Review Article

Transcutaneous PO_2 measurement

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Key words
MEASUREMENT TECHNIQUES: transcutaneous PO_2; COMPLICATIONS: hypoxia; OXYGEN: blood levels, tension

Transcutaneous oxygen ($PtcO_2$) measurements are made by placing an oxygen electrode directly on the skin surface. The electrode is the same type used in a conventional blood gas machine – the Clark polarographic PO_2 electrode. To enable the sensor to respond quickly to changes in oxygenation, it is heated to between 43 and 45° C. The transcutaneous sensor continuously and noninvasively measures heated skin PO_2.

The technique of $PtcO_2$ measurement was first presented by two groups in Germany in 1972.[1,2] They reported that a heated Clark electrode placed on the skin of a neonate produced PO_2 values which closely approximated arterial PO_2 (PaO_2). The technique became known as transcutaneous monitoring of arterial PO_2 and was quickly introduced in neonatal intensive care.[3–6] For neonates with respiratory distress syndrome, $PtcO_2$ monitoring has become a standard of care, because it reduces the number of invasive arterial blood gas samples and by continuous monitoring it improves control of oxygenation.

In retrospect, it was fortunate that the $PtcO_2$ values of neonates nearly equaled PaO_2 values, as this led to almost immediate acceptance of the technique. Physiologically, however, there is no reason why $PtcO_2$ should equal PaO_2. In fact, in paediatric and adult patients this equality is not found. In additon, it was reported in the mid 1970s, that the $PtcO_2$ values were much lower than the PaO_2 values in haemodynamically compromised neonates. This led at first to a belief that the technique was unreliable in patients in shock, because the $PtcO_2$ values were low.[7,8] The original observers of this pheonomenon considered it to be a "problem" that limited the usefulness of the $PtcO_2$ sensor to monitor changing clinical conditions.[7–10] The lack of correlation between $PtcO_2$ and PaO_2 values during shock, which has been considered a shortcoming of the technique, actually quantitates the degree of impairment of blood flow to the skin.

It is known that PaO_2 is a poor measurement of the patient's circulatory condition in shock and an unreliable variable to follow during resuscitation.[11–13] Tissue oxygen tensions would be the more reliable variable to follow because their maintenance or restoration may be considered the primary goal of the peripheral circulation. The transcutaneous oxygen sensor measures the PO_2 through the skin and thus reflects the skin tissue oxygen tension beneath it. Since decreasing skin perfusion is one of the earliest compensations for low flow shock, a sensor on the skin may give early warning of a decreased cardiac output. It has recently been demonstrated in experimental animals and confirmed in adult critically ill and

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operative patients that $PtcO_2$ follows the trend of PaO_2 values during adequate blood flow states, but it decreases and follows changes in cardiac output (CO) during circulatory shock.[14–17] $PtcO_2$ is a new PO_2 measurement which has the advantages of being continuous, noninvasive and tissue related. This article will review the history and physiology of transcutaneous PO_2 measurement, and present the results of recent experimental and clinical studies.

History

In 1851, Von Gerlach, an instructor at the Royal Veterinarian School of Berlin, observed exchange of O_2 across the skin.[18] He accomplished this by shellacking the shaved skin of horses, dogs and men, and then analyzing the gas bubbles that formed beneath the shellac. He concluded that "blood on its way through the dense capillary network in the most superficial layer of the skin 'respires.'"[18] It is remarkable that the quantitative measurements of O_2 made by Von Gerlach in 1851 compare well with those measured with modern techniques in 1957.[19] Von Gerlach was not only the first to measure oxygen through the skin, but also the first to understand that the values obtained were blood flow dependent.

One hundred years later, in 1951, Baumberger and Goodfriend reported measurement of the PaO_2 in man through the intact skin.[20] In their experiment, the subject's finger was immersed in a phosphate buffer solution at 45° C and the PO_2 of the solution was measured after an equilibration time of 15 minutes. The PO_2 of the buffer nearly equaled the PaO_2, whether the starting PO_2 of the buffer was higher or lower than the PaO_2. In 1956, Clark presented a polarographic oxygen electrode which made routine PO_2 measurements practical.[21] A year later, Rooth *et al.* confirmed the findings of Baumberger and Goodfriend using a Clark electrode to measure the PO_2.[22] Huch *et al.* reported in 1969 that PO_2 values nearly equal to those of arterial values could be obtained with a PO_2 electrode placed on the skin surface of a newborn, if the skin was made hyperemic by drugs applied topically.[23] In 1972 Huch and Eberhard independently demonstrated that stable skin surface PO_2 values were obtained on infants if the electrode was heated.[1,2] In the late 1970s when the technique was applied to adults, good correlation was found between $PtcO_2$ and PaO_2, but the actual $PtcO_2$ values were considerably lower than the PaO_2 values. Changes in the skin with age cause the $PtcO_2$ values to decline to an average of 80 per cent of the PaO_2 in an adult.[17] These values assume haemodynamic stability. There are many complex factors which affect the heated skin surface PO_2, which will be discussed later in this review.

Clark polarographic PO_2 electrode

In 1954 Leland Clark, Jr. built a simple electrochemical sensor for rapid measurement of PO_2.[21] Although the original electrode and circuit cost less than one dollar, it had a tremendous impact on clinical medicine as it allowed rapid, routine determination of blood PO_2 for the first time. Clark entitled the first publication about his electrode, a method to "monitor and control blood and tissue oxygenation." This title in many ways describes the transcutaneous PO_2 sensor which was developed from his electrode 18 years later.[1,2] The Clark polarographic electrode is composed of a platinum cathode and a silver anode connected to a battery and a current meter, with electrodes immersed in an electrolyte. The following reaction takes place at the cathode:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

There are some differences in the design of transcutaneous PO_2 electrodes. The electrodes used in transcutaneous PO_2 sensors are smaller and designed to be applied to the skin surface. The electrodes in the blood gas machines are heated to 37° C, while the transcutaneous sensors are heated to between 43° and 45° C. Because transcutaneous electrodes are smaller, they have a smaller reservoir for the electrolyte. This small volume of electrolyte and the higher electrode temperature cause a problem of evaporation of the electrolyte. To solve this problem most commercial transcutaneous sensors use an electrolyte base with a lower vapour pressure (usually ethylene glycol) to extend time between changing the membrane and adding electrolyte.[24] The membrane used should be permeable to oxygen and relatively impermeable to the electrolyte. Many polymer films meet this criteria, and polypropylene is commonly used in blood gas machines.

