Hispanic, or White) was used as a surrogate for skin pigmentation.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Low Included pairs of measurements occurring with 10 minutes of one another. Information on whether the SaO2 reading was measured by CO-oximetry was not available. Do not include Hispanic patients in all analyses.	Moderate
Wang 1987	Unclear Unclear whether consecutive patients meeting criteria were included.	High All patients were characterized as 'pigmented;' do not report how this judgment was made or on variation within the sample.	Low Index test was conducted prior to interpretation of results from reference test.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low Arterial blood was drawn simultaneously with PO readings. Oxygen saturation was measured with a CO-oximeter for some samples and a blood gas analyzer for others. Either an ear or finger PO reading was obtained from all patients, but not both.	Moderate

Study Name or Author Year	Patient Selection	Patient Categorization	Index Test	Reference Standard	Flow and Timing	Overall Rating
Wiles 2022	Low Retrospective study that included all consecutive patients meeting criteria with both Spo2 and SaO2 measurements available; exclusions were appropriate.	High Race/ethnicity was used as a surrogate for skin pigmentation.	Low Used the mean value of SpO2 readings that occurred during the 4 minute period prior to ABG analysis.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low Used the mean value of SpO2 readings that occurred during the 4 minute period prior to ABG analysis. Arterial oxygen saturation was determined by CO-oximetry for all patients. All study patients included in analysis.	Moderate
Wiles 2022 letter	Low Retrospective study that included critically ill patients with COVID-19 pneumonitis receiving invasive mechanical ventilation with pairs of SpO2 and SaO2 measurements during the study period. Other exclusions are appropriate.	High Categorized patients by ethnic group (South Asian, Black, White, and other).	Low SpO2 measurements performed automatically by bedside monitoring system. Used the mean value of SpO2 readings that occurred during the 4 minute period prior to ABG analysis.	Unclear Does not state whether reference test results were interpreted without knowledge of index test results.	Low Used the mean value of SpO2 readings that occurred during the 4 minute period prior to ABG analysis. Same CO-oximeter device type used for all SaO2 measurements. Appear to include all study patients in analysis.	Moderate
Wong 2021	Low Retrospective study that included patients from all units available in the data sets with SpO2 measurements within the specified range and with self-identified race/ethnicity classified as Asian, Black, Hispanic, or White.	High Classified patients by race/ethnicity, not skin pigmentation.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Unclear Retrospective data and timing/conduct of measurements is unknown.	Low Each ABG-measured SaO2 was matched with the closest SpO2 value recorded within the previous 5 minutes. Do not report how blood gas analysis was conducted. All included patients included in analysis; excluded patients from subgroup analysis when data on corresponding characteristics were missing.	Moderate

Abbreviations. ABG=arterial blood gas, PO=pulse oximeter, ER=emergency room, HER=electronic health record, ITU=intensive treatment unit, ICU=intensive care unit, FDA=Food and Drug Administration, ARDS=acute respiratory distress syndrome, ECMO=extracorporeal membrane oxygenation.

OBSERVATIONAL STUDIES (QUIPS)

Study Name or Author Year	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall Risk of Bias
Burnett 2022	Low Included all patients who received an anesthetic with at least 1 ABG sample during the time period of the study.	Low Retrospective cohort study. Appear to include all data where both measurements were identified during the specified time period.	High Used self-reported race/ethnicity obtained from medical record data as a proxy for pigmentation.	Low Occult hypoxemia defined as SaO2 less than 88% despite SpO2 greater than 92%. SaO2 measurement was the same for all patients and changes in SpO2 devices were accounted for by year measurement was taken.	Moderate Used a multivariable model which controlled for all of the collected demographic, comorbidity, and operative variables. Do not account for all potential confounding variables (*eg*, socioeconomic factors).	Low GEE modeling was used to determine if race was an independent predictor of occult hypoxemia. No evidence of selective reporting of results.	Moderate
Chelsey 2022	Low Included all critically ill patients with paired measurements within 10 minutes of each other during the study period.	Low Retrospective cohort study. Some analyses only included Black and White patient groups due to sample size, otherwise all patients appear to be included in analyses.	High Used self-reported race/ethnicity (White, Other, Hispanic/Latinx, Black, Asian) as a proxy for pigmentation.	Low Occult hypoxemia defined as SaO2 < 88% when pulse oximeter oxygen saturation was between 92–96%. The 2 sites used different blood gas analyzers, but these devices are regularly calibrated. Different pulse oximeters were used at the 2 study sites but there were no differences between sites when compared.	Moderate Multivariable model controlled for a limited number of potential confounders (age, sex, hemoglobin).	Low Used multivariable logistic regression model to examine the association between self-reported race and occult hypoxemia. No evidence of selective reporting of results.	Moderate
Crooks 2023	Low Retrospective study that included patients admitted to a level 3 intensive treatment unit bed with COVID-19	Low Retrospective cohort study. Patients without race data were not included in multivariate analysis	High Used self-reported race/ethnicity (White, Black/mixed, Indian/Pakistani,	High Used last recorded observations and blood tests prior to the time of ITU admission. Timing of these	Moderate Model adjusted for age, sex, weekend ICU admission, and vaccination status. Other potential confounding	Low Utilized a multivariate model. No evidence of selective reporting.	High

