Analysis of the Time-Dependent Relationship between Pulse Oximetry and Society

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Pulse oximetry is a painless, noninvasive method to measure blood oxygen saturation that is most commonly used to quickly assess a patient's health or to monitor the blood oxygen saturation of patients at risk of low blood oxygen levels due to lung and heart disorders (Yale Medicine, 2021). However, the method of calculating blood oxygen saturation based on the passage of light through the patient's skin, the usage of calibration data likely biased towards those of lighter skin, and studies revealing that pulse oximetry is less accurate for those of darker skin indicate that racial bias has been integrated into the design of the pulse oximeter (Open Critical Care, n.d.; Sjoding et al., 2020, p. 2477-2488; Yale Medicine, 2021).

It may appear that the pulse oximeter was designed with racial bias integrated into the calculation of blood oxygen saturation and always has been. However, an early pulse oximeter design developed by Hewlett-Packard in the 1970s was created for use in the healthcare system to measure blood oxygen saturation using a racially and ethnically unbiased method due to the societal pressures placed on Hewlett-Packard following the Civil Rights Movement, the movement that fought for the equality of Black Americans and other people of color in the United States (Anti-Defamation League, 2022; Merrick & Hayes, 1976, p. 4). If we continue to think that the pulse oximeter always had racial biases incorporated into its design, then we will not understand how its role and influence in society, specifically in the healthcare system, has evolved.

I argue that although the pulse oximeter was designed to determine a patient's blood oxygen saturation in a racially unbiased manner, over time pulse oximetry gained momentum, becoming routinely used in healthcare in a multitude of settings to identify different health conditions, ultimately shaping the healthcare system with racial bias integrated into the treatment of health conditions characterized by low blood oxygen saturation. Applying the concept of technological momentum, I will analyze how pulse oximetry gained momentum over time, becoming less shaped by society and increasingly beginning to shape it (Hughes, 1994, p. 148). To undertake this analysis, I will utilize evidence from papers detailing the design of pulse oximeters, studies using pulse oximetry as a diagnostic tool, and studies about the impact of pulse oximetry on healthcare for conditions characterized by low blood oxygen saturation.

Literature Review

A wealth of research exists analyzing the usage and accuracy of the pulse oximeter. These analyses typically focus on the limitations of pulse oximetry and the racial bias integrated into the design of the pulse oximeter, while occasionally acknowledging the past existence of the racially unbiased design by Hewlett-Packard. However, these works do not adequately consider how the relationship between society and the pulse oximeter design has evolved.

In *Pulse oximetry*, Joseph F. Kelleher details the history, technology, clinical uses, and limitations of the pulse oximeter, ultimately concluding that “pulse oximeters are sufficiently accurate and precise to monitor trends in oxygenation… however, they are not accurate enough for all applications.” These inaccuracies can be due to “machine limitations or to the shape of the oxyhemoglobin dissociation curve” (Kelleher, 1989, p. 56). While he does note that the “eight-wavelength Hewlett-Packard ear oximeter” existed, that black individuals have been found to have “slight variations in pulse oximeter error,” and pulse oximeter calibration based on healthy volunteers generally has not included individuals with dark pigmentation, there is no acknowledgment of Hewlett-Packard’s attempt to create a racially unbiased pulse oximeter or further discussion of racial bias integrated into the device (Kelleher, 1989, p. 38, 55).

Michael Sjoding et al. further explore the potential racial biases built into the design of the pulse oximeter by noting that the pulse oximeter was originally developed in populations lacking racial diversity and detailing the results of a 2020 study at the University of Michigan about occult hypoxemia in patients. Occult hypoxemia is characterized by low blood oxygen saturation despite normal pulse oximetry measurements, potentially resulting in delayed medical care when in critical condition. The study found that Black patients experienced occult hypoxemia almost three times more frequently than White patients, suggesting "that reliance on pulse oximetry to triage patients and adjust supplemental oxygen levels may place Black patients at increased risk for hypoxemia." Because pulse oximetry is used on a large scale, Sjoding et al. conclude that this may have major implications on medical decision-making, especially during the COVID-19 pandemic. Although this article further details the implications of racial biases in the pulse oximeter, it also does not relate the pulse oximeter design to societal influence (Sjoding et al., 2020, p. 2477-2488).

