

Pulse Oximetry for Monitoring Patients with COVID-19 at Home

Potential Pitfalls and Practical Guidance

Andrew M. Luks¹ and Erik R. Swenson^{1,2}

¹Division of Pulmonary, Critical Care and Sleep Medicine, University of Washington, Seattle, Washington; and ²Medical Service, VA Puget Sound Health Care System, Seattle, Washington

Abstract

During the ongoing coronavirus disease (COVID-19) pandemic, reports in social media and the lay press indicate that a subset of patients are presenting with severe hypoxemia in the absence of dyspnea, a problem unofficially referred to as “silent hypoxemia.” To decrease the risk of complications in such patients, one proposed solution has been to have those diagnosed with COVID-19 but not sick enough to warrant admission monitor their arterial oxygenation by pulse oximetry at home and present for care when they show evidence of hypoxemia. Though the ease of use and low cost of pulse oximetry makes this an attractive option for identifying problems at an early stage, there are important considerations with pulse oximetry about which patients and providers may not be aware that can interfere with successful implementation of such monitoring programs. Only a few independent studies have examined the

performance of pocket oximeters and smart phone–based systems, but the limited available data raise questions about their accuracy, particularly as saturation falls below 90%. There are also multiple sources of error in pulse oximetry that must be accounted for, including rapid fluctuations in measurements when the arterial oxygen pressure/tension falls on the steep portion of the dissociation curve, data acquisition problems when pulsatile blood flow is diminished, accuracy in the setting of severe hypoxemia, dyshemoglobinemias, and other problems. Recognition of these issues and careful counseling of patients about the proper means for measuring their oxygen saturation and when to seek assistance can help ensure successful implementation of needed monitoring programs.

Keywords: hypoxemia; COVID-19; pulse oximetry; oxygen saturation

(Received in original form May 4, 2020; accepted in final form June 10, 2020)

This article is open access and distributed under the terms of the Creative Commons Attribution Non-Commercial No Derivatives License 4.0 (<http://creativecommons.org/licenses/by-nc-nd/4.0/>). For commercial usage and reprints please contact Diane Gern (dgern@thoracic.org).

Correspondence and requests for reprints should be addressed to Andrew M. Luks, M.D., Professor of Medicine, Division of Pulmonary, Critical Care & Sleep Medicine, Harborview Medical Center and the University of Washington, 325 Ninth Avenue, Box 359762, Seattle, WA 98104. E-mail: aluks@uw.edu.

Ann Am Thorac Soc Vol 17, No 9, pp 1040–1046, Sep 2020

Copyright © 2020 by the American Thoracic Society

DOI: 10.1513/AnnalsATS.202005-418FR

Internet address: www.atsjournals.org

Anecdotal reports in the lay press, social media, and free open-access medicine from the beginning of the coronavirus disease (COVID-19) pandemic have highlighted a problem whereby patients are presenting for evaluation with clinically significant hypoxemia in the absence of dyspnea. Unofficially referred to as “silent hypoxemia,” this phenomenon poses significant risks to patients, as it may delay presentation to a point that their viral-mediated lung injury is far advanced, increasing the likelihood of complications such as unrecognized systemic organ dysfunction, severe periintubation hypoxemia, or cardiac arrest. One solution

that has been proposed for avoiding this problem is having patients diagnosed with COVID-19 who are not sick enough to warrant hospital admission be discharged from the emergency department or clinician’s office to monitor pulse oximetry at home on a regular basis (1). If the oxygen saturation falls below a specified threshold, they would then present for evaluation or call their medical provider for guidance. Though the ease of use, relatively low cost of many finger oximeters, and ubiquity of smart phones makes this an attractive option for monitoring patients and identifying problems at an early stage, there are important considerations with these

devices about which patients and providers may not be aware that have the potential to affect successful implementation of such monitoring programs.

The purpose of this review is to consider these issues in greater detail. After reviewing the types of available devices and their principles of operation, we discuss the main tools for assessing the accuracy of monitoring devices and examine the available data on the performance of inexpensive pulse oximeters and smart phone–based systems. We then review some potential pitfalls with pulse oximetry monitoring that could affect accuracy and implementation of a monitoring program

and conclude by providing practical guidance for patients and medical providers who decide to use these devices for home monitoring.

Types of Devices and Their Principles of Operation

All pulse oximeters provide an estimate of the arterial oxygen saturation, that is the percentage of hemoglobin binding sites occupied by oxygen, which, in turn, is a function of the arterial oxygen pressure/tension (P_{aO_2}), as defined by the hemoglobin-oxygen dissociation curve. The principles by which these estimates are derived varies based on the type of monitoring device. The output from these systems is saturation measured by the pulse oximeter (Sp_{O_2}), where the *p* refers to a pulse oximetry measurement, in contrast to a value measured directly from arterial blood by cooximetry, which is denoted by Sa_{O_2} . There are two general categories of tools for monitoring pulse oximetry.

