J Anesth (2003) 17:216–217
DOI 10.1007/s00540-003-0200-x

Journal of
Anesthesia

Do we really know how pulse oximetry works?

Katsuyuki Miyasaka

Department of Anesthesia and ICU, National Childrens' Medical Center, National Center for Child Health and Development, 2-10-1 Okura, Setagaya, Tokyo 157-8535, Japan

The two articles on pulse oximetry in this issue of the *Journal of Anesthesia*, by Aoyagi [1] and Suwa [2], brought to mind the work of Mr. Koichi Tanaka, the 2002 Nobel Laureate in Chemistry. This work was brought to mind not only because I believe that pulse oximetry is an invention worthy of a Nobel Prize and not because Dr. Aoyagi once worked for Shimadzu (the company Mr. Tanaka works for), but because, as Dr. Suwa [2] points out, their work did not receive much attention in Japan before being discovered by the foreign community. While pulse oximetry is not new, it faces a new frontier, which requires our focused attention. We must learn from the past and face the future with enthusiasm.

Over 30 years have passed since the invention of pulse oximetry by Aoyagi et al. [3], but there still remains an important question to be answered. The question is, how do pulse oximeters really work? This may sound odd to many readers, as pulse oximeters are used so widely and we know how they work in general, but the reality is that the details are still somewhat mysterious. In this issue of the *Journal of Anesthesia*, Aoyagi mounts a convincing argument regarding the question—which has long been denied much-deserved attention—of what is the theory behind pulse oximetry?

There is no doubt that pulse oximetry has made a significant contribution to the safety of anesthesia and that it has saved tens of thousands of patients from morbidity and mortality associated with anesthesia. In fact, its application has now expanded well beyond the operating room. Pulse oximetry has been the subject of many basic and clinical studies, but even though it is still an exceptional clinical monitoring device, it has no bench calibration method. The main reason for this is the lack of a theoretical understanding of pulse oximetry [4].

Pressure transducers have mercury manometers as their gold standard, and blood gas analyzers have standard gases for calibration. But with pulse oximeters, all we can do is to attach a pulse oximeter probe to our own fingers and assume its proper calibration by observing likely numbers. Although this seems to be a practical method and satisfies most clinical needs, it is a very crude and nonscientific method of calibration. Not only do we not know the exact arterial hemoglobin oxygen saturation (S_{pO_2}) value at the time of calibration, but even if we did, it would at best be a quasi-one-point calibration, as we cannot make S_{pO_2} go to near zero and still sustain life. It would be impossible to know the calibration slope of the pulse oximeter involved, and thus there is no way to assume that lower values of S_{pO_2} are reliable.

Why is it that pulse oximeters function reasonably well without proper calibration? We have simply been fortunate. The two very basic assumptions we have made—that there are only two variables of hemoglobin in the blood (oxy- and deoxy-) and that all pulsation is arterial blood and nothing else—have worked extremely well. Without a proper bench calibration method, pulse oximeters are being empirically calibrated against the arterial blood gas data of healthy adult human volunteers. These factory calibrations have worked well over a wide range of clinical conditions.

It is now obvious that this simplified approach has been a key element in the success of pulse oximetry for clinical monitoring. But, what if pulse oximeters displayed up to 120% and users had to precisely calibrate to 100% upon each use? What if pulse oximeters blacked out every time the device could not show the so-called true S_{pO_2} values? While engineers and basic researchers might be satisfied by such a logical approach, the majority of clinicians would not.

Address correspondence to: K. Miyasaka
Received: September 17, 2003

There should be a clear distinction between devices used for precision measurement and devices used for monitoring.

Precision is of paramount importance in any measurement device, but for patient monitoring, precision must be kept within the practical limits of the costs of invasiveness and response time. Due to the nature of indirect measurements and response time, there is more clinical value with less invasiveness and more continuity of method and data display, even if accuracy may be sacrificed. We all know that it is often the case that having some data is better than having none.