While there is much to be learned about the limitations of the pulse oximeter, there is also great value in thoroughly analyzing the time-dependent relationship between pulse oximetry and society. Existing research analyzes the technological aspects of the pulse oximeter in the healthcare system while failing to consider the societal relationship to the pulse oximeter.

Conceptual Framework

The evolution of the relationship between pulse oximetry and society over time can be methodically analyzed using the technological momentum framework, revealing how pulse oximetry gained momentum in healthcare over time and the implications of its momentum. Developed by Thomas P. Hughes, technological momentum can be thought of as the time-dependent relationship between the concepts of technological determinism and the social construction of technology (SCOT) (Hughes, 1994, p. 141-142).

The technological determinism model refers to the belief that technical artifacts, such as physical objects or software, shape society (Hughes, 1994, p. 141-142). Technological determinism has two main principles: “technology develops independently from society” and “when technology is taken up and used, it has powerful effects on the character of society” (Johnson, 2005, p. 1792). In contrast, SCOT was developed by Trevor Pinch and Wiebe Bijker and is the belief that the development and usage of technology are shaped by society (Hughes, 1994, p. 141-142). A major concept of SCOT is relevant social groups: relevant social groups are those who contribute to the development of technology and shape its meaning (Kline & Pinch, 1999, p. 113).

According to the technological momentum framework, technological systems are initially constructed by society, however, as the system gains momentum and societal influence, these systems become less shaped by society and begin to shape it. Therefore, as technological systems gain momentum and influence, they shift from SCOT to technological determinism (Hughes, 1994, p. 148-149). Characteristics of momentum include “acquired skill and knowledge, special-purpose machines and processes, enormous physical structures, and organizational bureaucracy” (Hughes, 1994, p. 146). Drawing on the technological momentum framework, the following section analyzes the pulse oximeter based on SCOT, the momentum gained over time, and technological determinism.

Analysis

The pulse oximeter was originally shaped by societal pressures for racial equality, modeling SCOT, then gained momentum and influence in society to the extent that it began to shape society around the racial biases integrated into its design, modeling technological determinism. The following paragraphs utilize the three key concepts of technological momentum, SCOT, momentum, and technological determinism, to detail the relationship between pulse oximetry and society at each stage in the technology's lifecycle, highlighting the shift of influence in the relationship over time.

Social Construction of Technology

The representation of the pulse oximeter initially by SCOT is evident in the first few pulse oximeter designs that were developed. To understand how the development and usage of the pulse oximeter were shaped by society, it is necessary to provide technical background on how the Hewlett-Packard pulse oximeter was designed to be racially unbiased and the societal context of its development. The ear pulse oximeter design by Hewlett-Packard was created to address the urgent need for "a noninjurious method of measuring blood oxygen on a continuous level" and was "based on the observation that oxygenated blood is much more transparent to red light than deoxygenated blood." However, calculating the blood oxygen saturation based on the transmission of blood proved difficult because the measurement would be impacted by the amount of blood flowing through the ear. This issue was solved by making "reference measurements at an infrared wavelength where absorbing abilities of oxygenated and deoxygenated bloods are the same," which results in a measurement "sensitive to the amount of blood" but not sensitive to the level of oxygenation. This method of measurement "made relative saturation measurements practical where it was desired to monitor short-term changes in the blood oxygen level," however, this method was not able to produce absolute measurements as skin pigmentation and other absorbers impacted the measurement (Merrick & Hayes, 1976, p. 2-3). At this point in the design process, Hewlett-Packard was already successful in creating a design that worked for the desired purpose of the pulse oximeter: to measure blood oxygen saturation. However, the issue of not producing absolute measurements due to skin pigmentation and other absorbers was deemed to be an issue that required addressing. Thus, this was a turning point in the design process of the ear pulse oximeter in which Hewlett-Packard decided that making the pulse oximeter racially unbiased was a priority.