Systems That Rely on Light Transmission through Cutaneous Tissue

The first category includes those that rely on transmission of light through cutaneous tissue, usually a finger or an ear lobe. This category encompasses traditional pulse oximeters, which range in size from monitors used in emergency departments, intensive care units, and operating rooms to smaller more portable units including tabletop units, handheld monitors, and finger or “pocket” oximeters. Given their small size and the fact that large numbers of models are available for as low as \$20–\$50, it is the pocket oximeters that are most appropriate for monitoring in this clinical setting. This category also includes systems like the Massimo iSp_{O_2} (Massimo Personal Health), which uses a traditional pulse oximeter finger probe connected to a smart phone through universal serial bus or lightning connectors, but the cost of such a system makes its use as part of a large monitoring program infeasible.

The systems described above estimate the oxygen saturation by shining two wavelengths of light (660 and 940 nm) from light-emitting diodes through a cutaneous vascular bed to a sensor on the other side of the tissue. Whereas in the hospital setting, the fingers and earlobes are the typical

monitoring sites, the pocket oximeters and phone-based systems utilize only the fingers. Because hemoglobin absorbs these wavelengths of light to different degrees depending on the extent to which binding sites are occupied, varying amounts of light make it through the cutaneous bed to a detector located opposite the emitter. After subtracting out the constant absorption by hemoglobin in capillary and venous blood as well as that by nonvascular structures, the device then uses an internal algorithm to convert the absorbance pattern into an estimate of the arterial oxygen saturation. Pulsatile arterial flow is critical to this measurement, as it is the only means by which the arterial signal can be identified and separated from the other factors that absorb the two wavelengths of light.

Systems That Rely on Reflected Light

A second category is the increasing number of systems that rely on reflected light, in which light reflects off hemoglobin and is detected by a sensor on the same surface as the emitter. This is the approach used by smart phone applications, such as Pulse Oximeter (digiDoc Technologies). On the surface, this category of systems is appealing for the purposes of home monitoring given the ubiquity of smart phones among the general population, but, as will be discussed below, significant concerns persist regarding their accuracy. Forehead reflectance oximeters, such as the Nellcor Sp_{O_2} Forehead Sensor (Medtronic), operate on the same principle and have a degree of accuracy comparable to traditional pulse oximeters, particularly in patients with poor digital perfusion (2, 3), but are not feasible for a home monitoring program given their much higher cost than smart phone-based systems.

Applications that utilize the smart phone in the absence of finger probes use the camera’s flash as the light source. Rather than traveling through the digit, the light is reflected off hemoglobin in arterial blood and then detected by the phone’s own camera. Proprietary internal algorithms are then used to convert the received signal to an estimate of the arterial oxygen saturation. This technique is challenging because the systems have lower signal-to-noise ratios than traditional pulse oximeters. Many phone cameras have filters that block near-infrared light to improve photograph quality, which limits the contrast in signals between oxygenated and deoxygenated

blood, a critical feature of an oximeter’s ability to estimate oxygen saturation (4). To overcome this issue, some applications equip the phone with additional illuminants (5) or use the phone’s own multicolored display rather than the flash for the purpose of illumination (4).

Evaluating the Accuracy of Monitoring Devices

The following three variables must be taken into consideration when evaluating the performance of any monitoring device: 1) accuracy, or how close the measured value is to the true value; 2) precision, or how close repeated measures of the value are to each other; and 3) bias, the difference between the average of the measurements made by a monitor and the true value. The ideal monitoring system will have high accuracy and precision but minimal bias.

The standard technique for evaluating the performance of monitoring systems is Bland-Altman analysis. Plain correlation analysis is insufficient for this purpose, as values measured by two devices may correlate well with each other but show poor agreement. In Bland-Altman analysis, the variable in question is measured simultaneously using the device being assessed and an accepted standard for the measurement, with the average of those two values plotted on the *x*-axis and the difference plotted on the *y*-axis. The mean difference indicates the bias, whereas the 95% confidence intervals around the bias, referred to as the level agreement, provide information about the precision (Figure 1A). The ideal monitoring system will have a bias close to zero and narrow levels of agreement. The difference between the measures should also remain relatively narrow across the range of possible values (Figures 1B and 1C).