Study Name or Author Year	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall Risk of Bias
	infection during the study period.	but otherwise all patients were retained.	Other) as a proxy for pigmentation.	measurements relative to one another is unknown. Do not report device types for PO and ABG measurements but these measurements are automatically uploaded to the EHR. Don't provide detail on measurement of other clinical variables (*eg*, mean respiratory rate).	variables (*eg*, socioeconomic factors, comorbidities) were not controlled for.		
Fawzy 2022	Low Included patients for whom specified data were available during the study period.	Low Retrospective cohort study. Flow diagrams shows reasons for exclusion of patients from each analysis and exclusions are appropriate.	High Used self-reported race/ethnicity (Asian, Black/African American, White and Hispanic or non-Hispanic) as a proxy for pigmentation.	Moderate All ABG samples were analyzed via CO-oximetry using an ABL brand device. PO device type and reading location was not reported and likely varied between sites. Delayed treatment recognition was defined as those patients with a predicted SaO2 of 94% or less before a measured SpO2 of 94% or less or oxygen treatment initiation. Unrecognized treatment eligibility was defined as those patients with a predicted SaO2 of 94% or less who did not initiate treatment with oxygen or have a	Moderate Model was adjusted for covariates that captured disease severity or an underlying comorbidity or had a known or theoretical association with PO accuracy, including demographic characteristics along with time-varying clinical and laboratory variables. Do not account for all potential confounding variables (*eg*, socioeconomic factors).	Moderate The difference in time to recognition of treatment eligibility between patients of racial and ethnic minority groups and White patients was estimated using a Cox proportional hazards model. Among individuals with delayed recognition of treatment eligibility, Wilcoxon rank sum tests were used to compare the distributions of length of delayed recognition between groups. Only patients with complete data on covariates were included in adjusted model. No evidence of selective reporting of results.	Moderate

Study Name or Author Year	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall Risk of Bias
				recorded SpO2 of 94% or less at any time.			
Henry 2022	Low Retrospective study that included adults meeting criteria from 4 self-identified racial groups with paired measurements.	Low Appear to include all patients in analysis.	High Patients were categorized into 4 self-identified racial groups.	Moderate PO readings and blood samples were done simultaneously (*ie*, zero minutes of separation). Method of blood gas analysis and pulse oximetry not reported and may have differed between study sites. Occult hypoxemia was defined as SaO2 less than 88% despite a normal SpO2 (*ie*, ≥ 92%). Hospital-free days were counted as the number of days alive and out of hospital following the index time through 28 days of follow-up.	Moderate Adjusted for select potential confounders in both analysis of occult hypoxemia (age, mean arterial pressure less than 65 mmHg or the use of continuous infusions of IV vasopressors at the time of SaO2 assessment, and presence of COPD or home oxygen use) and analysis of treatment outcomes (age, sex, COPD or home oxygen use, index location [ICU vs surgical], and acuity of illness).	Low GEE was used to account for multiple observations. No evidence of selective reporting.	Moderate
Seitz 2022	Low Retrospective study that included all patients meeting criteria with paired measurements and race documented as Black or White during the study period. Excluded patients with COVID-19. Patients with other values for race were not included due to an	Low Retrospective study and all patients included in study were included in analysis.	High Race (Black or White) was used as a surrogate for skin pigmentation	Low Measurements occurred within 10 minutes of each other and the SpO2 value closest in time was used. SaO2 and SpO2 measurements were done using the same devices for all patients. Occult hypoxemia was defined as SaO2 <	High Did not examine occult hypoxemia with a multivariate model that accounts for potential confounders.	Low Compared rate of occult hypoxemia between groups (t test?). No evidence of selective reporting.	Low

Study Name or Author Year	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall Risk of Bias
	inadequate number of patients for comparison.			88% with SpO2 values of 92–96%.			
Sudat 2022	Low Appear to include all patients meeting their criteria during the study period. Excluded patients who were not non-Hispanic Black or non-Hispanic White. Second cohort included ED patients with COVID-19. Excluded visits with no documented SpO2.	Low Retrospective study; appear to include all patients meeting their criteria in the respective cohort analyses.	High Race (Black or White) was used as a surrogate for skin pigmentation.	Moderate Paired each SaO2 measurement with the nearest recorded SpO2 for the same person, truncated at ± 10m from the earlier of the ABG specimen time or result time. No information provided on ABG or PO measurement. Treatment outcomes (time spent in ED, hospital admission, dexamethasone administration and timing, oxygen supplementation and timing, return to the hospital after discharge home) from EHR data. Defined hypoxemia as an SaO2 < 90%.	Moderate Important differences were noted between NHB and NHW groups at baseline (homelessness, insurance types, comorbidities), but these and additional demographic and clinical covariates were included in the model. Do not account for all possible confounders.	Low Used G-computation to build 2 counterfactuals to assess the possible impacts of differential SpO2 measurement error on COVID-19-related outcomes for NHB patients. Computed the mean difference between the predicted outcome with the observed SpO2 values and the predicted outcome with SpO2 values shifted by the measurement difference from the initial PO bias analysis. Also compared prevalence of OH between groups and reported p value. No evidence of selective reporting.	Moderate
Valbuena 2022 ECMO	Moderate Retrospective study including adult patients with ARDS or COVID-19 on ECMO for respiratory failure during the study period. Included patients with relevant data (blood gas samples had to meet certain criteria for timing). For	Low Retrospective study using registry data.	High Race/ethnicity was used as a surrogate for skin pigmentation.	High No data on the timing of measurements were available. No information provided on SaO2 or SpO2 measurement. Occult hypoxemia was defined as low arterial oxygen saturation (SaO2 ≤ 88%) on arterial	High Only adjusted for sex and measured SpO2.	Low Multivariable analyses were performed by logistic regression for each race and ethnicity group compared with White patients to examine the relationship between these variables with the odds of occult hypoxemia. No evidence of selective reporting.	High