Transcutaneous sensors used in the operating room must not be affected by anaesthetic gases. Halothane and nitrous oxide are the two anesthetics

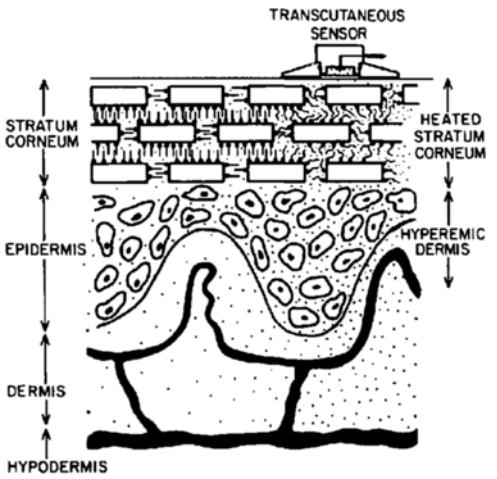

FIGURE 1 Schematic cross section of the transcutaneous electrode and skin: Stratum corneum, epidermis, dermis and hypodermis. The irregular structure of the stratum corneum beneath the electrode represents the melted lipid. The dots represent oxygen. From Tremper *et al.*: Crit Care Med 1979; 7: 530.

known to cause an upward drift of a Clark electrode. With the proper selection of the polarizing voltage, this problem can be eliminated for nitrous oxide.[25] Halothane interference may be significant in the standard Clark electrode if a polypropylene membrane is used. Clinically significant drift due to halothane can be eliminated, however, if a teflon membrane is used.[26,27] Muravchick found no drift after two hours of *in vitro* exposure to 0.5 per cent halothane and less than two per cent drift per hour after two hours of exposure to one per cent halothane. He did report a larger upward drift with *in vitro* exposure to three per cent halothane.[27] Our personal experience in monitoring several hundred patients during halothane anaesthesia is that there has been no clinically significant drift in the $PtcO_2$ sensor that could be attributed to halothane interference when a teflon membrane was used. Most manufacturers currently use teflon membranes.

Skin physiology

The transcutaneous PO_2 sensor measures the O_2 which diffuses from the heated skin beneath it (Figure 1). Heating the skin causes changes in the normal physiology, which allows the values obtained by the sensors to respond quickly to changes in blood gas tensions if local blood flow is adequate. If the local blood flow is significantly diminished, the transcutaneous PO_2 values will respond to changes in the blood flow. This type of response is due to the fact that the sensors are actually measuring a tissue tension. This section will discuss skin physiology as related to transcutaneous measurement of O_2 and the theoretical considerations which govern the relationship between arterial and transcutaneous values.

Stratum corneum

The stratum corneum is composed of keratin filaments in a matrix of lipid and nonfibrous protein. It provides the mechanical strength of the epidermis from which it develops. The epidermal cells rise, dry, and are compressed to form the interdigitated solid stratum corneum. In doing so the stratum corneum becomes a very effective barrier to diffusion averaging 10 microns in thickness. The diffusion constants for water through epidermis and stratum corneum are 2×10^{-6} and 5×10^{-10} $cm^2 \cdot sec^{-1}$, respectively.[28] For oxygen, the diffusion constants are approximately 2×10^{-5} $cm^2 \cdot sec^{-1}$ for epidermis and 2×10^{-8} $cm^2 \cdot sec^{-1}$ for stratum corneum. To put these constants in perspective, the 10^{-8} or 10^{-10} range is what would be expected for the diffusion of a gas through a solid metal foil.[28,29] Diffusion through the stratum corneum appears to be a rate-limiting process in gas transport to the skin surface as evidenced by the vast increase in gas exchange when this layer is removed.[30] In 1975, Van Duzee studied the structure of stratum corneum at increasing temperatures. He noted reversible structural changes from the regular crystalline structure to a random architectural appearance at temperatures greater than 41°C. When the temperature was lowered, the regular crystalline structure reappeared. He concluded that the lipid component of the stratum corneum was melting at approximately 41°C.[31] This transition from solid to the liquid phase is thought to increase the diffusion constant and allow gases to diffuse through the stratum corneum 100 to 1000 times faster.

Decreasing the diffusion resistance of the stratum corneum should decrease the response time. Because the O_2 electrode is a consuming electrode, there is theoretically a diffusion gradient across the stratum corneum which will be proportional to the

diffusion resistance of the layer. Due to the very small rate of oxygen consumption by the micro cathode electrode, this gradient will be small. If a large "macro" cathode electrode is used (with subsequently larger O_2 consumption) there may be a significant O_2 gradient produced across the skin. To minimize this gradient, the electrode membrane must have a large resistance to O_2 diffusion compared to the stratum corneum. This balancing of the electrode membrane resistance to O_2 transport to the skin surface resistance is done to minimize the O_2 gradient in the skin produced by the O_2 consumption of the electrode.[32]

The stratum corneum is an extremely effective barrier to transport, except to materials which are solvents of the lipid in the stratum corneum. The crystalline structure of this layer is responsible for its impermeability, and at temperatures greater than 41°C this structure melts. Thus the heated transcutaneous sensor "melts" a diffusion window to the living tissue beneath.