The bias of pulse oximetry is technically assessed using a modified version of Bland-Altman Analysis. Because there is a true gold standard for measuring arterial oxygen saturation—cooximetry performed on an arterial blood gas sample—the horizontal axis can simply be the Sa_{O_2} measured by cooximetry, whereas the *y*-axis remains the difference between the Sp_{O_2} and the Sa_{O_2} . Typically, for reasons described further below, most bias plots for pulse oximeters have a nonzero slope because accuracy decreases at lower oxygen saturations. The

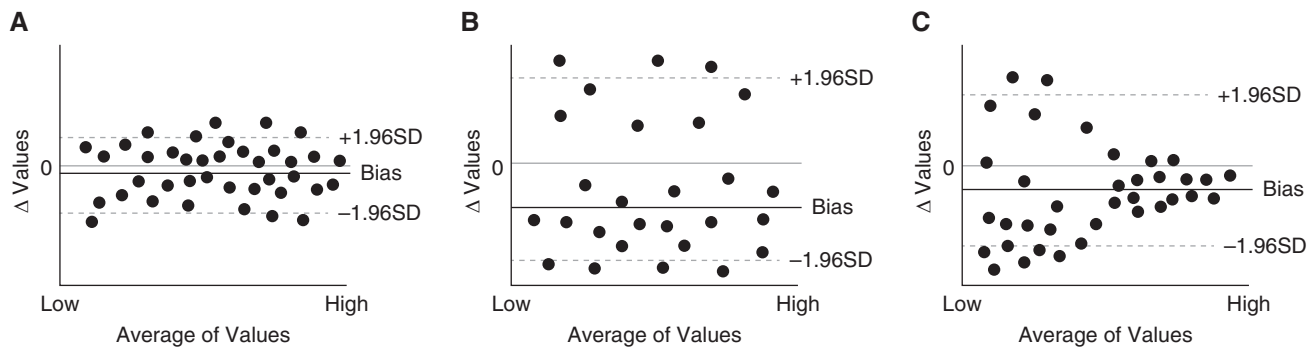


Figure 1. Examples of data plots from Bland-Altman analysis. (A) An example on an ideal monitoring device. The bias is close to zero and the levels of agreement are narrow. (B) An example of monitoring device with poor performance. Compared with A, the bias is further away from zero and the limits of agreement are wider. (C) Another example of a monitoring device with poor performance. The differences between the monitor and the gold standard are markedly larger at the low end of the measured values than at the high end. Increased spread in values at the low end of the spectrum of oxygen saturation is a known feature of pulse oximeters. SD = standard deviation.

key issue is how big the scatter of values becomes in this low range and at which degree of hypoxemia the scatter starts to increase.

The reporting of accuracy data for pulse oximeters in materials available to physicians and the public is more complex, however, than initially meets the eye. Product information documents generally indicate the accuracy as plus or minus a certain percent from the true value (e.g., $\pm 2\%$). On the surface, this would appear to indicate that the measured value falls within 0–2% of the true value in most patients. Under old U.S. Food and Drug Administration (FDA) guidelines, however, this value represented only one standard deviation from the bias, which was assumed to be zero (6). As a result, if the actual arterial oxygen saturation were 90%, a device with an accuracy of 3% might read values $< 87\%$ or $> 93\%$ one-third of the time. The FDA changed the reporting standards in 2013 and now requires manufactures to report the root mean square of the differences between the measured and actual value (A_{RMS}) (7). This variable combines the bias and precision into a single measure intended to reflect the accuracy of the devices and is calculated as follows:

$$A_{RMS} = \sqrt{[(\text{bias})^2 + (\text{precision})^2]}$$

The FDA currently requires that finger oximeters have an $A_{RMS} \leq 3.0$, whereas ear clip oximeters and forehead reflectance oximeters have an $A_{RMS} \leq 3.5\%$ (7). Although lower A_{RMS} values signify a more accurate device, a reported A_{RMS} of 3% does

not imply that the measured value is within 3% of the true value. In other words, this does not represent a 95% confidence interval or two standard deviations around the mean difference. This aspect of assessing accuracy is likely not apparent or as helpful to most users of these devices, as the precision's contribution to a dual component value cannot be ascertained.

Available Data on Pulse Oximeter Accuracy

Data on the accuracy of inexpensive pulse oximeters is limited for both stand-alone finger (i.e., “pocket”) oximeters and the phone-based products.

Stand-Alone Finger Oximeters

The amount of information regarding these parameters varies depending on the particular device. Among finger oximeters, information is reliably available only for the more expensive devices on the market ($> \$150$). This information, which can be difficult to locate in the product information, is generally limited to the A_{RMS} rather than all the parameters in a Bland-Altman analysis. For example, the Massimo MightySat (Massimo Personal Health) product information (8) reports an $A_{RMS} \pm 2\text{--}3\%$ when the oxygen saturation is $> 70\%$ depending on the adequacy of digital perfusion and the amount of motion, whereas the Nonin Onyx Vantage 9590 (Nonin Medical Inc.) product information (9) lists an A_{RMS} of $\pm 2\%$ in the same saturation range. Such data, however, are only variably available for the inexpensive

devices in the less-than-\$50 range that would likely form the basis for home monitoring. This information can sometimes be found on websites for the different products but is often lacking. When available, it is not always clear if the listed information is the A_{RMS} or the old method of reporting accuracy. To get around the A_{RMS} reporting requirements necessary for FDA approval, many pocket oximeters are marketed as nonmedical use (NMU) devices, whereas others are imported into this country from abroad and, despite labeling that suggests they have been cleared by the FDA, are completely untested.

