Knowing Your Monitoring Equipment

PULSE OXIMETRY: ANALYSIS OF THEORY, TECHNOLOGY, AND PRACTICE
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ABSTRACT. Interest in two-wavelength classic, that is, non-pulse, oximetry began early in the 20th century. Noninvasive in vivo measurements of oxygen saturation showed promise, but the methods were beset by several problems. The pulse oximetry technique, by focusing on the pulsatile arterial component, neatly circumvented many of the problems of the classic nonpulse arterial approach. Today's pulse oximeter owes a good measure of its success to the technologic advances in light emission and detection and the ready availability of microcomputers and their software. Many clinicians have recognized how valuable the assessment of the patient's oxygenation in real time can be. This appreciation has propelled the use of pulse oximeters into many clinical fields, as well as nonclinical fields such as sports training and aviation. Understanding how and what pulse oximetry measures, how pulse oximetry data compare with data derived from laboratory analysis, and how the pulse oximeter responds to dyshemoglobins, dyes, and other interfering conditions must be understood for the correct application and interpretation of this revolutionary monitor.


THEORY

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Light was, therefore, recognized to contain all colors of the visible spectrum of electromagnetic energy. Measurements of electromagnetic vibrations are frequency, expressed in hertz (Hz) (1 Hz = one cycle per second) and wavelength, expressed in nanometers (nm) (1 nm = one thousand millionth \(1 \times 10^{-9}\) of 1 m). Red light, as used in PULSE OXIMETRY, can be measured at a frequency of \(4.3 \times 10^{14}\) Hz or a wavelength of 660 nm. The nanometer, yielding numbers much easier to deal with, is the unit typically used when discussing this part of the spectrum.

Newton’s theory fostered the techniques of spectral analysis—that is, the ability to detect elemental composition by defining the unique light absorption “fingerprints.” A major theoretic statement in early laboratory spectral analysis was the Beer-Lambert (or Bouguet’s) law. Simply, this law states that the concentration of absorbant in solution can be determined as a mathematical function of the amount of light transmitted through the solution, providing that the intensity of incident light, the path length, and the EXTINCTION CO-

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EFFICIENT of a substance at a particular wavelength are known. The absorbance of light by hemoglobin (Hb) and oxyhemoglobin (HbO2) as a function of wavelength is shown in Figure 1. The absorbance or, more correctly, extinction of HbO2 at the red wavelengths (650 to 750 nm) is less than that for Hb. Hence, HbO2 is more transparent to red light than Hb is. Figure 1 also shows that the reverse is true, to a lesser degree, in the infrared region (900 to 1,000 nm). Research led by Nicolai, Kramer, Elam, Matthes, Millikan, and Wood in the early to mid-1900s sought ways to apply these facts to determine the HbO2 concentration, or arterial blood oxygen saturation (SaO2) [1].

Complex and numerous problems of applying the Beer-Lambert law to in vivo analysis brought the development of two-wavelength, in vivo oximetry to a halt during the 1950s. Why the Beer-Lambert law was not totally effective becomes apparent when we examine how light behaves in this application.

As the law of conservation of energy states, energy cannot be “created or destroyed”—and this applies to light energy. For the Beer-Lambert law to work, all light in the system should be accounted for, that is, incident light = light transmitted + light absorbed. This can work in a very controlled experiment with relatively short path lengths. Experiments with human tissue present several obstacles. Consider: incident light = light transmitted + light absorbed + light scattered + light reflected. On human subjects:

- Light is scattered by the skin surface, tissue, muscle, bone, and blood.
- Light is absorbed by tissue components other than the blood and absorption is also dependent on pigmentation and thickness of the test site.
- The blood is a nonhomogeneous liquid capable of nonlinear absorption of light, particularly as hematocrit varies.

The classic oximetry (that is, nonpulse, two-wavelength, in vivo oximetry) could not deal effectively with all the variables.

**Evoluation of Pulse Oximetry**

The prominent forerunner to the pulse oximeter was the Hewlett-Packard ear oximeter (HP 47201A), which used a tour de force of technology to solve the problems found in the two-wavelength approach. By using eight wavelengths (from 650 to 1,050 nm), this unit compensated for all the effects of “skin pigmentation, ear thickness, or earprobe motion” [2]. Featuring precalibration, ear vascularization via heat, and a fixed path length, this unit solved many of the problems that plagued earlier devices [3].

Clinical accuracy tests pointed to the ear oximeter as an acceptable device that was a boon to the pulmonologists and sleep researchers of the mid-1970s. Although it was thought to be the “gold standard” for oximeters, recent tests at low saturations uncovered unstable performance below an arterial oxygen saturation (SaO2) of 70%, and its inability to deal with carboxyhemoglobin (HbCO) is documented [4,5].

A major advance came with the recognition that the pulsatile nature of the arterial blood can be exploited in oximetry. Pulse oximetry uses the physiologic activity of the cardiac pulse as the basis for a system to determine SaO2. The idea of using the cardiac rhythm as a “filter” for in vivo measurement was first attempted in Japan. This new concept took commercial form in the Mochida Oximet (eventually Minolta), the first pulse oximeter manufactured and marketed. This unit relied on analog electrical circuitry and had bulky fiberoptic cables similar to those of the Hewlett-Packard ear oximeter. Its performance was nearly acceptable clinically, with marginal accuracy, “±5% of that obtained from the blood gas method” [6], and it exhibited some problems with artifacts: “The measurement is interrupted when the fingertip changes its position against the light beam. This frequently occurs when the patient is shivering” [6]. As with classic oximetry, early pulse oximetry had to contend with limitations inherent in the hardware.