The Design, Use, and Results of Transcutaneous Carbon Dioxide Analysis: Current and Future Directions

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Transcutaneous carbon dioxide (CO_2) analysis was introduced in the early 1980s using locally heated electrochemical sensors that were applied to the skin surface. This methodology provides a continuous noninvasive estimation of the arterial CO_2 value and can be used for assessing adequacy of ventilation. The technique is now established and used routinely in clinical practice. Transcutaneous partial pressure of CO_2 ($tcPco_2$) sensors are available as a single Pco_2 sensor, as a combined Pco_2/Po_2 sensor, and more recently, as a combined Pco_2/Spo_2 sensor. CO_2 is still measured potentiometrically by determining the pH of an electrolyte layer. The methodology has been continuously developed during the last 20 yr, making the $tcPco_2$ systems easier and more reliable for use in clinical practice: smaller sensor size (diameter 15 mm, height 8 mm), less frequent sensor re-membraning (every 2 wk) and calibration (twice a day), sensor ready to use when connected to the monitor, lower sensor temperature (42°C or less), shorter arterialization time (3 min), and increased measurement reliability through protection of the membrane. The present $tcPco_2$ sensors still need to be regularly re-membraned and calibrated. One way to overcome these procedures is to use optical-only detection means. Two techniques have been developed using optical absorption in the near-infrared light, in the evanescent wave of a waveguide integrated in the sensor surface, or in a micro-optics sampling cell. Preliminary *in vitro* and *in vivo* CO_2 measurements have been performed. The sensor is not affected by drift over several days, and its response time is <1 min.

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The measurement of blood gas oxygen and carbon dioxide (CO_2) is an integral aspect of monitoring the respiratory status of a patient. The "gold standard" used to access these parameters is the analysis of arterial blood samples. The fact that arterial blood gas values may change rapidly in many clinical situations has stimulated the interest for a continuous measurement of these parameters. For monitoring the partial pressure of CO_2 (Pco_2), several methods have been described during the last three decades. Continuous intraarterial Pco_2 monitoring has been proposed since the 1970s. In this case, Pco_2 is either measured intraarterially using a miniaturized electrochemical or optical sensor, or fed into a gas chromatographic or a mass spectrometric detection system using a carrier gas or a vacuum (1–5). These techniques are not widely used clinically, mainly because of technical reasons: invasivity, size of the catheter, instability of the calibration due to clotting, or lack of reusability (6,7). It also is relatively expensive. End-tidal CO_2 measurement provides a noninvasive estimate of the arterial Pco_2 ($Paco_2$). It is routinely used in operating rooms, but it suffers limitations in patients with respiratory disorders and in nonintubated patients. Transcutaneous Pco_2 ($tcPco_2$) devices provide another option for the continuous noninvasive estimation of $Paco_2$, and in several situations is preferred to end-tidal CO_2 analysis (8–10). The purpose of this article is to review the current and future directions of $tcPco_2$ analysis.

A REVIEW

The measurement of Pco_2 on human skin surfaces was first described in 1960 by Severinghaus (11). Using a specially designed temperature-stabilized tissue Pco_2 electrode, he measured Pco_2 values of over 130 mm Hg on slightly blanched skin. Johns et al. (12), who attached an unheated Pco_2 electrode on skin from which part of the stratum corneum was stripped off, reported systematic studies in this direction in 1969. They were able to show that there is a linear relationship between skin surface Pco_2 and $Paco_2$ in the range from 20 to 74 mm Hg. A few years later, heated Po_2 sensors were described by Eberhard et al.[1] and by

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[1]Eberhard P, Mindt W, Hammacher K. Perkutane Messung des Sauerstoffpartialdrucks: Methodik und Anwendungen. Medizin-Technik 1972:26 (Tagungsausschuss Medizin-Technik, Stuttgart, 1972).

Huch et al.[2] These sensors measure the oxygen partial pressure at the surface of the skin and gave a close estimate of the arterial Po_2. The use of local heating through the sensor was the breakthrough allowing the continuous measurement of blood gases for prolonged time periods. This method was patented in 1971 (13). The initial goal was the measurement of oxygen in newborns to avoid the deleterious effects of both hypo- and hyperoxygenation (14). Several designs of this type of sensor have been described (15,16), and more than 10 companies have introduced them in the market. The methodology was later applied to the measurement of CO_2 (17). The first commercially available $tcPco_2$ sensors were introduced in 1980, and the combined $tcPo_2$–Pco_2 sensors in 1985. They have been continuously improved but are still using the same methodology to arterialize the cutaneous tissue. Initially, and correctly, the word "cutaneous" was introduced to describe the technique consisting of analyzing the concentration of the gas diffusing through the cutaneous tissue at the skin surface. "Cutaneous" is still used in the United States standards to describe blood gas measurements by skin surface sensors (18). However, most of the numerous publications describing the application of this technology in clinical routine have been using the word "transcutaneous," which is now the term most commonly used. European standards also use the word "transcutaneous" (19). The commercially available $tcPco_2$ sensors are electrochemical in nature. Other measurement techniques such as mass spectrometry and gas chromatography have also been proposed for the transcutaneous determination of blood gases, but have not been further developed (20,21).