For those devices that meet FDA standards, the data are generally based on calibration studies performed by the manufacturers in healthy volunteers and are not widely available for review. Such studies are only performed on those who are normothermic and who lack medical conditions such as peripheral vascular disease, which, as discussed below, could affect the accuracy of the device. These conditions may not hold for patients with COVID-19 or other diseases.

The solution to this issue is to perform studies in clinical patient populations, but, unfortunately, only a few studies in the literature independently examine the accuracy of finger oximeters in this setting. In the best study available on this issue, Lipnick and colleagues (10) compared six low-cost finger pulse oximeters in 22 healthy individuals to arterial saturation measured by cooximetry across a range of oxygen saturations from 70% to 100%. Overall, only two of the six devices met the International Organization for Standardization criteria for

accuracy ($A_{RMS} < 3\%$). Four of the six oximeters had large errors (-6.3% mean bias) when the true saturation was $< 80\%$. The A_{RMS} was $> 3.0\%$ in three of the six devices when the true saturation was 80–90% and $> 5.0\%$ in four of the six devices when the saturation was 70–80%. In all cases, the positive and negative bias increased at low oxygen saturations. Though this is common with all pulse oximetry systems for reasons discussed below, the changes in bias were larger than those typically seen with more expensive systems (10). This pattern has been seen in other studies. Smith and colleagues (11) compared a single pocket oximeter to a conventional bedside pulse oximeter in patients presenting for elective and emergent surgery and found agreement decreased in individuals with $SpO_2 < 93\%$ on the bedside monitor.

In one of the only studies to specifically examine NMU oximeters, Hudson and colleagues (12) compared oxygen saturation measurements from eight NMU devices with those from a single medical use oximeter or cooximetry and found that NMU devices had a positive predictive value of only 33% and a negative predictive value of 99% for identifying patients with hypoxemia (defined as an oxygen saturation $< 90\%$ on the medical use device or cooximetry). The authors claim that there were no clinically significant differences in measured values between the NMU devices and the medical use oximeter, but a review of their modified Bland-Altman analysis indicates that there were not an insignificant number of cases in which the NMU device yielded saturation values more than 5% below the medical device, even when the true saturation was $> 95\%$. Beyond the fact that the bias and precision were not reported, interpretation of the data in this study is limited by the fact that the authors pooled all of the NMU data, making it difficult to identify whether one brand performed better than another. In addition, only a few of the patients were hypoxemic, thereby limiting information about the performance of these devices when the oxygen saturation is, in fact, low.

A major challenge when considering these data is the fact that the number of pocket oximeters tested in these studies is limited relative to the number of devices on the market, which is increasing over time. Though one can find studies for particular devices, such as that of Ross and colleagues

(13) in which a single pocket oximeter, the Nonin Onyx 9500, was found to have acceptable agreement with saturation measured by an i-Stat (Abbot) at 2,100 m in elevation, an altitude sufficient to produce a degree of hypoxemia similar to that in patients with mild COVID-19, whether other commercially available inexpensive devices would meet such a standard is unknown.

Smart Phone Systems

As with the stand-alone finger oximeters, only a few studies have examined the accuracy of the smart phone systems. Tayfur and Afacan (14) compared saturation measurements using the Samsung Galaxy S8 with that measured by arterial blood gas and found a small bias of -0.7% with relatively narrow levels of agreement (-2.4% to $+1.1\%$). However, the majority of individuals in the study had oxygen saturation $> 93\%$, and when one looks more closely at the individuals whose oxygen saturation was $< 91\%$, the variability increased significantly. Jordan and colleagues (15) compared a standard emergency department oximeter to two iPhone camera-based applications, “Pulse Oximeter” and “Heart Rate and Pulse Oximeter” (LIJUN LIU) as well as an iPhone system using an external finger probe connected to the phone, iOx (Safe Heart), in patients presenting to an emergency department. None of the systems performed well, as the sensitivity for detecting hypoxemia, defined as an $SpO_2 < 94\%$ on the standard monitor, was 69%, 0%, and 7% for the iOx, Pulse Oximeter and Heart Rate, and Pulse Oximeter, respectively. Despite having better sensitivity, the iOx incorrectly classified 11% of patients as nonhypoxemic and 12% as hypoxemic. Although the bias was reasonable for each device, the levels of agreement were unacceptably high for all the devices, ranging from -8.9% to $+7.6\%$ in the case of the iOx system. Similar problems with very wide levels of agreement were demonstrated by Alexander and colleagues (16) who compared vital signs obtained by a standard, clinical pulse oximeter with two smart phone-based systems, Pulse Oximeter and Pulse Oximeter Pro, in healthy volunteers. Despite the fact that the mean saturation for the subjects was quite high ($98 \pm 2.5\%$) on the clinical monitor, the levels of agreement ranged from -5.1 to 7.6 for Pulse Oximeter and from -4.8% to 6.4% for Pulse Oximeter

