Commentary

Noninvasive Monitoring of Oxygenation and Ventilation
40 Years in Development

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In 1986 continuous monitoring of oxygenation with pulse oximetry and ventilation with the capnometer became a standard in operating rooms.[1] Over the next few years these devices have been applied in intensive care units as well. Although widespread use of these monitors did not begin until the 1980s, their development started 40 years earlier. It was clear that continuous noninvasive monitors that ensure oxygenation, ventilation, and perfusion would be extremely useful for critically ill patients, but it took about 40 years to overcome technical limitations in the design of these oximeters and capnometers.

Although many persons have contributed to the development of noninvasive oximetry, there are several who have made particularly significant contributions.[2] During World War II, Glen Alan Millikan was working on a method of assessing the oxygenation of pilots as they flew to higher elevations. The Germans were the first to institute compressed oxygen for high-altitude flying. It was important that we understood the effects of altitude on oxygenation and psychomotor performance. Millikan was the son of the Nobel Prize-winning physicist who was the cofounder of the California Institute of Technology in Pasadena. He realized from work completed in England and Europe that the intensity of light transmitted from transilluminated tissue changed with the oxygenation of the blood. He therefore developed an optical device, an "oximeter," that illuminated the tissues of the ear. The light source was placed on one side of the pinna and a detector on the other. He was hoping to determine the changes in arterial blood oxygenation by measuring the change of light absorbance by blood as it passed through the tissues. Unfortunately, the light was absorbed by multiple substances within the ear in addition to the blood. To eliminate the effect of light absorbance by the skin, cartilage, and other nonblood tissues, he first compressed the ear by inflating a cuff around the ear to eliminate the blood. He then used the light absorbance of this bloodless ear tissue as the 0 point. The cuff was deflated, allowing blood to return to the ear. A second problem was that not only arterial but venous and capillary blood contributed to the light absorbance. To eliminate this effect, he heated his device to 44°C, thereby arterializing all the blood beneath the device. He had the subject breathe oxygen to fully saturate the hemoglobin, producing a second calibration point of 100% saturation. The device would then follow changes in saturation with fair accuracy. Unfortunately, Millikan died in a mountain climbing accident at the age of 41.

After the war Millikan-type ear oximeters were used in physiologic research. A classic study was conducted by Comroe and Botelho in 1947.[3] These investigators tried to assess the ability of trained clinicians to detect cyanosis in humans. In all, 7,204 observations were made by medical students and medical staff while subjects breathed varying levels of inspired oxygen concentration. It was found that cyanosis could not be detected consistently until the saturation was below 80% and that multiple subjects were considered to be cyanotic at saturations in the 90s. This study concluded that even in a controlled setting, the clinical detection of cyanosis is extremely unreliable. It was also estimated that it requires about 5 grams of desaturated hemoglobin to produce cyanosis—that is, anemia makes cyanosis more difficult to detect. In 1951 an article appeared in which it was recommended that an oximeter would be useful on every anesthetized patient for it provided important continuous data regarding patient oxygenation.[4] It identified routine desaturation during normal anesthetic procedures in healthy patients. The authors also stated that there were many technical problems with the device, including the potential of burns to the ear. The clinical usefulness of the device was clear to the initial users 40 years ago.

In the 1970s, Hewlett-Packard developed an 8-wavelength ear oximeter that did not require calibration by squeezing blood from the ear and had improved accuracy due to its multiple wavelength technique. It did heat the ear to some extent but not to a temperature high enough to cause burns. This device became routinely used in pulmonary function laboratories. Also in the mid-1970s, an engineer named Takuo Aoyagi working for Nihon Kohden Corporation made an ingenious discovery. He was working on a noninvasive method to measure cardiac output by injecting dye in a peripheral vein and measuring the dye dilution curve noninvasively with an ear oximeter-like device. In the process of this work, he found that there was a pulsatile component to the absorbance detected by the ear oximeter. He noted that the amplitude of this pulsatile component changed with changing oxygenation. He surmised that the pulsatile absorbance was due to the pulsatile arterials and that it could be assumed that whatever was pulsing was arterial blood. Given that information, if only the pulsatile component of absorbance was analyzed, a signal related to arterial blood could be determined without heating the ear. He then developed the first "pulse" oximeter by analyzing the pulsatile component of absorbance in 2 wavelengths of light (red and infrared) and calibrated the ratio of these absorbances empirically to arterial saturation using human subjects. Although this device