Epidermis

The epidermis is the nonvascular living tissue between the stratum corneum and the dermis. It does not comprise a major diffusion barrier because of its larger diffusion constant. These living cells consume oxygen as it diffuses to the surface where it can be measured by the electrode. The epidermis is variable in thickness, but averages 100 microns.[28]

Dermis

The dermis is the highly vascular layer beneath the epidermis. The dermal capillaries are convoluted and rise in loops in the dermal papillae (Figure 1). The blood flow in these capillaries is highly variable and acts as a radiator in the thermal regulation of the body. There are several effects of heating the blood vessels in this layer. Heating causes capillary vasodilation and increases the local blood flow. This increased blood flow increases the PO_2 at the tip of the capillary loop by two mechanisms. First, because the capillary oxygen delivery is increased to a much greater extent than the local oxygen consumption, there is less oxygen extracted from the blood, thus the capillary blood is arterialized. Second, it is thought that the capillary loop acts as a counter current exchange column, that is, the oxygen in the arterial blood with a high PO_2 diffuses across to the outgoing capillary loop with a low PO_2. The counter-current exchange of oxygen produces a gradient of decreasing PO_2 toward the tip of the capillary.[33] This counter exchange of O_2 which maintains a lower than venous PO_2 at the capillary loop tip, diminishes as capillary blood flow increases. When the capillary blood velocity increases such that the time to traverse the loop is much less than the time it takes to diffuse across the space between the ingoing and outgoing limbs, the counter-current exchange becomes ineffective. Increasing dermal capillary blood flow, therefore, increases dermal PO_2. Heating the dermal and epidermal tissue increases the tissue metabolic rate and consequently increases O_2 consumption (decreasing PO_2).

Finally, heating the capillary blood itself causes a shift to the right of the oxyhaemoglobin dissociation curve and increases the capillary blood PO_2.[33] The magnitude of the changes in gas tension caused by the shifting dissociation curve is dependent on the gas tension itself (i.e., where it falls on the dissociation curve). To make the problem more complex, the temperature to which the surface electrode heats the capillary blood is blood flow, body temperature, and electrode temperature dependent.[34,35] Of course all of the determinants of the transcutaneous to arterial blood gas tension relationship are dependent upon the anatomical and physiological variability of skin as a function of age and patient.

In spite of the complexity of the transcutaneous PO_2 to arterial PO_2 relationship, there have been attempts to relate these two oxygen tensions mathematically.[33] For practical purposes, the heating of the dermal capillary bed by the skin surface electrode produces a stable hyperemic blood flow which raises the tissue PO_2 in the dermis. As dermal blood flow decreases, the PO_2 tension declines due initially to the reinstitution of the counter-current exchange of gases in the capillary loop and, during severely decreased flow, due to the lack of perfusion (inadequate O_2 delivery).

Experimental studies

In 1977, Parzinger presented his doctorial thesis on the effects of haemorrhagic shock on $PtcO_2$ in mongrel dogs.[36] Parzinger measured cardiac output, $PtcO_2$, mixed venous PO_2 ($P\bar{v}O_2$), mean arterial pressure (MAP), heart rate, and arterial and mixed venous pH during haemorrhage to a MAP of

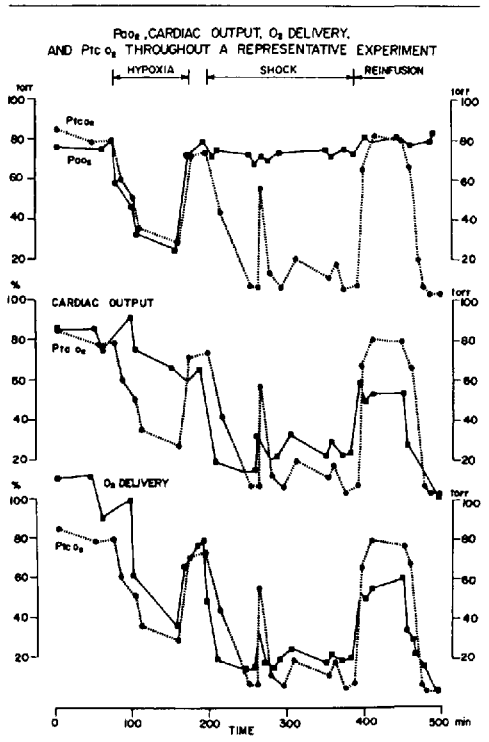

FIGURE 2 Hypoxia and hypovolemic shock study in dogs. Serial $PtcO_2$ and PaO_2 (upper section), $PtcO_2$, and cardiac output (middle section), and $PtcO_2$ and O_2 delivery (lower section) throughout a representative experiment. Note $PtcO_2$ values follow the PaO_2 values during hypoxia, but not during shock; $PtcO_2$ values follow cardiac output during shock, but not during hypoxia; however, $PtcO_2$ values most closely follow O_2 delivery throughout the entire experiment. From Tremper *et al.*: Crit Care Med 1979; 7: 529.