To address this issue, a technique of calibrated measurements was proposed: blood would be removed from the ear by squeezing, and then light transmission through the ear would be measured at two wavelengths. The measured light absorbance could "be attributed to skin and underlying tissue pigments alone and… used to correct the readings obtained with blood present, achieving absolute calibration." This technique was not entirely feasible as multiple sources of error could be identified, leading to the technique of using eight wavelengths (Merrick & Hayes, 1976, p. 3). Hewlett-Packard found this method to be accurate regardless of skin pigmentation based on experiments with Black and Non-Black subjects (Merrick & Hayes, 1976, p. 4-7). This reveals that Hewlett-Packard not only decided that inaccurate readings across skin pigmentations were an issue but was a large enough issue that required multiple steps to address it until their tests determined that their method was accurate. Although the technique of calibrated measurements was not the final measurement technique used in their ear pulse oximeter design, even considering this as a measurement technique reveals that Hewlett-Packard prioritized accuracy across skin pigmentations over their device being more time efficient, as calibrating the device to each patient would be time-consuming. The efficiency of the device could also reflect poorly on the company if the calibration and usage of the device took a while, however, Hewlett-Packard also prioritized accuracy across skin pigmentations over a more efficient technique. The technique of eight wavelengths was the final technique that Hewlett-Packard decided on: creating this novel technique, designing the device, and testing the device on a range of subjects added more time to and increased the cost of the entire design process. Again, however, Hewlett-Packard prioritized the creation and testing of new designs to yield accurate measurements across skin pigmentations over a shorter and cheaper design process.

The prioritization of the ear pulse oximeter's accuracy for those of different skin pigmentations over the efficiency of the device, length of the design process, and cost of the design process can be connected to the societal context surrounding the device's fabrication. The 1976 pulse oximeter by Hewlett-Packard was designed throughout the Civil Rights Movement of the 1950s and 1960s that began due to the "need and desire for equality and freedom for African Americans and other people of color" (Anti-Defamation League, 2022). Inclusivity may not have been prioritized in Hewlett-Packard's pulse oximeter design as much as it was if not for the Civil Rights Movement co-occurring with the design's development.

The key concept of SCOT in technological momentum is that technological artifacts are initially shaped by society until the technology gains momentum (Hughes, 1994, p. 148). Although Hewlett-Packard did not produce the original pulse oximeter design, their design was one of the first few pulse oximeter designs so the technological system of pulse oximetry had not yet gained momentum. Therefore, the technological system was still malleable to societal influence, like that of the Civil Rights Movement. Society at the time of the design's development also consisted of relevant social groups that contributed to the development and meaning of a technology (Hughes, 1994, p. 141-142). The relevant social groups include the activists participating in the Civil Rights Movement, potential buyers, and those working on the design. Because of civil rights activists, the fight for racial equality could not be ignored by society. This suggests that Hewlett-Packard's immense efforts to be inclusive were related to the Civil Rights Movement. Making the pulse oximeter measurements independent of skin pigmentation was extremely important to Hewlett-Packard, evident by the effort they put in to create and test new, inclusive techniques that made their design more complicated. Furthermore, the pulse oximeter design was initially malleable to societal pressures for racial equality.

Now, some might argue that just because the Hewlett-Packard pulse oximeter was designed throughout the Civil Rights Movement, it does not mean that the pulse oximeter system was originally malleable to societal pressures and that it can be represented by SCOT. However, Hewlett-Packard also designed the pulse oximeter to "[study] an astronaut's physiological response to forces generated in a centrifuge" (Merrick & Hayes, 1976, p. 4). This is significant because this means Hewlett-Packard's pulse oximeter design was also influenced by the pressures placed on NASA. The space race between the U.S. and the Soviet Union was occurring throughout the 1960s, with the Soviets winning the race. Thus, President John F. Kennedy pledged that "the U.S. would land a man on the moon before" the end of the decade. This was exciting for many Americans, however, many Black Americans were frustrated by the amount of money spent on the space race and not on the advancement of civil rights. In addition to the frustrations expressed by Black Americans, the Soviets called attention "to the racial inequality in the U.S. to show the superiority of the Communist system." To counteract the Soviet Union and attempt to alleviate frustrations in the Black community, pressures to send the first Black American into space rose (Hazel, 2022). This is significant because the same societal pressure for equality placed on Hewlett-Packard during the Civil Rights Movement was also placed on one of the consumers of the device, NASA. It can be stated that the extensive efforts by Hewlett-Packard to create a racially unbiased pulse oximeter can ultimately be attributed to societal pressures at the time, showing that the pulse oximeter initially was shaped by society and, therefore, could be represented by SCOT.