Study Name or Author Year	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall Risk of Bias
	hypoxemia analyses, only included race/ethnicity categories that met their calculated sample size threshold (N ≥ 400). Excluded a large number of patients for this reason, including groups where patients may have had more pigmented skin (*eg*, North African).			blood gas measurement despite a pulse oximetry reading in the range of 92% to 96%.			
Valbuena 2022 VHA	Low Retrospective study including all SpO2 and SaO2 data available for hospital stays, with some exclusions for indicators of critical illness (to capture a general hospital sample, not ICU). Valid records in the database require core identifiers, including race and ethnic origin, to be present.	Low Retrospective study and all patients included in study were included in analysis, although Hispanic patients were not included in all analyses.	High Race (Black, Hispanic, or White) was used as a surrogate for skin pigmentation.	Moderate Included pairs of measurements occurring with 10 minutes of one another. No information on device/location for PO and SaO2 measurements was available. Occult hypoxemia was defined as defined as arterial SaO2 <88% despite a SpO2 reading of ≥92%.	Moderate Models were adjusted for patient level characteristics that included age, sex, patient comorbidities, supplemental oxygen, and diagnoses on admission. Do not account for all potential confounders.	Low Fit a multivariable logistic regression model to predict the odds of occult hypoxemia. No evidence of selective reporting.	Moderate
Wong 2021	Low Retrospective study that included patients from all units available in the data sets with SpO2 measurements within the specified range and with self-identified	Low Retrospective study. All included patients included in analysis; excluded patients from subgroup analysis when data on corresponding characteristics were missing.	High Classified patients by race/ethnicity, not skin pigmentation.	Moderate Each ABG-measured SaO2 was matched with the closest SpO2 value recorded within the previous 5 minutes. Do not report how blood gas analysis was conducted or	Moderate Adjusted only for age, sex, SOFA score.	Low Multivariate logistic regression was used for assessing binary end points, multivariate ordinal regression for numerical end points, and multivariate linear models for continuous end points, using analysis of variance to	Moderate

Study Name or Author Year	Study Participation	Study Attrition	Prognostic Factor Measurement	Outcome Measurement	Study Confounding	Statistical Analysis and Reporting	Overall Risk of Bias
	race/ethnicity classified as Asian, Black, Hispanic, or White.			device/location of PO measurement. Occult hypoxemia was defined as SpO2 > 88% but SaO2 < 88%. Clinical outcomes (in-hospital mortality, length of stay, organ dysfunction [SOFA scores], laboratory values) extracted from HER.		test for the impact of hidden hypoxemia while adjusting for other covariates. Calculated relative risk of OH by race/ethnicity. No evidence of selective reporting.	

Abbreviations. ABG=arterial blood gas, GEE=generalized estimating equation, ITU=intensive treatment unit, PO=pulse oximeter, HER=electronic health record, ICU=intensive care unit, COPD=chronic-obstructive pulmonary disease, ED=emergency department.

SYSTEMATIC REVIEWS (ROBIS)

Study Name or Author Year	Study Eligibility Criteria	Identification and Selection of Studies	Data Collection and Study Appraisal	Synthesis and Findings	Overall Risk of Bias
Shi 2022	Low Reasonable and clearly defined eligibility criteria.	Low Multiple databases searched. Conducted searches of clinical trial registries. Hand-searched reference lists of included studies and relevant reports. Dual independent study selection.	Low A single reviewer abstracted data and assessed risk of bias, checked by another reviewer. Risk of bias was assessed using appropriate criteria.	Low Appears all data were included, as appropriate. Performed both pre-planned and post-hoc sensitivity analyses.	Low