Pro. As with the study by Jordan and colleagues, these limits of agreement indicate that the applications are both over- and underestimating the true saturation.

Though several of these studies were limited by the fact that the smart phone applications were not compared with saturation measured by arterial blood gas, when viewed together, the available data suggest that these systems have poor accuracy even in the presence of mild hypoxemia, which raises even further questions about how they would perform for patients with COVID-19 as they develop more significant degrees of hypoxemia (oxygen saturation $< 90\%$).

Sources of Error in Pulse Oximetry Monitoring

Providers encouraging patients to monitor oxygen saturation at home should also be aware of several sources of error in pulse oximetry monitoring that likely account for some of the accuracy issues noted above and may complicate efforts of patients to use them effectively as part of a monitoring program.

Position on the Hemoglobin-Oxygen Dissociation Curve

There are several important features of the hemoglobin-oxygen dissociation curve and its sigmoidal shape. The flat portion of the curve in the higher range of partial pressures prevents significant decreases in oxygen saturation as the oxygen pressure/tension (PO_2) begins to fall, whereas the steeper portion of the curve greatly facilitates the unloading of oxygen in the lungs and offloading in the tissues (Figure 2). It is this latter feature, however, that poses challenges when monitoring pulse oximetry to identify worsening acute lung disease. As lung injury progresses and gas exchange is progressively impaired, the PO_2 for many individuals may fall on the steep portion of the dissociation curve (20–60 mm Hg) where small changes in PO_2 can lead to marked fluctuations in the measured oxygen saturation. The likelihood of this will be increased for individuals living at or traveling to high altitude, as the PO_2 already lies closer to this range in the healthy state (Figure 2) (17). Beyond the natural variability of ventilation to fluctuate by 10–15% over periods of 5–10 minutes, ventilation may change, for example, because of talking, laughing or breath

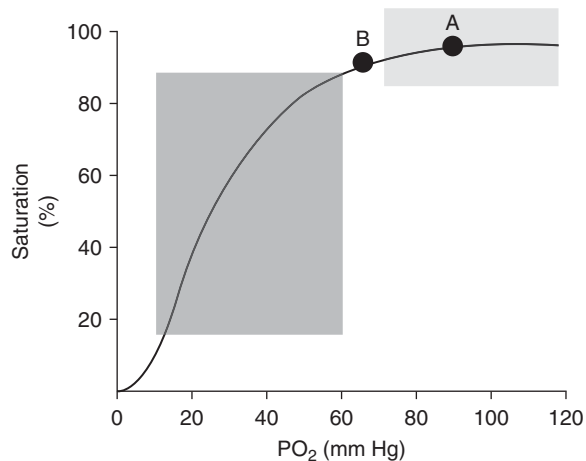


Figure 2. The hemoglobin-oxygen dissociation curve. The light-gray shaded area highlights the flat portion of the curve where the oxygen saturation remains relatively stable as the partial pressure of oxygen (P_{O_2}) falls. The dark-gray shaded area highlights the steeper portion of the curve where small changes in the P_{O_2} lead to large fluctuations of the oxygen saturation. Point A denotes the average P_{O_2} for a healthy person with normal lung function living at sea level, whereas Point B denotes the average P_{O_2} for a healthy person living at $\sim 1,600$ m in elevation. This position lies closer to the steeper portion of the dissociation curve than in an individual at sea level.

holding, or physical activity just prior to taking the measurement. As a result of such changes, the alveolar P_{O_2} will increase or decrease, thereby leading to changes in the $P_{a_{O_2}}$. The measured saturation may fluctuate significantly as a result, making it difficult to identify a stable, true value. Because of this problem, it is also important for the individual to not simply accept the first value provided by the oximeter upon putting it on the finger; the monitor should be observed for at least several minutes to identify the most frequently measured values.

The position of the hemoglobin-oxygen dissociation curve itself will also be altered by the patient's acid-base status, with acidemia shifting it rightward and alkalemia in the opposite direction. Early in the course of worsening lung function, many patients begin to hyperventilate to compensate for their falling $P_{a_{O_2}}$. The resulting respiratory alkalosis will shift the dissociation curve to the left such that the expected fall in oxygen saturation with a falling $P_{a_{O_2}}$ will be less or even prevented for a time.