<u>Momentum</u>

After the original pulse oximeter design was shaped by society, the pulse oximeter gained momentum and influence in society, demonstrated by its applicability and ease of use in a wide range of settings and its role in identifying different health conditions. One way that the pulse oximeter gained momentum, following the technological momentum framework, was through "acquired skill and knowledge" contributing to the improvement of the technology (Hughes, 1994, p. 146). Cardiovascular malformations are the most common type of congenital malformation; malformations present from birth, however, a significant number of malformations, like duct-dependent circulation, "are not detected by routine neonatal examination." Babies with duct-dependent circulation are at risk of early discharge after birth because "their condition may not be apparent at an early discharge examination." This leads to about 10-30% of babies dying from this condition without a diagnosis until after an autopsy. Infant screening using the pulse oximeter offers a potential solution to this issue, as cardiovascular malformations can cause low blood oxygen saturation. The study found that "introducing pulse oximetry screening before discharge improved [the] total detection rate of duct-dependent circulation to 92%," meaning that "92% of all babies with duct-dependent circulation were diagnosed before leaving [the] hospital." This proportion was higher than "the detection rate of blind physical examination alone," which was found to be 62.5%, and significantly higher than the detection rate of other regions that did not utilize pulse oximetry screening. Additionally, the survival rate of babies with duct-dependent heart disease was higher when the condition was detected in the hospital, with 0.9% mortality, than when babies were discharged undiagnosed, with 14.8% mortality (de-Wahl et al., 2009, p. 1, 7, 8).

Note that without the detection of duct-dependent circulation using pulse oximetry screening, the detection of the disease before leaving the hospital and the survival rate of those who left the hospital without detection were significantly lower. In addition, pulse oximetry screening greatly increased the rate of detection of the condition before leaving the hospital, as compared to detection by physical examination alone (de-Wahl et al., 2009, p. 7-8). This suggests that, without pulse oximetry, the condition would have remained widely underdiagnosed and the health outcomes would have remained worse due to a lack of detection of the condition. As a result, it appears to be beneficial for neonatal health to implement the usage of neonatal pulse oximetry screening on a widespread level. With the implementation of pulse oximetry screening into regular neonatal care, the healthcare system could significantly improve health outcomes related to duct-dependent circulation. Furthermore, pulse oximetry can be identified as a technology that can greatly improve the quality of life or save the lives of those born with this condition. The introduction of pulse oximetry into society and the healthcare system resulted in acquired skills and knowledge for the identification of health conditions, such as duct-dependent circulation, allowing the technological system of pulse oximetry to gain momentum and become known as a life-saving technology.

Another way that the pulse oximeter has gained momentum in society is through "special-purpose processes" (Hughes, 1994, p. 146). An issue in the developing pulse oximetry technology was that motion and poor tissue perfusion, referring to poor blood flow, limited the accuracy of continuous monitoring using the pulse oximeter. Measurement error due to motion was partially caused by the "widespread implementation of a theoretical pulse oximetry model which assumes that arterial blood is the only light-absorbing pulsatile component in the optical path" (Goldman et al., 2000, p. 475). During motion, blood in the veins and "other non-arterial absorptive substances generate a pulsatile optical signal as they move and attenuate the transmitted light" thus adding components that contribute to the saturation measurement (Goldman et al., 2000, p. 477). This results in a high rate of false alarms due to motion-induced measurement errors that not only cause "nuisance interruptions," but desensitization to true emergencies (Goldman et al., 2000, p. 481-482). Motion and poor tissue perfusion reducing the accuracy of the pulse oximeter is important because it limits the range of scenarios in which the usage of the pulse oximeter is accurate and complicates the usage of the pulse oximeter for its intended purpose. Masimo, a company that develops medical technology, designed Signal Extraction Technology (SET) as a solution to this issue. In contrast to previous pulse oximetry methods that use "the ratio of transmitted pulsatile red and infrared light" to calculate oxygen saturation, SET "uses a new conceptual model of light absorption for pulse oximetry and employs the discrete saturation transform (DST) to isolate individual saturation components in the optical pathway" (Goldman et al., 2000, p. 475). As a result of the SET technology, the "nuisance interruptions" due to inaccurate readings resulting from motion or poor tissue perfusion could be minimized (Goldman et al., 2000, p. 481-482).