CHARACTERISTICS OF INCLUDED STUDIES

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
Abrams 2002 N=294	US Clinical	Prospective liver transplant candidates with cirrhosis and controls with an indication for ABG measurement Mean age: 53.3 % male: 54.4 % non-Hispanic White: NR	Nellcor N-200 *Finger* Radiometer ABL520	Race (Black, White) NR	Bias
Adler 1998 N=298	US Clinical	NR Mean age: 60 % male: 51 % non-Hispanic White: NR	Nellcor D-25 *Finger* 4-wavelength spectrophotometer or CO-oximeter (Radiometer OSM3)	Skin pigmentation (dark, intermediate, light) Munsell color system	Bias
Bangash 2022 N=18,069	UK Clinical	NR Median age: 63 % male: 57.9 % non-Hispanic White: 81.2	NR NR	Race (White, Asian, Black, Other) Self-reported	Bias, prevalence of occult hypoxemia
Blanchet 2023 N=193	Canada Clinical	Stable adults in the intensive care unit with an arterial catheter in place Median age: 66.3 years % male: 79.3	Nellcor N-600 *Finger* Radiometer ABL 800Flex OSM-3	96.2% light skin (types 1 and 2) Fitzpatrick scale	Bias, root mean square error, prevalence of occult hypoxemia, observations
Bothma 1996 N=100	US Clinical	Critically ill patients wrth arterial lines in situ	Simed S100e *Finger* Nihon Koden *Finger* Ohmeda 3740 *Ear* Instrumentation Laboratories IL482 CO-oximeter System	Subjects (darkly pigmented patients) had a mean reflectance of 19.9 Portable EEL Reflectance spectrophotometer	Bias
Burnett 2022 N=46,253	US Clinical	Patients receiving anesthetic Median age: 57± 21 years % male: 54.5 % White: 47.8	Primarily Nellcor prior to 2011 and Masimo after GEMStat Premier 3000	NR	Bias, prevalence of occult hypoxemia, OR observations

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
Cecil 1988 N=152	US Clinical	ABG determination was needed Median age: 64.1 ± 18.7 years % male: 53.9 % White: 89.5	Nellcor N-100; Ohmeda 3700 *Finger* IL 282 CO-Oximeter	For Black patients, the subjective estimate of pigmentation level ranged from 1 to 3 (2.5 ± 0.6). A subjective assessment of skin pigmentation was made using a scale of I to 3 for light, medium, and dark pigment levels, respectively.	Bias
Chelsey 2022 N=7,693	US Clinical	Critically ill patients admitted to ICUs Median age: 64 years % male: 58.9 % White: 60	Covidien Nellcor oximeter and OxiMax disposable finger sensors; Masimo pulse oximeter and LNCS disposable sensors *Finger* Multi-wavelength CO-oximeter (ABL90 and GEM 4000)	NR	Bias, intrasubject variability in measurement error, prevalence of occult hypoxemia, OR both
Crooks 2023 N=748	UK Clinical	Patients admitted to a level 3 intensive treatment unit bed with COVID-19 infection Median age: 56 years % male: 62.5 % White:56.1	NR	NR	Bias, prevalence of occult hypoxemia, treatment delivery
Ebmeier 2018 N=394	Australia and New Zealand	ICU patients Median age: 62.5 ± 15.1 % female: 36.6 % European: 80.6	Marquette Rac-4A and Masimo (NZ); Philips IntelliVue MP70 monitors with Philips Adult Reusable SpO2 sensors (Australia) *Ear, finger, or toe* Alpha-stat method using Radiometer ABL 800 FLEX	Dark 3.1% Medium 34.0% Light 61.9% The Fitzpatrick Scale	Bias, limits of agreement, association with oxygen saturation
Escourrou 1990 N=101	France Research	Patients with COPD, emphysema, sarcoidosis, pulmonary fibrosis, Hodgkin's disease, primary pulmonary hypertension, cirrhosis of the liver, restrictive pulmonary disease, miscellaneous	Ohmeda Biox 3700 *Ear* Criticare CSI 501 + *Ear* Nellcor N200	5 patients were moderately pigmented but not black NR	Bias, standard error

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
		diseases, dyspnea of unknown origin Age: 17 – 81 years % male: 71.3	Sampled using a microsampler and analyzed using a Corning 178 gas analyzer. Measured SaO2 was determined by a spectrophotometric method.		
Fawzy 2022 N=1216 (accuracy) 6673 (treatment eligibility analysis)	US Clinical	For sample with concurrent SaO2 and SpO2 measurements: Median 59.8 years % male: 58.3 % White: 37.8	NR	NR	Bias, prevalence of occult hypoxemia, treatment delivery
Gabrielczyk 1988 N=21	UK Clinical	Hypothermic patients after cardiac surgery Median age: 59.5 years	Nellcor N-100 *Finger* Hemoglobin saturation (Radiometer OS2), blood gas estimation (ABL30 Radiometer)	Racially pigmented skin 19% (4 patients and 14 paired obs) NR	Bias
Harskamp 2021 N=35	Netherlands Clinical	ICU patients primarily admitted for respiratory failure due to COVID-19 or other pulmonary diseases Median age: 69 years % female: 40	Direct-to-consumer pulse oximeters: AFAC FS10D, AGPTEK FS10C, ANAPULSE ANP 100, Cocobear, Contec CMS50D1, HYLOGY MD-H37, Mommed YM101, PRCMISEMED F4PRO, PULOX PO-200 and Zacurate Pro Series 500 DL Included a hospital-grade SpO2 monitor (Philips M1191BL sensor glove) as a clinical index test ABL90 Flex Plus	Fitzpatrick IV-VI skintype 14.3% Fitzpatrick classification scale	Bias, root mean square difference, mean absolute error
Henry 2022 N=26,603	US Clinical	Patients admitted to the ICU or undergoing surgery during inpatient hospitalization Median age: 64 years % male: 58.4 % White: 92.1	NR	NR	Bias, prevalence of occult hypoxemia, OR Obs, treatment delivery
Hinkelbein 2007 acrylic N=46	Germany Clinical	Critically ill and mechanically ventilated (for at least 24	Siemens (monitor SC1281 and module SIREM connected to a re-usable Nellcor DS-100A Durasensor finger probe) or	Only included patients with white skin color (Caucasian race)	Bias