40 mmHg followed by volume resuscitation. He found that $PtcO_2$ correlated with cardiac output, MAP, and $P\bar{v}O_2$, but not PaO_2 during shock and resuscitation. Unfortunately this excellent work was never published other than as Parzinger's thesis at the university. Two years later, experiments nearly identical to Parzinger's were performed by two groups in the United States.[36,14,15] One group used a pig model and the other used mongrel dogs. Their conclusions were the same as those found by Parzinger, i.e., that $PtcO_2$ follows changes in cardiac output and oxygen delivery during shock and resuscitation and therefore is a more useful variable to follow than PaO_2 to determine the adequacy of tissue oxygenation.[36,14,15]

Figure 2 illustrates the function of $PtcO_2$ as related to PaO_2 and cardiac output. In this experiment, anaesthetized, mechanically ventilated dogs were first subjected to a period of hypoxemia and then haemorrhagic shock, followed by volume resuscitation. In this way each of two factors in oxygen delivery were varied independently. Oxygen delivery is defined as the product of arterial oxygen content and cardiac output. During induced hypoxemia, $PtcO_2$ was found to accurately follow the changes in PaO_2 ($r = 0.95$). This close correlation between $PtcO_2$ and PaO_2 during adequate cardiac output was similar to that reported for neonates with respiratory distress.[14] With the onset of haemorrhage, $PtcO_2$ decreased with decreasing cardiac output, while PaO_2 remained essentially unchanged (Figure 2). This large PaO_2-$PtcO_2$ gradient dramatically demonstrates the lack of skin oxygenation during shock. Ironically when the $PtcO_2$ fell significantly below PaO_2 in clinical studies, it was reported that the $PtcO_2$ values were "unreliable," when it was actually the patients' haemodynamic status that was "unreliable" and the low $PtcO_2$ values were correctly detecting the decreased blood flow. The ratio of $PtcO_2$ to PaO_2, more recently referred to as transcutaneous PO_2 index ($PtcO_2$ index = $PtcO_2/PaO_2$), has been used to assess the adequacy of cardiac output and peripheral blood flow.[17]

Similar shock experiments have subsequently been reported. Komatsu *et al.* produced shock in dogs by inflating a balloon in the right atrium and found similar $PtcO_2$, PaO_2 and cardiac output relationships.[37] Halden used $PtcO_2$ to monitor the titration of positive end expiratory pressure (PEEP) in pigs with oleic acid induced pulmonary failure. He found that as PEEP was progressively increased, $PtcO_2$ followed the increasing PaO_2 until the cardiac output declined, and then it decreased with decreasing cardiac output. The maximum $PtcO_2$ values corresponded with the maximum $P\bar{v}O_2$ and was reached at a PEEP of 12 cm H_2O, whereas the maximum oxygen delivery occurred at 8 cm H_2O of PEEP. The author concluded that $PtcO_2$ was at least as useful as any of the monitored variables for optimizing PEEP and it had the additional advantage of being noninvasive and continuous.[38]

It has also been demonstrated experimentally that

$PtcO_2$ values are more sensitive to blood flow than blood pressure. In mongrel dogs, progressive normovolemic hypotension was induced with an infusion of sodium nitroprusside while cardiac output remained within the control range. The $PtcO_2$ values followed PaO_2 and the $PtcO_2$ index remained unchanged to a mean arterial pressure of less than 50 mmHg.[39]

Johnson *et al.* followed $PtcO_2$ during induced hypoxemia in monkeys by ventilating for 15 to 60 minutes with five per cent inspired oxygen. They found that the PaO_2 values fell to between 20 and 25 torr while the $PtcO_2$ values were between 0 and 7 torr. Moreover, when the animals were ventilated with room air, the $PtcO_2$ in the three surviving monkeys rose to a value close to PaO_2, while in the other seven monkeys the $PtcO_2$ values never recovered and the animals died.[40] Although cardiac output was not measured in this experiment, the blood pressure depression was associated with low $PtcO_2$ values.

Another application of $PtcO_2$ monitoring which has been investigated both experimentally and clinically is monitoring of adequacy of blood flow to surgical skin flaps. Keller *et al.* monitored free skin flap transplants in a rabbit model. They found that viable autografts showed a progressive increase in $PtcO_2$, while autografts which were rejected had increasing $PtcO_2$ values for the first four to five days, followed by progressive drops in $PtcO_2$ to zero at eight days.[41] Achauer *et al.* compared $PtcO_2$ monitoring of pedical flaps in rats to the standard fluorescein dye method to determine perfusion and viability. They found $PtcO_2$ values as low as zero during surgery in both surviving and non-surviving flaps, but in the surviving flaps a measurable $PtcO_2$ was obtained within six hours after surgery when the animals breathed 100 per cent oxygen, while the non-surviving flaps had no measurable $PtcO_2$.[42]

Clinical studies

Since the first abstracts presented on the subject in 1972, clinical studies on transcutaneous monitoring have abounded.[1,2] Initially most of the work involved monitoring of neonates. Since the mid 1970s, the technique has been applied to paediatric and adult patients with increasing frequency. It has now expanded to not only cover the entire age spectrum, but also to different clinical settings: intensive care and intraoperative monitoring; assessment of the effectiveness of mechanical ventilation; stress testing; assessment of the effectiveness of shock resuscitation with various fluids, including perfluorochemical emulsions (artificial blood).[4,10,16,17,43–55] This section will review the more instructive reports on neonatal and adult applications of $PtcO_2$ monitoring.

Clinical reports on transcutaneous monitoring are spread throughout the medical literature, although there are some publications which resulted from international meetings on the subject: The Workshop on Methodologic Aspects of Transcutaneous Blood Gas Analysis, held in San Francisco in 1978;[56] The First International Symposium, held in Marburg, West Germany in 1978;[57] and papers presented at a symposium at the Third World Congress on Intensive and Critical Care Medicine, held in Washington, D.C. in 1981.[58]

Neonatal and paediatric studies

It is generally believed that $PtcO_2$ nearly equals PaO_2 in the haemodynamically stable neonate. Actually when data from neonate studies are reviewed, it becomes evident that the $PtcO_2$ values, on the average, are greater than the PaO_2 values. In the early data reported by Huch *et al.*, the $PtcO_2$ values averaged 12 per cent higher than the PaO_2 values.[59] Eberhard's data predicts a PaO_2 of 100 torr when the $PtcO_2$ is 116 torr.[60] In a review of the literature, both neonatal and adult, it is consistently reported that $PtcO_2$ reliably follows the trend of PaO_2 in haemodynamically stable patients. When the actual $PtcO_2$ and PaO_2 values are compared, the $PtcO_2$ values range approximately ± 10 per cent of the PaO_2 for newborns. Monaco *et al.* reported in paediatric patients ranging in age from one to 16 years, that the $PtcO_2$ index ($PtcO_2/PaO_2$) averaged 0.84 ± 0.18.[61] The usual range for the $PtcO_2$ index therefore gradually decreases with the increasing age of the patients.