Note that continuous pulse oximetry monitoring was previously inaccurate due to a theoretical assumption that did not apply when a patient was in motion. However, when this incorrect theoretical assumption was realized, a method was developed to remedy this issue. The use of SET pulse oximetry streamlined the process of continuous monitoring of blood oxygen saturation, avoiding false alarms and producing a feasible method of continuous monitoring. This suggests that SET improved the design and use of the pulse oximeter for continuous monitoring and, therefore, improved the overall efficiency and effectiveness of the pulse oximeter in the healthcare system. The range of situations in which the pulse oximeter produced accurate measurements was widened, resulting in increased pulse oximetry usage in healthcare and increased societal influence of the pulse oximeter. The creation and usage of the special-purpose process of signal extraction technology (SET) in pulse oximetry allowed the technological system to gain further momentum in healthcare by increasing the accuracy of continuous monitoring of blood oxygen saturation and, therefore, decreasing the pulse oximeter's limitations of use.

Technological Determinism

Lastly, after gaining momentum, the pulse oximeter is now able to shape society, as evident by the usage of the pulse oximeter throughout the COVID-19 pandemic. A study by JAMA Internal Medicine details the implications of racial and ethnic biases in pulse oximetry in the identification of treatment eligibility of patients with COVID-19. Pulse oximetry has "played a prominent role in guiding triage and therapy" throughout the pandemic, as hospitalization and therapy recommendations are commonly based on blood oxygen saturation values. The accuracy of pulse oximetry during the pandemic is essential because hospitalization and therapy recommendations can have a great impact on a patient's health outcomes. This study revealed an association between racial and ethnic biases in the accuracy of pulse oximetry and rates of occult hypoxemia, a condition characterized by low blood oxygen saturation despite normal pulse oximetry measurements, in Asian, Black, and non-Black Hispanic patients with COVID-19.

Overestimating blood oxygen saturation in the occult hypoxia condition may lead to "premature [de-escalation] of therapies or hospital discharge, or could be associated with the delay or withholding of therapies that shorten the disease course, slow progression, or reduce mortality." For example, Black patients were shown to have a "median delay of 1.0 hour" in the recognition of treatment eligibility. This disparity in healthcare "may contribute to worse outcomes among Black and Hispanic patients with COVID-19" (Fawzy, 2022, p. 730-731). Thus, inaccurate pulse oximetry readings can have a great impact on the quality of healthcare that minorities and people of color receive.

The pulse oximeter strongly influences the identification of health conditions characterized by low blood oxygen saturation, as it is shown across multiple studies to increase the time of recognition for treatment eligibility throughout the COVID-19 pandemic (Fawzy, 2022, p. 730). This suggests that the pulse oximeter contributes to racial and ethnic biases in the treatment of COVID-19. Although the pandemic has highlighted social and health disparities resulting in a push for racial justice, the racially biased pulse oximeter is still widely used in healthcare. Thus, pulse oximeter technology has developed independently from society, following the first principle of technological determinism. This also reveals that the pulse oximeter follows the second principle of technological determinism: "when technology is taken up and used, it has powerful effects on the character of society" (Johnson, 2005, p. 1792). Because the pulse oximeter has determined the quality of widespread healthcare for racial and ethnic minorities throughout the pandemic, it has had a great impact on the character of the healthcare system. Because the usage of the pulse oximeter in healthcare follows the two main principles of technological determinism, it can be stated that the pulse oximeter technology now follows the technological determinism model, reaching a point in its lifetime that it is now the shaper of society, specifically the shaper of healthcare for conditions characterized by low blood oxygen saturation.

Conclusion

Although one of the original pulse oximeter designs deliberately incorporated methods to measure blood oxygen saturation in a racially unbiased manner, pulse oximetry gained momentum in society, to the extent that it is now routinely used in a range of scenarios and in the identification of different health conditions, resulting in the treatment of health conditions characterized by low blood oxygen saturation in a racially biased manner. This can be shown by the initial design of the pulse oximeter by Hewlett-Packard which took measures to avoid racial bias, the widening range of and increasing rates of diagnosis using the pulse oximeter, and the current usage and impact of the pulse oximeter in society during COVID-19. As the technological momentum framework details, the relationship between the pulse oximeter and racial biases in society does initially model SCOT and, after the technological system gains momentum, models technological determinism.

The pulse oximeter is likely one of many technological artifacts within the healthcare system that incorporates racial biases or another type of bias into its design. It is not always evident that technological artifacts have bias integrated into their design and the potential consequences of this bias are difficult to predict. While it may be challenging to question others' work or test the accuracy of all medical devices, a good place to start is considering how commonly used devices may incorporate bias. Identifying bias in medical devices, especially those that have the potential to be life-saving, is essential to improve healthcare for those impacted by these biases.

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