Lack of Pulsatile Flow

On its way through the finger, the two wavelengths of light emitted by the pulse oximeter are not only absorbed by hemoglobin in arterial blood but also by hemoglobin in capillary and venous blood as well as the other soft tissues of the finger. To

limit the signal-to-noise ratio and provide an accurate estimate of the oxygen saturation, the pulse oximeter must be able to distinguish arterial blood from these other source of absorption, which it does by honing in on the pulsatile signal of arterial blood flow that is absent in these other spaces (18). Factors that limit pulsatile flow in the digits, including hypotension, use of vasoconstricting medications, and, most importantly for patients monitoring pulse oximetry at home, the presence of peripheral vascular disease or Raynaud's phenomenon, may decrease the signal-to-noise ratio and lead to erroneous readings. Given that peripheral vascular disease is associated with several diseases including diabetes and coronary artery disease, common comorbidities in patients who progress to more severe COVID-19 (19), this issue could limit the ability to use pulse oximetry monitoring in a cohort of people at risk for severe manifestations of COVID-19. In the acute care setting, this problem is overcome by using earlobe probes or forehead reflectance oximetry, but devices capable of estimating oxygen saturation in this manner are not as readily available or as inexpensive as the finger oximeters and, therefore, are not feasible for use on a wider basis. One way to overcome this problem in a home monitoring program would be to use oximeters that provide information about the strength of the pulse signal and

encourage users to only accept values with strong signals.

Accuracy in Patients With Hypoxemia

As noted above, pulse oximeters do not directly measure the oxygen saturation. Instead, they measure an absorbance ratio and make use of an internal algorithm to convert the measured ratio to an estimate of the arterial saturation. These algorithms have all been derived from experiments in healthy volunteers, in which absorbance ratios were measured under various hypoxic conditions and compared with simultaneous assessments of arterial oxygen saturation by arterial blood gas and cooximetry. For ethical reasons, volunteers could only be exposed to modest degrees of hypoxia, during which the oxygen saturation was about 75–80%. As a result, when the true saturation falls below this threshold, the pulse oximeter output is based on extrapolation from the data obtained at higher values rather than a direct comparison of pulse oximetry and cooximetry. Given this extrapolation, the accuracy of pulse oximeters may decrease significantly when the saturation is below 75% and may vary significantly between devices (18, 20). Whereas the reported A_{RMS} is 2–3% when the true saturation is above 75–80%, most manufactures do not even report the A_{RMS} for saturation values below 70%. This problem can be mitigated when monitoring patients with COVID-19 by setting oxygen saturation thresholds for seeking medical attention well above the 75–80% threshold, although it should be noted that accuracy information at any degree of hypoxemia is generally lacking for many of the inexpensive devices that can easily be purchased online.

Dyshemoglobinemias

Pulse oximeters and smart phone devices cannot distinguish carboxy- and methemoglobin from oxygenated and deoxygenated hemoglobin and, as a result, provide misleading information about the oxygen-carrying capacity in the setting of either carboxyhemoglobinemia or methemoglobinemia. Carboxyhemoglobinemia, which leads to overestimates of the arterial oxygen saturation, could conceivably be seen in individuals with heavy tobacco use or who are using gas grills or heaters in enclosed spaces. Methemoglobin is less likely to be seen in the general population,

although some drugs, including chloroquine (21) and antibacterial sulfonamides like dapson (22), can be problematic. However, the typical values measured by these devices when methemoglobin levels become clinically important always fall below <90% and would fortunately lead patients to present to care by any reasonable threshold of apparent developing hypoxemia.

Other Sources of Artifact

Other important sources of artifact include excessive motion of the digit as well as interference from ambient light (18, 23). Nail polish can also interfere with readings, with the affect varying based on the particular color of the polish (24, 25). Bias may also be increased in individuals with increased skin pigmentation, particularly when the true oxygen saturation is decreased (26, 27), an issue that would be of concern with use of these monitors in communities with large numbers of people of color. Individuals with markedly elevated body mass index are prone to dependent atelectasis and ventilation-perfusion mismatch in the sitting and recumbent position (28, 29), which may lower oxygen saturation below that expected because of the lung disease alone.

Practical Guidance

Although the use of finger oximeters for monitoring acute pulmonary issues outside the hospital has not previously been studied, they have been shown to be feasible for monitoring for people with various forms of stable, chronic pulmonary disease (30, 31). Although there are concerns regarding their accuracy and potential pitfalls that may affect the measured results, the ease of use and low cost of these devices, combined with the large burden of illness in COVID-19 and the risks of silent hypoxemia, make them a reasonable solution to monitor at-risk individuals.