Versmold *et al.* reported a very interesting study on the effects of blood pressure, blood volume, blood flow, blood viscosity and acid base state on the $PtcO_2 - PaO_2$ relationship in neonates.[7] They measured blood volume by I^{121} albumin dilution, musculocutaneous blood flow by venous occlusion plethysmography and blood viscosity with a Wells–Brookfield viscometer. Of the 73 newborn infants studied ten were identified as "extremely sick" because their pH was <7.05, haematocrit was <30

per cent and the systolic blood pressure was <33 mmHg (each of these variables is 2.5 standard deviations below the normal value). For the less seriously ill newborns the $PtcO_2$ index was approximately 1.0 and a $PtcO_2$–PaO_2 linear regression produced an r value of 0.95. For the extremely sick infants, the $PtcO_2$ index ranged from 0.85 to 0.2 with six of the ten having a $PtcO_2$ index of less than 0.6. A fall in pH of 0.05 units or greater was associated with a decline in the $PtcO_2$ index. There was no consistent relationship between blood volume deficit and the $PtcO_2$ index, except that the patient with the greatest deficit had the lowest $PtcO_2$ index, which increased after a transfusion. Apparently blood viscosity had no effect on the $PtcO_2$ index in the range measured. Versmold *et al.* concluded from these data that severe hypovolemia (blood volume < than 58 $ml \cdot kg^{-1}$), hypotension (systolic blood pressure 10–33 mmHg), anaemic hypoxemia (Haematocrit < 28 per cent), and severe acidemia (pH < 7.02) were associated with $PtcO_2$ index < 0.78 in the neonate. They also concluded that the $PtcO_2$ index was a valuable variable to monitor haemodynamics in the neonate.

Peabody *et al.* compared $PtcO_2$ monitoring to conventional apnoea monitoring in a group of preterm infants with recurrent apnoea.[62] They wanted to assess the effectiveness of thoracic impedance respiratory rate monitoring and heart rate monitoring for the detection of the frequency and severity of apnoeic episodes. They found that only 61 per cent of the hypoxic episodes ($PtcO_2$ < 40 torr) were associated with a heart rate less than 100 beats per minute. Thoracic impedance only detected 39 per cent of the significant apnoeic episodes (>15 seconds and a $PtcO_2$ < 40 torr). This group also studied the effectiveness of aminophylline treatment to improve respiratory patterns. It was documented with $PtcO_2$ tracings that aminophylline treated neonates had fewer episodes of hypoxia.[63] Hobar *et al.* reported microprocessor analysis of 552 hours of neonatal monitoring data. They concluded that they were able to improve the control of oxygenation with $PtcO_2$ monitoring. Their analysis demonstrated that $PtcO_2$ was maintained within their control limits for 96.84 per cent of the time: 2.9 per cent of the time with $PtcO_2$ < 40 torr and 0.26 per cent of the time with $PtcO_2$ > 100 torr.[64]

The control of oxygenation and blood volume during surgery on the neonate is difficult. Marshall *et al.* reported their experience while monitoring 15 neonates during anaesthesia and surgery. They found the $PtcO_2$ monitor to be extremely useful.[65] $PtcO_2$ correlated well with PaO_2 in 13 of 15 patients. One of the other two patients was severely hypovolemic ($PtcO_2$ index = 0.48) but after transfusion, the $PtcO_2$ index was 1.0 and the $PtcO_2$ correlated well with the PaO_2. It is remarkable that the authors found that the $PtcO_2$ monitor detected serious problems during the anaesthetic management of nearly half of the patients monitored, i.e., empty air cylinder, kinked endotracheal tube, inadvertent extubation, right mainstem bronchus intubation, hypoxemla, and severe hypovolemia.[65] The author of this review has had similar experiences during anaesthesia and surgery with neonates.

Clinical studies in adult patients

In spite of the rapid acceptance of transcutaneous monitoring in neonates, the application of $PtcO_2$ monitoring for adult patients has been slow. Their gradual increase in the use of the monitor for adult patients, however, has coincided with a better understanding of the physiology of $PtcO_2$. When transcutaneous sensors were applied to critically ill adults, the patients' ages and diseases varied greatly. Most patients had multiple system failure and poor peripheral perfusion. The $PtcO_2$ sensors detected the degree of inadequate tissue perfusion by large gradients between PaO_2 and $PtcO_2$. Unfortunately, at first these deviations were attributed to malfunction of the transcutaneous monitor. This misinterpretation of the data has more recently been resolved with more comprehensive investigations in animals and humans. With a better understanding of the technique, its applications have broadened to the monitoring and assessing of critically ill patients, patients at risk for cardiopulmonary compromise or even regional tissues.