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
		hours via a tracheal tube or cannula) patients Median age: 58.1 years	Philips (IntelliVue MP70 attached to the finger probe M1191A) device Radiometer Copenhagen System ABL625		
Hinkelbein 2007 nail polish	Germany Clinical	Critically ill and mechanically ventilated (for at least 24 hours via a tracheal tube) patients Median age: 59 ± 14.2 % female: 38	Siemens monitor SC1281 and module SIREM, connected to a reusable finger sensor probe Nellcor DS100-A Durasensor *Finger* Radiometer Copenhagen ABL System	Only included patients with white skin color (Caucasian race)	Bias
Jubran 1990 N=54	US Clinical	Patients in the MICU receiving mechanical ventilation Median age: 53 years % female: 55.6 % White: 46.3	Nellcor *Finger, ear, or toe* Ohmeda-Biox 3700 *Ear or finger* Arterial O2 saturation was measured with a CO-oximeter	NR The skin of each of the Black patients was inspected by one of the investigators and subjectively graded as light, moderately dark, or very dark	Bias, frequency of inaccurate readings (*ie*, bias > 4%)
Lee 1993 N=33	Singapore Clinical	MICU patients Median age: 54.4 years % Chinese: 66.7 % Malay: 18.2 % Indian: 15.2	Nellcor, Simed, Critikon *NR* Nova Stat Profile 3 pH/blood gas analyser (This represents functional oxygen saturation and not fractional oxygen saturation as would be given with a CO-oximeter.)	NR	Bias
McGovern 1996 N=8	US Research	Patients in stable condition with severe COPD Median age: 63.2 ± 9.6 % male: 100	Ohmeda 3700 *Finger* IL 482 CO-oximeter	All subjects were White NR	Bias, bias after correction for COHb level
Muñoz 2008 N=846	Spain Clinical	Patients under assessment for long-term home oxygen therapy in a specialized outpatient clinic Median age: 68.4 ± 12.2 % male: 70	Minolta Pulsox-7 IL 682 CO-oximeter	All were Caucasian NR	Bias, impact of arterial oxygen tension (Pa, O2)

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
Nguyen 2022 N=55	France Clinical	Patients with acute respiratory distress syndrome (ARDS) with and without COVID-19. All patients were mechanically ventilated Median age: 60 ± 17 years % male: 60 % Black: 31%	Masimoset *Finger (all but 3) or ear* ABL800 Radiometer	NR	Bias, Correlations, agreement, concordance between relative changes in SpO2 and SaO2
Pilcher 2020 N=400	Australia and New Zealand Clinical	Patients who were to have an ABG measurement as part of routine clinical care Median age: 64 ± 15.2 % male: 53	Most common were Nonin Avant 9700, Masimo Rainbow Radical 7, and Nonin Avant 4000) *Ear or finger* The model used was recorded for each patient	Fitzpatrick Score 1 11% II 49.5% III 31.8% IV 7.5% V 0.3% VI 0% Based on modified Fitzpatrick scale with patient skin color classified as either: Light (Type I to Type II), Medium (Type III to Type IV) or Dark (Type V to Type VI)	Bias
Ries 1985 N=116	US Clinical	Pulmonary patients referred for evaluation of ABG changes during exercise NR	Hewlett-Packard 47201A and Biox IIA *Ear* IL813 and 513 blood gas analyzers. The SaO2 was measured both directly with the CO-oximeter and calculated from the measured PaO2, PaCO2, and pH, assuming a normal body temperature and P50	Only reported skin pigmentation in Phase 3 patients (simultaneous testing of both ear oximeters): Moderate skin pigmentation 21.7% Light skin pigmentation 78.3% Skin pigmentation was assessed using a semiquantitative scale of light (1) to dark (4)	Bias
Ries 1989 N=187	US Clinical	Pulmonary patients referred to the laboratory for clinical exercise testing NR	Ohmeda Biox III and Hewlett-Packard 47201A *Ear*	Group 1, value of 8 (very light); group 2, value of 7 (light); group 3, value of 6 (average); and group 4,	Bias, prevalence of technical problems