Table 1. Recommendations for pulse oximetry monitoring

Monitoring Program
Use U.S. Food and Drug Administration–approved finger (i.e., “pocket”) oximeters rather than smart phone applications Recommend use of devices that provide information about pulse signal strength In patients with vascular disease, test pulse oximeter function prior to discharge Provide instructions to patients about best practices for use of the devices Translate instructions into languages appropriate for the community being served Readjust thresholds for seeking care in communities located at higher elevations
Patient Measurements
Make measurements indoors, at rest, and during quiet breathing Use the index or middle finger; avoid the toes or ear lobes Only accept values associated with a strong pulse signal Observe readings for 30–60 s to identify the most common value Measure and record values two to three times per day Remove nail polish from the finger on which measurements are made Warm cold extremities prior to measurement

Given the issues noted earlier, several steps can be instituted to decrease the risk of problems with pulse oximetry and ease implementation of home monitoring (Table 1). Hospital systems should rely only on FDA-approved stand-alone pocket oximeters rather than smart phone applications and utilize devices that provide information on the strength of the pulse signal. For all individuals, and particularly those with peripheral vascular disease, efforts should be made to test whether the oximeter generates valid and comparable values prior to discharging the person to home. Instructions should be provided to patients prior to starting home monitoring and efforts made to translate those instructions into languages appropriate for the communities being served.

When monitoring their saturation at home, individuals should be at rest, breathing quietly without talking for several minutes before taking a measurement. Measurements should be made indoors with the device seated securely on the middle or ring finger rather than an earlobe or toe. Nail polish should be removed from the finger on which measurements will be made.

Cold extremities should be warmed prior to measurement. Rather than accepting the first number that appears on the screen, the individual should observe the readings for 30–60 seconds to identify the most commonly measured value and should only accept values associated with a strong pulse signal. The values should be measured multiple times a day to accurately gauge trends in arterial oxygenation. Though specific numerical thresholds can be set for encouraging people to seek care, given issues with accuracy as individuals become more hypoxicemic, individuals should be encouraged to seek care if the overall trend in oxygen saturation over a period of time is downward, even if the measured values remain above a particular threshold. The thresholds for seeking care may need to be adjusted downward when monitoring is conducted in communities located at higher elevations. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

Acknowledgment: The authors thank Phillip Bickler, M.D., Ph.D., for his thoughtful feedback on the contents of this manuscript.

References

- Gandhi RT, Lynch JB, Del Rio C. Mild or moderate Covid-19. *N Engl J Med* [online ahead of print] 24 Apr 2020; DOI: 10.1056/NEJMcp2009249.
- Hodgson CL, Tuxen DV, Holland AE, Keating JL. Comparison of forehead Max-Fast pulse oximetry sensor with finger sensor at high positive end-expiratory pressure in adult patients with acute respiratory distress syndrome. *Anaesth Intensive Care* 2009;37: 953–960.
- Schallom L, Sona C, McSweeney M, Mazuski J. Comparison of forehead and digit oximetry in surgical/trauma patients at risk for decreased peripheral perfusion. *Heart Lung* 2007;36:188–194.
- Holz C, Ofek E. Doubling the signal quality of smartphone camera pulse oximetry using the display screen as a controllable selective light source. *Conf Proc IEEE Eng Med Biol Soc* 2018;2018:1–4.