In 1976 three studies were published involving $PtcO_2$ monitoring of adult volunteer and clinical subjects.[8,66,67] Sacci *et al.* monitored three groups of patients: young adult volunteers, while varying inspired oxygen from 15 to 100 per cent, at rest and during exercise; young and old volunteers, breathing 21 and 100 per cent oxygen; and nine adult patients suffering from respiratory failure. A problem with this study was that the $PtcO_2$ electrode was heated to only 42° C (normal $PtcO_2$ temperature for

adults is 44° to 45° C). In spite of this low electrode temperature, they found excellent correlation between $PtcO_2$ and PaO_2 in all cases. They noted a decreased correlation coefficient during exercise which they attributed to impaired skin blood flow. Because of the low electrode temperature used, the $PtcO_2$ values averaged only 34.7 per cent of the PaO_2. The authors found that once the relation between $PtcO_2$ and PaO_2 was determined, the trend could be followed for 24 hours without burning the skin. There was, however, a downward drift with their electrodes, so they recommended calibration every eight to 12 hours.[66]

Rooth *et al.* reported the results of monitoring five volunteers and seen critically ill patients with an electrode temperature of 45° C. They found a linear regression correlation coefficient of 0.98 between $PtcO_2$ and PaO_2 with actual PO_2 values for healthy volunteers nearly being equal. For the critical patients, the correlation was still excellent ($r > 0.98$), but the $PtcO_2$ values ranged from 108 to 45 per cent of the arterial PO_2. The low $PtcO_2$ values they attributed to the patients' poor cardiovascular status, but did not document low blood flow objectively.[8]

A third study published in 1976 dealt with $PtcO_2$ monitoring during anaesthesia.[67] In this study, 46 arterial blood samples were collected from 23 patients and corrected in a linear manner with $PtcO_2$ with an r value of 0.94 and a slope and intercept of the regression line at 0.88 and 6 respectively. The patients' ages varied from 18 to 83 years. The arterial samples were collected before, during and after anaesthesia. The authors concluded that the monitor was useful to detect and treat hypoxia not only during anesthesia but in the preinduction and postextubation periods.[67] All three of these articles reported a 10 to 15 minute warm up time for the electrodes on the skin surface.

The following year, Huch *et al.* reported an excellent correlation between $PtcO_2$ and PaO_2 over a range of 82 to 2,180 torr in volunteers in hyperbaric chambers.[68] Rooth *et al.* reported on $PtcO_2$ monitoring of 135 adult intensive care patients.[69] Again the electrode temperatures were maintained at 45° C. They recorded the lowest $PtcO_2$ values obtained during the warmup phase and compared these to the final equilibrated $PtcO_2$ values (Figure 3). They found the $PtcO_2$ values reached a minimum between one and two minutes of application and plateaued at a stabilized value in 10 to 15 minutes. They also noted that in 25 per cent of the patients it took 20 minutes or more to reach the plateau value. The minimum $PtcO_2$ value during the stabilization was usually 30 torr less than the final value for patients breathing room air. In this paper for the first time the relationship between $PtcO_2$ and PaO_2 was quantitated for normal versus shock states. They correlated the difference between PaO_2 and $PtcO_2$ (ΔPO_2) and blood pressure. This produced a fairly significant negative correlation, i.e., as blood pressure decreased the ΔPO_2 increased. They concluded that the function of $PtcO_2$ during shock needed further investigation.[69] Coincidentally it was this same year that two groups in the United States performed shock studies on animals, determining the blood flow (and not necessarily blood pressure) dependence of $PtcO_2$. (See section on Experimental Studies.)[14,15]

In 1980 we reported monitoring nine critically ill patients before and during cardiopulmonary resuscitation (CPR). It was found that $PtcO_2$ followed PaO_2 until the cardiac index (CI) fell below $2\,L \cdot min^{-1} \cdot m^{-2}$ at which time the $PtcO_2$ values became flow dependent. It was also found that $PtcO_2$ values, which remained below 20 torr in spite of maximal resuscitation efforts, preceded cardiac arrest in those patients by 43 ± 27 minutes.[16]

We subsequently performed a study involving comprehensive haemodynamic monitoring of a large number of patients. One thousand and seventy-three data sets were collected from 106 patients in the ICU and the operating room.[17] The objectives of the study were to determine the normal range for $PtcO_2$ relative to PaO_2 during adequate output and during the progression of low cardiac output shock. Table I presents the results. The ratio of $PtcO_2/PaO_2$ was defined as transcutaneous index to assess the degree of peripheral perfusion deficit. It was found that for patients with a CI > $2.2\,L \cdot min^{-1} \cdot m^{-2}$, that the $PtcO_2$ index was 0.79 ± 0.12 (i.e., $PtcO_2$ averages approximately 80 per cent of PaO_2). As CI decreased to the range of 2 and $1\,L \cdot min^{-1} \cdot m^{-2}$, the $PtcO_2$ index decreased to 0.49 and 0.12 respectively (Table I). As the ratio of $PtcO_2$ to PaO_2 decreased with CI, the linear regression coefficient decreased from 0.89 for the normal flow group to 0.78 and 0.06 as flow decreased (Table I). In the severe shock group (CI $\simeq 1\,L \cdot min^{-1} \cdot m^{-2}$), the $PtcO_2$ values correlated well