METHODOLOGY

Transcutaneous measurement of Pco_2 makes use of the fact that CO_2 gas diffuses through body tissue and skin and can be detected by a sensor at the skin surface. By warming the sensor, a local hyperemia is induced, which increases the supply of arterial blood to the dermal capillary bed below the sensor. In general, this value correlates well with the corresponding $Paco_2$ value. Because of the elevated temperature of the sensor, the $tcPco_2$ is higher than the arterial value, and it has become a common practice to apply a correction to the transcutaneous value to provide a reading that corresponds as close as possible to $Paco_2$, the gold standard. The shift of $tcPco_2$ towards higher values is attributed to two main factors. First, the elevated temperature increases local blood and tissue Pco_2 by approximately 4.5%/°C (anaerobic factor). Second, the living epidermal cells produce CO_2, which contributes to the capillary CO_2 level by a constant amount (metabolic constant). The skin metabolism increases the $tcPco_2$ by approximately 5 mm Hg. The theoretical basis of the correction algorithm used by the manufacturers of $tcPco_2$ systems has been specifically described by Severinghaus (22).

In the case of oxygen determination by skin surface sensor, a sensor temperature of approximately 44°C is needed to obtain a significant correlation with the arterial value. At this temperature, especially in the premature infant, it is necessary to reposition the sensor every few hours. In the case of CO_2, a lower temperature can be applied, usually 42°C (23–26). Even at a sensor temperature of 37°C, a good correlation with $Paco_2$ has been reported (27), but the dynamic behavior of the $tcPco_2$ is influenced by the sensor temperature. At a high sensor temperature, the reactivity to fast Pco_2 fluctuations is considerably shortened (28). At a lower temperature, the application of heat creates an initial over-shooting of the $tcPco_2$ (29).

In the presently used transcutaneous electrochemical sensors, CO_2 is measured potentiometrically by determining the pH of an electrolyte layer separated from the skin by a highly permeable membrane, according to the method described by Stow and Randall (30) and Severinghaus and Bradley (31). A change of the pH is proportional to the logarithm of Pco_2 change. The pH is determined by measuring the potential between a miniaturized pH glass electrode and an Ag/AgCl reference electrode (17).

CURRENT AND FUTURE DIRECTIONS

$tcPco_2$ sensors are available as a single Pco_2 sensor, as a combined Po_2/Pco_2 sensor, mainly used in neonatology and, more recently, as a combined Spo_2/Pco_2 sensor for use in adults and infants (32) (Figs. 1 and 2).

The typical characteristics of a $tcPco_2$ sensor are listed in Table 1.

The sensor must be re-membraned every 1–2 wk, an easy straightforward procedure. The sensor must also be regularly calibrated. This implies that the monitor includes a calibration module and a gas cylinder. The monitor can automatically perform these calibration procedures. The sensor can then always be ready to use, eliminating the waiting time before use.

Today, $tcPco_2$ monitors are mainly used to estimate $Paco_2$ and/or to follow the trend of $Paco_2$ in a patient. It has found an application mostly parallel to the determination of oxygen through $tcPo_2$ or Spo_2 in various fields of medicine, such as neonatal intensive care (33), adult critical care (34,35), mechanical ventilation (36,37), anesthesia (38,39), bronchoscopy,[3] sleep

[2]Huch A, Huch R, Meinzer K, Lübbers DW. Eine schnelle, beheizte Pt-Oberflächenelektrode zur kontinuierlichen Überwachung des Po_2 beim Menschen; Elektrodenaufbau und –eingeschaften. Medizin-Technik 1972:26 (Tagungsausschuss Medizin-Technik, Stuttgart, 1972).

[3]Männle C, Herth FJ, Becker HD, Wiedemann K. Controlling of High Frequency Jet Ventilation (HFJV) by measurement of the transcutaneous carbon dioxide tension ($TcCO_2$) during rigid bronchoscopy. Chest 2003;124:125S (abstract).