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included all the theoretic aspects of the current-day pulse oximeter, it had considerable technical problems. The Nihon Kohden pulse oximeter used fiberoptic cables from the device to the ear to transmit the light signals. These cables were heavy, making it difficult to maintain the position on the ear. Its accuracy was also limited because of its simplified calibration process. In the late 1970s an engineer named Scott Wilbur in Boulder, Colorado, saw this device and decided to make an improved version. He used lightweight light-emitting diodes (LEDs) and photodiodes as light sources and light detectors. They could be made into an ear clip and placed directly on the ear. He also used a microprocessor to improve the empiric calibration and the accuracy of the device. His additions made the pulse oximeter a clinically usable device that was quickly adopted by pulmonary function laboratories. The final contributor to this developmental process was an anesthesiologist named Bill New. New was the faculty member at Stanford University who saw the pulse oximeter made by Wilbur and immediately realized its direct application to the operating room. He made an improved adhesive probe that included the photodiode and the LEDs. This Nellcor device quickly became a standard in operating rooms.

Today, if given the choice of one monitor, most anesthesiologists would quickly choose the pulse oximeter over the electrocardiogram (ECG) or noninvasive blood pressure devices. Its familiar beep that changes tone with saturation has become a reassuring sound for everyone in an operating room. In fact, if pulse oximeters had been developed before ECGs, it might be difficult to justify the purchase of ECGs for each operating room. Although the pulse oximeter does not detect perfusion changes per se, it will quickly detect the absence of a pulse.

Infrared CO_2 analyzers were also first developed during World War II. The original devices were used to measure CO_2 concentrations in German submarines. After the war this "Luft" analyzer became the standard device for CO_2 measurement. The absorbance of infrared light by carbon dioxide was used to determine the CO_2 concentration. Although there have been many improvements in the technical development of CO_2 analyzers over the past 40 years, the basic Beer's Law absorption theory on which the capnometer (and pulse oximeter, for that matter) is based is still the same. Its use in medicine was limited until the work of Smalhout and Kalenda in Holland.[5] They measured expired CO_2 waveforms from anesthetized patients and published an atlas of capnography. This atlas of their clinical experiences with the device demonstrated that it provided breath-to-breath assessment of ventilation and pulmonary perfusion. This was found to be so useful in assuring the stability of anesthetized patients that in Holland its use became routine by the end of the 1970s. In the United States capnography was only used in neuroanesthesia until appreciation for its usefulness gradually grew in the 1980s. By 1986 it was adopted as a routine monitor for all anesthetic procedures along with pulse oximetry.[1]

It is difficult to imagine caring for anesthetized patients in the 1990s without these two devices. Because surgical intensive care units are direct extensions of intraoperative care, it would seem only reasonable that critically ill patients receive similar monitoring. Because of its ease of interpretation, pulse oximetry has been quickly adopted in critical care units. Capnography requires more interpretation because it provides data that relate not only to ventilation but to pulmonary perfusion abnormalities.[6-8] For this reason, it took nearly half a decade for it to be appreciated in operating rooms and, most likely, will take several years of familiarity with it in intensive care units before it becomes routinely applied. These two noninvasive monitors of the cardiopulmonary system are extremely useful in all critical care settings, but users must have "an understanding of the underlying assumptions and limitations"[9] to employ them intelligently.

REFERENCES

1. Eichhorn JH, Cooper JB, Cullen DJ, Maier WR, Philip JH, Seeman RG: Standards for patient monitoring during anesthesia at Harvard Medical School. JAMA 1986; 256:1017-1020

2. Tremper KK, Barker SJ: Pulse oximetry. Anesthesiology 1989; 70:98-108

3. Comroe JH, Botelho S: The unreliability of cyanosis in the recognition of arterial anoxemia. Am J Med Sci 1947; 214:1-6

4. Stephen CR, Slater HM, Johnson AL, et al: The oximeter—A technical aid for the anesthesiologist. Anesthesiology 1951; 12:541-555

5. Smalhout B, Kalenda Z: An Atlas of Capnography. Zeist, The Netherlands, Kerckebosch, 1975

6. Gravenstein JS, Paulas DA, Hayes J: Capnography in Clinical Practice. Boston, Mass, Butterworth-Heinemann, 1989

7. Gazmuri RJ, von Planta M, Weil MH, Rackow EC: Arterial P_{CO_2} as an indicator of systemic perfusion during cardiopulmonary resuscitation. Crit Care Med 1989; 17:237-240

8. Isserles SA, Breen PH: Ten changes in end-tidal P_{CO_2} measure changes in cardiac output? Anesth Analg 1991; 73:808-814

9. Bongard F, Sue D: Pulse oximetry and capnography in intensive and transitional care units. West J Med 1992; 156:57-64