The pulse oximeters developed in Japan in the 1970s for clinical use were based on very logical, but nonclinical grounds. Even slight coughing or minute body movements caused display blackouts and showed no indication of where we were in the ball game. This behavior was considered honest to the data by the researchers, but the concept of clinical usefulness was greatly lacking. It was New et al. and the Nellcor group who successfully converted the concept of pulse oximetry into a clinically useful patient monitoring device [3].

Years have passed and we now realize that the two very basic assumptions we made can no longer stand firm [4]. While it is true that we can assume only two variables, there are many other hemoglobins to be considered. The existence of carboxyhemoglobin and methoxyhemoglobin are good examples of hemoglobins with clinical importance. The presence of hemoglobin F, which does not affect Sp_{O_2} measurement very much, may affect the interpretation of Sp_{O_2} values, especially in premature infants.

In addition, hemoglobins in arterial blood do not rest in plain glass test cuvettes in a free form in which the optical characteristics of light absorption and scattering are well defined. In the real world, hemoglobins are in red cells, suspended in plasma, and surrounded by other substances and various tissues. Optical characteristics in these conditions should be taken into account [4].

While it is true that arterial pulsation is large in healthy adults, venous pulsation may become more prominent in situations with lower perfusion or massive body movement. In fact, the very limited performance of pulse oximetry under these conditions has been the major clinical problem associated with its use [5]. The effort to overcome this problem resulted in sound competition in the industry, and, while several innovative technologies, such as the Masimo SET (Signal Extraction Technology, Masimo, Irvine, CA), have emerged and are being used rather successfully, they can be considered only as patch reinforcements of conventional two-wavelength pulse oximetry [6].

In this issue of the *Journal of Anesthesia*, Aoyagi [1] has summarized his very appealing views on the theory of pulse oximetry based on his past studies and thinking. In short, he applied and expanded Shuster's theory of scattering and absorption in opaque substances and included the effects of the presence and counterpulsation of tissues in surrounding vessels, which had largely been neglected in the past. With his theory, at least three wavelengths are needed to solve the equation of three variables. Five wavelengths should eliminate motion artifacts. He claims that his theory will improve accuracy, eliminate motion artifacts, and lay the ground for future expansion of noninvasive pulse oximetry technologies.

We now realize that two-wavelength pulse oximeters are far from perfect. Will it be possible to develop a practical pulse oximeter using Aoyagi's new theory? At present, there is not enough convincing data to support his equations, nor are there industrial incentives to move forward with the addition of more wavelengths, because this inevitably seems to increase the cost of production. To realize the possibilities of this new theory, we clinicians have to let our voices be heard and act now for patients in need. As Dr. Suwa [2] clearly illustrated in his article, the Japanese medical community has a history of not supporting ground-breaking world class inventions, and we should not repeat this history.

Twenty years ago, pulse oximeters cost over $30000, but now they cost a fraction of that. With a developed theory, the expansion of the market, and amazing advances in digital technology, even a five wavelength pulse oximeter is a realistic possibility. We may then realize a pulse oximeter with more reliability and versatility. The future of this promising technology rests both with the active voices of clinicians who need it and the adaptable response of the industry that will develop it.

References

1. Aoyagi T (2003) Pulse oximetry: its invention, theory, and future. J Anesth 17:259–266
2. Suwa K (2003) Pulse oximeters: personal recollections of the past and hopes for the future. J Anesth 17:267–269
3. Severinghaus JW, Honda Y (1987) History of blood gas analysis. VII. Pulse oximetry. J Clin Monit 3:135–138
4. Aoyagi T, Miyasaka K (2002) The theory and applications of pulse spectrophotometry. Anesth Analg 94 (1 Suppl):S93–S95
5. Miyasaka K (2002) Pulse oximetry in the management of children in the PICU. Anesth Analg 94 (1 Suppl):S44–S46
6. Dumas C, Wahr JA, Tremper KK (1996) Clinical evaluation of a prototype motion artifact resistant pulse oximeter in the recovery room. Anesth Analg 83:269–272