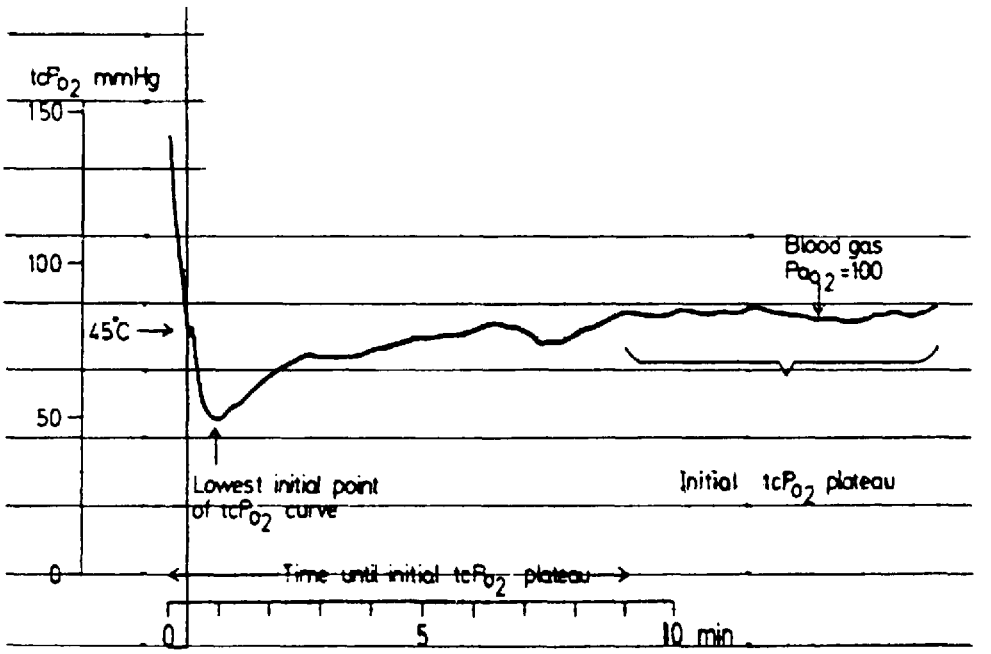

FIGURE 3 A representative warmup curve for a $PtcO_2$ electrode on an adult. Note the $PtcO_2$ value starts at approximately room air PO_2 (159 torr) and rapidly decreases as the oxygen in the electrode is consumed. The value reaches a minimum at one to two minutes and starts to rise as oxygen diffuses from the heated skin. The final value is approximately 30 torr higher than the minimum and occurs at about ten minutes after application. Adapted from Rooth *et al.* Interpretation of the $tcPO_2$ curve in adult patients in an intensive care unit. In Huch A., Huch R., Lucie J.F. (eds): Continuous Transcutaneous Blood Gas Monitoring. New York: Alan R. Liss for The National Foundation – March of Dimes, BD:OAS 15(4):558, 1979.

with cardiac index. Figures 4 and 5 are illustrative of patients with normal cardiac output and in haemorrhagic shock. Glenski recently reported that a decreasing $PtcO_2$ value was a more sensitive indicator for the detection of air embolism than end-tidal CO_2 in neurosurgical patients.[72]

A variety of clinical applications in adult medicine have recently been reported. Goeckenjan and Strasser correlated the response time of $PtcO_2$ to step increases in FiO_2 to other pulmonary function tests. They were able to discriminate between healthy patients and patients with mild chronic obstructive pulmonary disease.[70] Another group used $PtcO_2$ to test the exercise tolerance of volunteers while breathing room air and 12.6 per cent oxygen. These volunteers were members of a team about to embark on a mountain climbing expedition. They observed significant decreases in $PtcO_2$ at maximal exercise at both inspired oxygen concentrations which immediately returned to the baseline values when the exercise stopped.[71]

$PtcO_2$ sensors have been applied to acutely injured trauma victims during emergency department resuscitation. It was concluded that low $PtcO_2$ values predicted hypovolemia even in the presence of normal blood pressure.[49] In the area of regional perfusion, $PtcO_2$ has been applied in assessing peripheral limb viability to determine amputation level, the degree of peripheral vascular disease and the effectiveness of peripheral vascular by-pass grafts.[44,45,47,48]

Practical clinical considerations

Temperature and skin burns

There is always a potential of causing a small (electrode size) skin burn with the heated $PtcO_2$ electrode. A "burn" here is defined as a blister

TABLE I $PtcO_2$ versus linear regression values and $PtcO_2$ index for patients with three ranges of cardiac index

	Group I *Stable* *CI > 2.2*	*Group II* *Moderate shock* *2.2 > CI > 1.5*	*Group III* *Severe shock* *CI > 1.5*
No. Data sets/no. patients	934/92	74/5	65/9
CI ($L \cdot min^{-1} \cdot m^{-2}$)	4.1 ± 1.0	2.0 ± .2	0.9 ± .2
MAP (mmHg)	96 ± 17	94 ± 18	39 ± 21
$PtcO_2$ vs PaO_2: linear regression			
r value	0.89	0.78	0.06
Slope	0.79	0.05	—
Intercept	4.1	6	—
$PtcO_2$ Index	0.79 ± 0.12	0.48 ± 0.07	0.12 ± 0.12
$PtcO_2$ Index vs CI: linear regression			
r value	—	—	0.86

($PtcO_2$ Index = $PtcO_2/PaO_2$).
Adapted from Tremper *et al.*: Crit Care Med 1981; 9: 707.

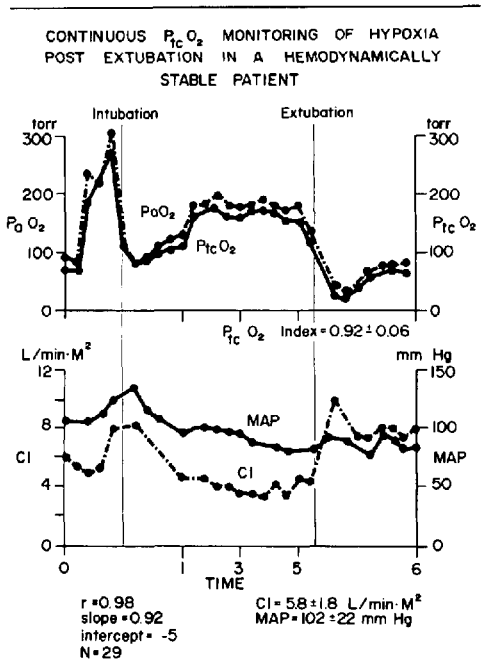

FIGURE 4 The time course of PaO_2, $PtcO_2$, MAP, and CI for a hemodynamically stable patient who suffered severe hypoxia. After undergoing a five and a half hour operation without complications, this patient was extubated in the operating room. The patient had naturally dark skin and did not appear to be cyanotic in spite of his minimal respiratory efforts. The $PtcO_2$ values dropped precipitously, reaching a value of 23 torr. Note the cardiac index rose to 9 $l \cdot min^{-1} \cdot m^{-2}$ (3 times normal) in an attempt to compensate for this hypoxic insult. From Tremper: Analyzer 1982; 12: 27.