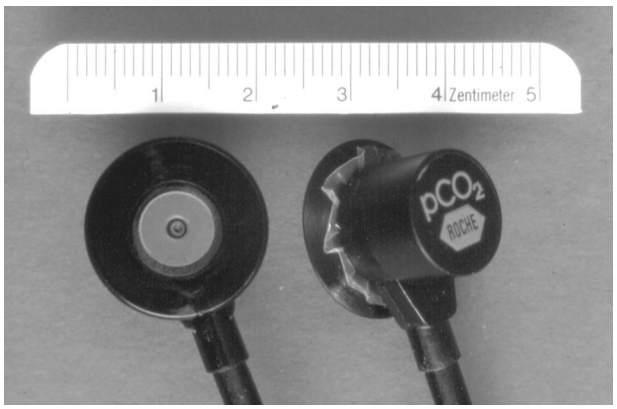

Figure 1. A $tcPco_2$ sensor in 1980.

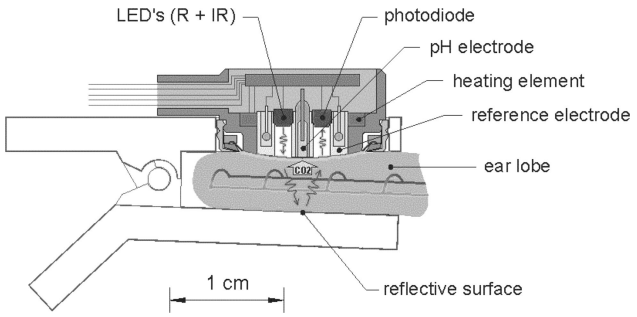

Figure 2. A combined $Spo_2/tcPco_2$ sensor at the ear lobe today.

Table 1. Typical Characteristics of a Transcutaneous Pco_2 ($tcPco_2$) Sensor

Size	
Diameter	15 mm
Height	8 mm
Weight	3 g
Pco_2 range	1–200 mm Hg (0.1–27 kPa)
In vitro response time (10%–90%)	50 s
In vitro drift	≤0.5%/h
Arterialization time after application of the sensor on the skin	3–10 min, depending on the site

studies and apnea testing (40,41), pulmonary stress testing, and respiratory research. It is of particular value in following the immediate effect of any therapeutic measure, which has a direct or indirect influence on the patient's ventilatory efficiency. When used to estimate $Paco_2$, the transcutaneous methodology is limited in some clinical situations, e.g., during profound peripheral vasoconstriction and circulatory centralization or in the presence of skin edema.

The most recent developments of $tcPco_2$ sensors have been oriented towards:

The combination with other parameters such as Spo_2 (32), e.g., in adults to overcome the limitation of $tcPO_2$ use for measuring the patient's oxygenation. The integration of Spo_2 in a heated sensor may also increase the reliability of the Spo_2 measurement in cases of low perfusion and the sensitivity to oxygen saturation change (40,42).

Use of lower sensor temperature, e.g., 42°C or lower, to avoid the frequent repositioning of the sensor.

Diminution of the size of the sensor, especially for application with premature infants and on specific peripheral sites such as earlobe, toe, etc. The measurement at the earlobe increases the sensitivity of the $tcPco_2$ sensor to CO_2 change (42).

Increasing the sensor's stability to decrease the need for recalibrating the sensor.

Increasing the function time between re-membraning.

Increasing the reliability of the measurement, e.g., by protecting the sensitive sensor surface to avoid any damage of the membrane during the functional period.

Digitalization of the signal inside the sensor[4].

And, in general, making the use of transcutaneous blood gas monitoring as easy as pulse oximetry.

A limitation of the presently used $tcPco_2$ methodology is related to the use of the electrochemical measurement technique, more specifically the need to periodically re-membrane and calibrate the sensor. One way to eliminate these procedures may be to apply an optical-only measurement principle as used in pulse oximetry and capnometry. A $tcPco_2$ sensor using an optical-only detection means was described by Salzmann et al. (43). CO_2 is determined by measuring its optical absorption in the evanescent wave of a waveguide integrated in the surface of the sensor. The surface sensing is combined with modulation spectroscopy providing high selectivity and sensitivity. The use of near-infrared light (1580 nm) allows the use of reliable and cost-effective devices such as standard telecommunication fibers and laser. The high selectivity is obtained by tuning the narrow spectral-width of the laser source on the specific absorption line of the molecule to be detected (Fig. 3). Alternatively, CO_2 has been measured in a micro-optics-type miniaturized sampling cell. The sample volume, adjacent to the skin surface, is reduced to approximately 1 mm^3 allowing a response time of <1 min. The optical sensor can be precalibrated in the factory and is not affected by drift over several days. This technique may offer an alternative to the electrochemical measurement of CO_2 as well as oxygen and other gases. Preliminary measurements performed on an adult volunteer (author) with the so-called "Microcell optical sensor" placed on the forearm and heated at 42°C have shown similar performance as that obtained with a

[4]Hayoz J, Schmid ER, Schmidlin D. Combined pulse oximetry and carbon dioxide tension ear sensor in adult patients early after cardiac surgery. EACTA 2002:34.