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
			Blood gas analyzers	value less than or equal to 5 (moderately dark to very dark). These value scores corresponded to rows of lightness (value) on the 5YR hue chart Skin color quantified by the Munsell color system. The 5YR hue chart was used as it corresponded most closely to the range of skin colors observed. A technician of normal color vision selected the tile from the 5YR hue chart which best matched the skin at the placement site for the ear probes.	
Seitz 2022 N=1,024	US Clinical	Critically ill adults receiving mechanical ventilation. Excluded patients with COVID-19 Median age (Black patients): 54 Median age (White patients): 58 % female (Black patients): 47 % female (White patients): 43	Nellcor Werfen GEM Premier 5000 blood gas analyzer	NR	Bias, prevalence of occult hypoxemia, obs
Sjoding 2021 N=10,001	US Clinical	One cohort was patients receiving supplemental oxygen. The other cohort was patients in ICUs. NR % White (UM cohort): 82.8 % White (multicenter cohort): 87.5	NR CO-oximetry	NR	Bias
Sudat 2022 N=11,237	US Clinical	All hospital patients who self-identified as non-Hispanic White or non-Hispanic Black (Cohort 1); all	NR NR	NR	Bias (cohort 1), prevalence of occult hypoxemia, obs

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
		adults who visited the ED with COVID-19 and self-identified as NHW or NHB (cohort 2) Median age (Cohort 2): 57.3 years % female (Cohort 2): 52.3 % NHW (Cohort 1): 81.1 % NHB (Cohort 1): 17.2 % NHW (Cohort 2): 87.5 % NHB (Cohort 2): 12.5			
Valbuena 2022 N=28,531	US Clinical	Inpatients in general care (medical and surgical not ICU) Median age (NHW): 69 years Median age (NHB): 66 Median age (Hispanic/Latino): 68 % male: 96	NR	NR	Bias, root mean square error, probability obs,
Valbuena 2022 ECMO N=372	US Clinical	Patients with ARDS or COVID-19 in respiratory failure and about to undergo extracorporeal membrane oxygenation % male: 68 % White: 50	NR	NR	Bias, prevalence of occult hypoxemia, OR obs
Wang 1987 N=31	Singapore Clinical	Most (27) patients admitted to the hospital with acute symptoms. In 4 outpatients, ABG was performed as part of lung function assessment Median age: NR % male: 96.8	Biox III *Finger and ear* NR	All patients were characterized as “pigmented” NR	Bias
Wiles 2022 N=194	UK Clinical	Patients who were critically ill with COVID-19 pneumonitis who received non-invasive respiratory	B1x5 M/P monitoring system using NellcorTM reusable or disposable probes *NR*	NR	Bias, prevalence of occult hypoxemia, Obs

Study Name or Author Year	Country Setting	Participant Characteristics	Pulse Oximetry *Location* CO-oximetry	Skin Pigmentation or Race/Ethnicity Factors Measurement	Outcome Types
		support CPAP, low-flow/high-flow oxygen therapy) within the first 7 days of critical care admission. Median age: 62 ± 12.4 % White: 69.6	RAPIDpoint 500 analyser		
Wiles 2022 Letter N=178	UK Clinical	Patients with COVID-19 pneumonitis who were receiving mechanical ventilation of their lungs Median age: 60 ± 14 years % male: 75 % White ethnic origin: 70.8	B1x5 M/P monitoring system using NellcorTM reusable or disposable probes *NR* RAPIDpoint 500 analyser	NR	Bias, prevalence of occult hypoxemia, obs
Wong 2021 N=NR	US Clinical	Patients with SpO2 within the range of 88%to 100% Median age: 62.2% % female: 42.9 % Black: 29.6	NR	NR	Bias, prevalence of occult hypoxemia, RR both

Abbreviations. ABG=arterial blood gas; NR=not reported, NHW=non-Hispanic White, NHB=non-Hispanic Black, CPAP=continuous positive airway pressure.

PEER REVIEW COMMENTS AND RESPONSES

Comment #	Reviewer #	Comment	Author Response
Are the objectives, scope, and methods for this review clearly described?			
1	1	Yes	
2	2	Yes	
3	3	Yes	
4	4	Yes	
5	5	Yes	
6	6	Yes	
Is there any indication of bias in our synthesis of the evidence?			
7	1	No	
8	2	No	
9	3	No	
10	4	No	
11	5	No	
12	6	No	
Are there any published or unpublished studies that we may have overlooked?			
13	1	No	
14	2	No	
15	3	No	
16	4	Yes - Okunlola et al 2021 Respiratory Care is important for putting pulse oximeter errors in perspective.	Thank you for this suggestion. We have incorporated this recommendation paper into the Discussion.
17	5	No	
18	6	No	
Additional suggestions or comments can be provided below.			
19	1	None	
20	2	None	