- 5 Kanva AK, Sharma CJ, Deb S. Determination of SpO₂ and heart-rate using smartphone camera. Presented at the Proceedings of the International Conference on Control, Instrumentation, Energy and Communication (CIEC). 2014. pp. 237–241.
- 6 Masimo Corporation. Assessing the accuracy of pulse oximetry in true clinical settings. Irvine, CA: Masimo; 2007 [accessed 2020 May 22]. Available from: https://www.masimo.co.uk/siteassets/uk/documents/pdf/clinical-evidence/whitepapers/lab4709a_whitepapers_pulse_oximetry_accuracy.pdf.
- 7 U.S. Food & Drug Administration. Pulse oximeters-premarket notification submissions [510(k)s]: guidance for Industry and Food and Drug Administration staff. Rockville, MD: Food and Drug Administration; March 2013 [accessed 2020 May 22]. Available from: <https://www.fda.gov/regulatory-information/search-fda-guidance-documents/pulse-oximeters-premarket-notification-submissions-510ks-guidance-industry-and-food-and-drug>.
- 8 Masimo. MightySat Rx fingertip pulse oximeter. 2019 [accessed 2020 May 4]. Available from: https://www.masimo.com/siteassets/us/documents/pdf/plm-11294e_brochure_mightysat_rx_us.pdf.
- 9 Nonin. Onyx Vantage 9590 finger pulse oximeter. 2018 [accessed 2020 May 4]. Available from: <https://www.nonin.com/wp-content/uploads/2018/09/Operators-Manual-Onyx-Vantage-9590.pdf>.
- 10 Lipnick MS, Feiner JR, Au P, Bernstein M, Bickler PE. The accuracy of 6 inexpensive pulse oximeters not cleared by the Food and Drug Administration: the possible global public Health implications. *Anesth Analg* 2016;123:338–345.
- 11 Smith RN, Hofmeyr R. Perioperative comparison of the agreement between a portable fingertip pulse oximeter v. a conventional bedside pulse oximeter in adult patients (COMFORT trial). *S Afr Med J* 2019; 109:154–158.
- 12 Hudson AJ, Benjamin J, Jardeleza T, Bergstrom C, Cronin W, Mendoza M, et al. Clinical interpretation of peripheral pulse oximeters labeled “not for medical use”. *Ann Fam Med* 2018;16:552–554.
- 13 Ross EM, Matteucci MJ, Shepherd M, Barker M, Orr L. Measuring arterial oxygenation in a high altitude field environment: comparing portable pulse oximetry with blood gas analysis. *Wilderness Environ Med* 2013;24:112–117.
- 14 Tayfur İ, Afacan MA. Reliability of smartphone measurements of vital parameters: a prospective study using a reference method. *Am J Emerg Med* 2019;37:1527–1530.
- 15 Jordan TB, Meyers CL, Schrading WA, Donnelly JP. The utility of iPhone oximetry apps: a comparison with standard pulse oximetry measurement in the emergency department. *Am J Emerg Med* [online ahead of print] 15 Jul 2019; DOI: 10.1016/j.ajem.2019.07.020.
- 16 Alexander JC, Minhajuddin A, Joshi GP. Comparison of smartphone application-based vital sign monitors without external hardware versus those used in clinical practice: a prospective trial. *J Clin Monit Comput* 2017;31:825–831.
- 17 Luks AM, Swenson ER. Pulse oximetry at high altitude. *High Alt Med Biol* 2011;12:109–119.
- 18 Sinex JE. Pulse oximetry: principles and limitations. *Am J Emerg Med* 1999;17:59–67.
- 19 Du Y, Tu L, Zhu P, Mu M, Wang R, Yang P, et al. Clinical features of 85 fatal cases of COVID-19 from Wuhan: a retrospective observational study. *Am J Respir Crit Care Med* 2020;201:1372–1379.
- 20 Severinghaus JW, Naifeh KH, Koh SO. Errors in 14 pulse oximeters during profound hypoxia. *J Clin Monit* 1989;5:72–81.
- 21 Rizvi I, Zaman S, Zaidi N, Asif MS, Abdali N. Acute life-threatening methaemoglobinaemia following ingestion of chloroquine. *BMJ Case Rep* 2012;2012:bcr1220115383.
- 22 Barclay JA, Ziemba SE, Ibrahim RB. Dapsone-induced methemoglobinemia: a primer for clinicians. *Ann Pharmacother* 2011; 45:1103–1115.
- 23 Schnapp LM, Cohen NH. Pulse oximetry: uses and abuses. *Chest* 1990; 98:1244–1250.
- 24 Rubin AS. Nail polish color can affect pulse oximeter saturation. *Anesthesiology* 1988;68:825.
- 25 Sütçü Çiçek H, Gümüş S, Deniz Ö, Yıldız S, Açikel CH, Çakir E, et al. Effect of nail polish and henna on oxygen saturation determined by pulse oximetry in healthy young adult females. *Emerg Med J* 2011;28: 783–785.
- 26 Bickler PE, Feiner JR, Severinghaus JW. Effects of skin pigmentation on pulse oximeter accuracy at low saturation. *Anesthesiology* 2005;102: 715–719.
- 27 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. *Anesth Analg* 2007;105:S18–S23.
- 28 Holley HS, Milic-Emili J, Becklake MR, Bates DV. Regional distribution of pulmonary ventilation and perfusion in obesity. *J Clin Invest* 1967;46: 475–481.
- 29 Hurewitz AN, Susskind H, Harold WH. Obesity alters regional ventilation in lateral decubitus position. *J Appl Physiol (1985)* 1985;59:774–783.
- 30 Shah SA, Velardo C, Farmer A, Tarassenko L. Exacerbations in chronic obstructive pulmonary disease: identification and prediction using a digital health system. *J Med Internet Res* 2017;19:e69.
- 31 Bonnevie T, Gravier FE, Elkins M, Dupuis J, Prieur G, Combret Y, et al. People undertaking pulmonary rehabilitation are willing and able to provide accurate data via a remote pulse oximetry system: a multicentre observational study. *J Physiother* 2019;65:28–36.