forming injury (second degree). A red hyperemic spot which fades in 24 hours is left on the skin after each use. The incidence of burns is a function of the electrode temperature and the length of time the electrode is left in the same location. The section on skin physiology describes why the skin must be heated to have a quickly responding $PtcO_2$ value. Although this author has been unable to find a study which documents burn incidence as a function of time and temperature, the following guidelines are given from his own experience. The choice of temperatures ranges between 43° C and 45° C. For premature infants a temperature of 43° C is commonly used and the location is changed every two hours. The electrode temperature and length of time it can be left on the skin site can be increased with the patient's age and skin thickness. For newborns a temperature of 43.5° C and a time of three hours is safe and for children and adults 44 to 45° C and four hours. An electrode temperature of 45° C is often used for adults, but in this author's opinion, 44° C or 44.5° C give very similar results with a lower incidence of burns. When the electrode temperature is 44° C on an adult, the same electrode location can be used for six to eight hours with a very low burn incidence (less than one per cent).

Sensor calibration and drift

As with any piece of electrical equipment, proper calibration and minimal drift are vitally important. Probably the most significant technical improvement in transcutaneous monitors in the past ten years has been the development of rugged elec-

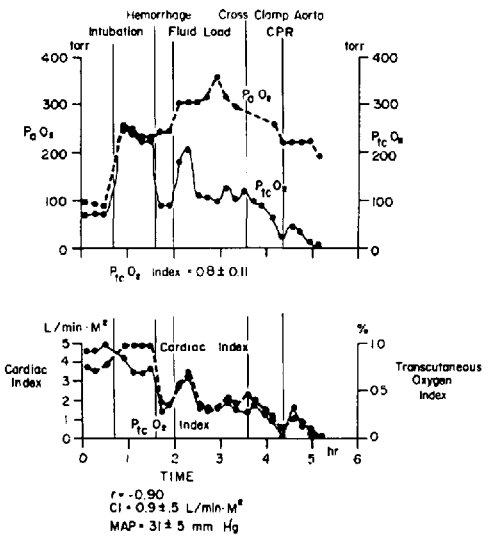

FIGURE 5 The time course of monitored data for a patient who arrested intraoperatively due to an acute hemorrhage. Note the drop in $PtcO_2$ value with decreasing CI and MAP during the hemorrhage, while the PaO_2 value was relatively unaffected. During the shock period (mean CI = 0.9 ± 0.5 $L \cdot min^{-1} \cdot m^{-2}$ and MAP = 31 ± 5 mmHg); the $PtcO_2$ index had a mean value of 0.2 ± 0.11 and correlated inversely with CI (r = 0.90). From Tremper, et al.: Crit Care Med 1981; 9: 706.

trodes with acceptable drift (less than one per cent per hour). In practice the majority of drift is in the high calibration point, therefore the high point calibration should be checked frequently. A two point calibration method should be employed initially. The zero is checked with a zeroing solution (sodium bisulfate), and room air is used for the high point (159 mmHg at sea level). The zero point is usually very stable and only requires checking weekly or after a membrane is changed. The high point should be calibrated to room air prior to each use, as with FiO_2 monitors. The electrode membrane should be changed when the drift exceeds one per cent per hour. If properly cared for the membrane usually lasts for a week or more. It is very important that the user of the equipment be familiar with the maintenance of the sensor. If the electrode drifts excessively during a procedure, the $PtcO_2$ values may contribute to an improper diagnosis of a clinical problem.

TABLE II Change in $PtcO_2$ index with age

$PtcO_2$ Index	*Age group*	*Reference*
1.14	Premature	Hutch *et al.*[3] Eberhard *et al.*[4]
1.0	Newborn	Versmold *et al.*[7]
0.84	Pediatric	Monaco *et al.*[61]
0.79	Adult	Tremper *et al.*[17]

($PtcO_2$ Index = $PtcO_2/PaO_2$).

Sensor location

Most of the clinical $PtcO_2$ data have been collected with the sensor placed on a central body location – chest, shoulders or abdomen. There is a variation of about ten per cent in $PtcO_2$ values even in adjacent sites. Peripheral limbs probably have slightly lower $PtcO_2$ values, especially in the presence of peripheral vascular disease. The most important consideration for intraoperative use is that the sensor be placed in a location which is accessible during the procedure. If the sensor becomes detached from the skin, it will read a room air PO_2 value (≈159 mmHg) and give a false sense of security that oxygenation is adequate (a false negative). If the sensor is near the surgical field and under surgical drapes, personnel may lean on the sensor which will cause the $PtcO_2$ values to decrease (a false positive). It is also very useful, if time permits, to obtain a reference baseline $PtcO_2$ value while the patient is awake and breathing room air, analogous to a preoperative room air arterial blood gas sample.

Summary

Transcutaneous PO_2 sensors have been developed over the past ten years from the same basic electrodes used in conventional blood gas machines. The skin is heated to enable the skin surface sensors to respond quickly to the gas tensions beneath them. $PtcO_2$ is a variable which reflects the PO_2 in the peripheral tissue. $PtcO_2$ has its own range of normal values and it responds to cardiopulmonary changes which affect tissue oxygenation.

In the majority of patients, those without decreased cardiac output, $PtcO_2$ follows the trend of the arterial gas tension, and the $PtcO_2$ value decreases relative to PaO_2 with increasing patient age (Table II). When there is severely reduced cardiac output and peripheral perfusion, the $PtcO_2$ values will deviate from their relationship with the arterial tensions and become blood flow dependent,

thus providing quantitative information regarding blood flow. It is likely that the technique of transcutaneous PO_2 monitoring will gain wider acceptance because it is a noninvasive and continuous monitor which provides useful information regarding tissue oxygenation.

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