Comment #	Reviewer #	Comment	Author Response
21	3	p.v. line 5/6 and line 11. Why do the first two key findings use the mitigating word “likely”? The data which has been graded as moderate strength shows that pulse oximeters often/typically overestimate Black patients’ O2 sat and that occult hypoxemia is more common among Black than White patients. Using mitigating language, while scientifically accurate, detracts from the very important message of this review. I suggest re-writing these top two key findings either by just removing the word “likely” or re-phrasing the sentences (for example, Pulse oximeters are more likely to overestimate Black or African American than White patients’ blood oxygen saturation level……)	Use of “likely” (or “may”) correspond to strength of evidence ratings (moderate or low, respectively), which we have clarified in the Methods section.
22	3	p.vi. line 30-32. “In Black or African American patients, pulse oximeters appear to overestimate blood oxygen saturation by an average of 150% compared with CO-oximetry in arterial blood...” I do not understand what is meant by 150%. This would benefit from more explanation. This same phrasing is used in the main findings section on p8. Lines 28-30, where is again is unclear to me what this means and would benefit from more explanation.	Thank you. This was a typographical error on our part that has been corrected.
23	3	On p9, line 30, I don’t understand how the addition of 68,455 paired observations with a mean bias of 1.4 to the Shi 2022 review of 2,646 paired observations with mean bias of 0.31, resulted in an updated estimate that is basically the same as the original mean bias described in the Shi paper (0.31). P9, line 48. Again, I don’t understand how the updated estimate of mean bias changed so little from Shi’s estimate, and I really don’t understand how the lower bound of the confidence interval moved lower than for either the Shi 2022 review of the recent studies. I assume that my lack of understanding is just because I don’t understand the math involved (I chose not to read Tang et al’s paper that is cited as the reference for the method of pooling the estimates because most other clinicians reading this ESP report also will not read the Tang paper). Provided the math is right and it is my lack of math knowledge that is the problem, I recommend explaining somewhere how the math has created these non-intuitive situations. This could be explained in the discussion – or it could be pre-empted by more explanation in the “synthesis” section.	Thank you for pointing this out. The reason the overall (updated) estimate is quite similar to the Shi estimate is because the precision estimates/standard deviations from the studies included in Shi were much smaller than those in the more recent (and much larger) studies. This results in Shi’s estimate being more heavily weighted in the final meta-analysis that pools pre-2021 and recent evidence, regardless of the fact that the more recent evidence includes a much larger amount of data.

Comment #	Reviewer #	Comment	Author Response
24	3	Three minor comments: 1) P12. Line 8. Final word on this line is “few”, I think it is supposed to be “fewer”. 2) P12, line 21. “No or delayed recognition of eligibility..” is hard to parse. I think this sentence means “Failure to recognize eligibility or delayed recognition of eligibility…” 3) P13, line 29-29. Cites ref 28 as having proposed use of a correction factor, whereas the authors of this paper explicitly state that a correction factor cannot be used. It would be a more accurate reflection of this paper to place the citation at the end of the sentence ie after stating that this approach “may have limited efficacy because the accuracy and variability of pulse oximetry readings is influenced by a number of factors that cannot be accounted for in a single correction factor.”	Thank you. We have corrected these issues.
25	4	This is an important and timely review that accurately describes a probable increased rate of missed diagnosis of hypoxemia in black patients monitored with current pulse oximeter technology. I think the authors have done a good job of capturing the concept that pulse oximeters can be biased to read too high in black patients. This issue has been observed multiple times, in multiple clinical scenarios, and with varying methodologies. Based on the weight of the published evidence, there is basis for concern and review.	Thank you for this comment.
26	4	I think the review needs to take several additional steps to increase its value. The first is that the reason for clinical errors in pulse oximeter function are not well understood, and contradict some very good clinical laboratory evidence that the magnitude of intrinsic pulse oximeter errors is smaller than observed clinically. The review by Okunlola points out this issue clearly This point is important because it emphasizes that factors in the clinical environment can amplify a small bias in the technology. Merely fixing this bias by technological means is unlikely to erase the structural issues with black patients having poor access to care, presenting to the hospital sicker, and possibly receiving a lower quality of care in the hospital. Structural racism will not yield to minute improvements in pulse oximeter technology.	Thank you for this feedback. We have elaborated on several of these points, particularly in the Discussion section.

Comment #	Reviewer #	Comment	Author Response
		The other missed opportunity is to emphasize that any medical technology is imperfect and needs to be interpreted with clinical judgement. Emphasizing that clinicians owe black patients more skepticism and investigation based on pulse oximeter readings is important at the present time. The problem is that clinical decision making is often based on a lab value threshold—e.g. administering supplemental oxygen at a saturation threshold of 89% or lower, not recognizing that if the pulse oximeter reads 89% the true saturation may be 85%-96% depending on signal quality, due to such factors as low perfusion, misapplied probes, patient movement, clinician inexperience, etc. This would have much more impact than waiting for manufacturers to fix an error that is probably in the 1-2% range.	
27	4	One problem that you want to fix is on page 20, line 30. The data do not indicate that pulse oximeters overestimate saturation by 150%-- that is clearly a wrong conclusion. The right analysis is rate of missed hypoxemia, assuming a threshold and range, as done by Sjoding and colleagues from the Univ. of Michigan. Mean bias or Arms values do not capture the clinically important ranges of readings or errors.	Thank you. This was a typographical error on our part that has been corrected.
28	5	None	
29	6	This report is extremely well written. Complex information is presented in a lucid and comprehensive manner. I deeply appreciated the detailed explanations of systematic review methodology and synthetic algorithmic evaluation.	Thank you for this comment.
30	6	Ln. 28 pg. vi: Please indicate whether any of the studies come from hospital systems comparable to VHA in any way.	Where such studies were not already highlighted, we have attempted to emphasize when a study or evidence base is comparable to the VA setting (eg, from integrated health systems).
31	6	Ln 30ff pg. vi: Are these patients comparable to Veterans in any way? Veterans are sicker, may have more toxic exposures etc. This should be considered to ensure the patient populations are truly comparable. If they are close in comparison, or are not representative or comparable to Veterans, it should be pointed out. I note that you bring out VA evidence a little later in the review. Perhaps moving it up in the review would be better.	We agree that Veterans are a unique population with a greater burden of chronic disease than the general population. At the same time, the complex and dynamic array of factors (including skin pigmentation level) that likely result in differential pulse oximeter accuracy make it challenging to identify specific patient characteristics (outside of skin pigmentation level, or by potentially imprecise proxy, race/ethnicity) that are relevant to use to evaluate the comparability of non-VA study samples