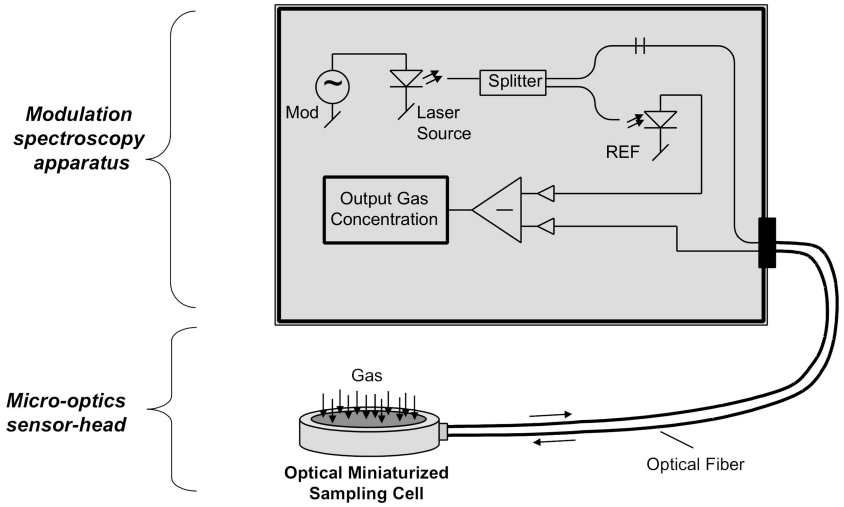

Figure 3. Optical transcutaneous blood gas measurement technique. Overview.

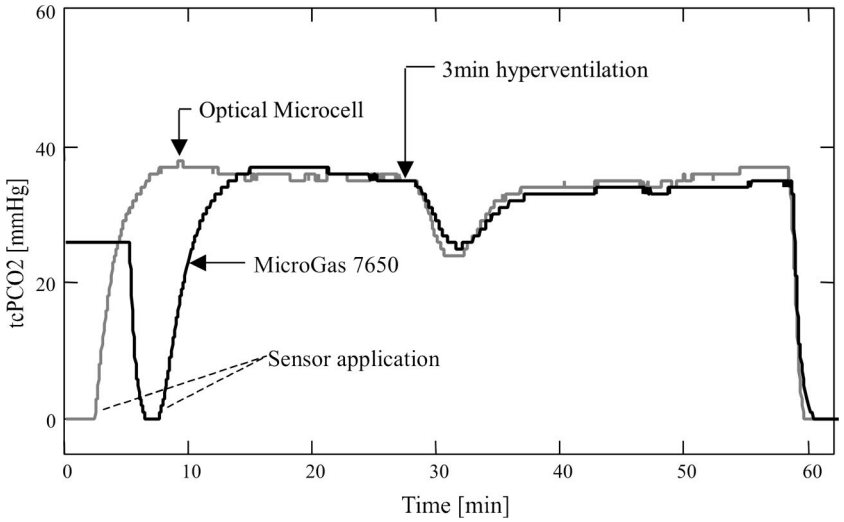

Figure 4. Comparative *in vivo* $tcPco_2$ measurements obtained with an optical Microcell system and a MicroGas.

commercially available electrochemical transcutaneous sensor (MicroGas 7650, Radiometer-Basel, Switzerland) (Fig. 4).

CONCLUSION

$tcPco_2$ sensors were introduced for clinical use about 20 yr ago. Initially, they were mainly used in neonatology together with the measurement of $tcPo_2$ and, more recently, in adult monitoring together with the measurement of Spo_2 to further specific applications, e.g., during mechanical ventilation, bronchoscopy, sleep studies, and pulmonary stress testing. The potentiometric CO_2 measurement technology has been continuously improved during the last two decades, making the $tcPco_2$ systems significantly easier and more reliable for use in clinical practice. It still requires for the regular re-membraning and calibration of the sensor. Preliminary results obtained with an optical-only CO_2 detection in the near-infrared light show that long-term stable and calibration-free CO_2 monitoring is possible. The same optical-only technology may also be applied to the measurement of other blood gas parameters, such as oxygen and anesthetic gases.

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