Comment #	Reviewer #	Comment	Author Response
			with the VA patient population. In our view, the most feasible way of addressing this (important) consideration is to emphasize studies conducted in the VA patient population, which we have done.
32	6	Ln 39 pg vii: It's not just structural "inequities," the disparities in this report are terrific examples of structural racism. The biases and unequal outcomes described in pulse oximetry readings here are racist (i.e., skin-tone based, poor correlation between science of device development and real-world use, etc.), maintained by structural factors in US healthcare to which VHA is not immune. That the historic component of this problem was well understood for decades yet no action was taken to address it is symptomatic of structural encasements that render the suffering of Black patients invisible. White Supremacy, therefore, is at the heart of this problem. What remains troubling is that I could not find the word 'racism' used to describe the underpinnings of this issue anywhere in this synthesis. By not doing so, the case is being (inadvertently) made that the lungs of Black or African Americans are somehow different biologically than those of White people, and therefore are more diseased. The ultimate point of this review may well be the dismantling of racially-tailored clinical practices in favor of identification and evaluation of more precise biomarkers. Yet, context of the likely structural conditions (i.e., the harms of clinicians using phenotypic race to determine treatment decisions) are merely hinted at in this review. Structural racism is not neutral, it is a harm to Veteran patients. More precision regarding how race is being defined and operationalized here would be helpful (e.g., self-identified, etc.). In addition, what was it about the COVID-19 pandemic that heightened awareness of the discrepancies in pulse oximetry? Was it more Black patients with poor lung function in the ER? Or similar? Because of the historicity of the problems, the harms are not new. Yet, something about COVID-19 brought this up and out.	Thank you for raising these important points. We have revised the section in which "inequities" were mentioned. Regarding the point about race definitions, we have added a section to the Discussion about the use of race/ethnicity (versus objective skin pigmentation measures) in accuracy studies. It is likely that there were many factors related to the pandemic that broadened awareness of biases in pulse oximeter accuracy, potentially including the ones you have mentioned. Another contributing factor may be the exponential increase in accuracy data that became available due to, or at least contemporary with, the pandemic.
33	6	Because systematic reviews are often predicated on assessing bias in published studies, and that this research was undertaken to examine racial bias, more selective wording or terminology	Thank you. We have attempted to better distinguish the various meanings of "bias" used throughout the review.

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		would be advisable. At times, I was confused as to which bias the authors were referring: risk of bias in systematic reviews versus bias in pulse oximetry readings.	
34	7	Well written with appropriate methods that are well explained. The tables are useful, though a figure could perhaps aid the reader in visually understanding the magnitude of differences better, as the main table has a lot of numeric data, perhaps akin to a forest plot in a meta analysis or systematic review.	Thank you for this comment.
35	7	Since the principal mechanistic argument is that skin pigmentation affects the wavelength of light being perceived by the photometer in the SpO2 probe, it would be helpful if a bit more discussion about how this was operationalized in these studies was done. For example, in the Shi paper that is referenced, did they use something semi-quantitative like the Fitzpatrick scale, or was based on the investigators in the study or something else? This would help clinicians who are familiar with the ways that skin tone is semi-quantitatively measured understand how that factored into the research that derived that SpO2 may be unreliable.	Thank you. We have added considerable discussion of this topic in the Discussion section.
36	7	page vi line 32: " an average of 150% compared with CO-oximetry in arterial blood (pooled mean bias = 1.54, 95% CI [0.99, 2.10])" wouldn't that be 54% overestimation? also CI crosses 1, is this significant?	Thank you. This was a typographical error on our part that has been corrected.
37	8	The report is quite thoughtful, rigorous, and extensive. It substantially exceeds any other synthesis yet available, and I hope it will be published. My compliments to the team for their care.	Thank you for this comment.
38	8	My major advice is clarifying the Table headings on page 9 -- moving between things where the null value is 0 and the null value is 1 was a little hard for me, given how often the Bias and Precision (for which the null value is 0) happened to have values in the "plausible aOR range of 1.xx". Similarly, in the footnote to that table, consider defining k.	Thank you for raising these points. We have simplified the table for clarity. *k* was previously defined in the table footnote.