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Transcutaneous measurement of blood Po_2 ($tcPo_2$) — Method and application in perinatal medicine

Renate Huch, Albert Huch, Dietrich W. Lübbers

Max-Planck-Institut für Arbeitsphysiologie, Dortmund/Germany,
Department of Obstetrics and Gynecology, University of Marburg, Marburg/Germany

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We have previously shown that it is possible to measure Po_2 transcutaneously by means of an electrode according to CLARK [1]. This Po_2 **correlates with the arterial values** both in newborns and in adults [2, 5, 8, 10, 11]. In order to obtain reproducible and representative $tcPo_2$ measurements, attention must be paid to several factors, such as the shape of the electrode, the size of the platinum cathodes, the thickness of the electrode membranes and the local "arterialization" of the skin at the site of measurement.

1. Types of arterialization

In our earlier studies, arterialization was induced by a nicotinic acid derivate*. At that time monitoring was limited to a maximum of one hour because the $tcPo_2$ values fell due to a reduction in the degree of vasodilatation.

Constant $tcPo_2$ readings in the newborn infant and in the adult only became possible when local vasodilatation was achieved by using heat. This heat is supplied by the electrode itself and the energy required for keeping the temperature constant is used as a relative measurement of local blood perfusion. **With this device $tcPo_2$ may be monitored for several hours.**

Clinical investigations with the heated electrode have been done both in adults and in newborn infants [6, 7]. The present paper describes the main features concerning the function, construction and handling of the electrodes and gives some examples of the application of the transcutaneous oxygen method in perinatal medicine.

Curriculum vitae

RENATE HUCH: *Study of medicine in Göttingen. Since 1968 assistant in physiology. Teamwork with* Prof. D. W. LÜBBERS *(Max-Planck-Institut für Arbeitsphysiologie, Dortmund) and* Prof. A. HUCH *(Dept. of Gynecology and Obstetrics, University of Marburg) in the Dept. of Gynecology and Obstetrics, University of Marburg.*
Main fields of interest: Continuous monitoring of blood gases in the fetus, in newborn infants and in the mother during labor. Physiology of respiration and circulation in perinatal medicine, especially lung and circulation adaptation of the newborn after birth.

2. Principle of transcutaneous Po_2 measurement

Modern Po_2 measurements are all based on the **polarographic** technique introduced by HEYROWSKY [4], according to which the current produced at a cathode by reduction of molecular oxygen is registered. CLARK [1] constructed the electrode with a **platinum cathode** and **a silver anode** covered with a **membrane permeable to O_2**. If a suitable voltage (depending on the

* Finalgon® (Anasco GmbH, Germany).

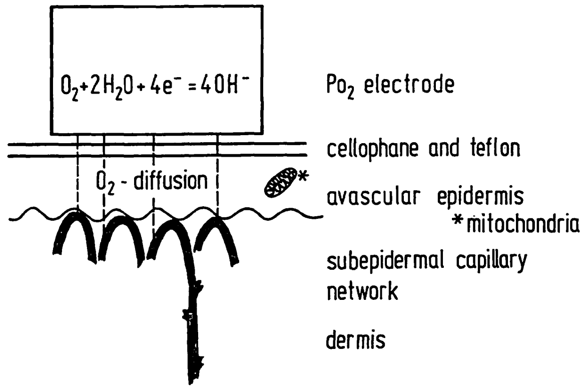

Fig. 1. Diagram of the O_2 diffusion pathway from the dilated capillaries to the cathode of the oxygen electrode.

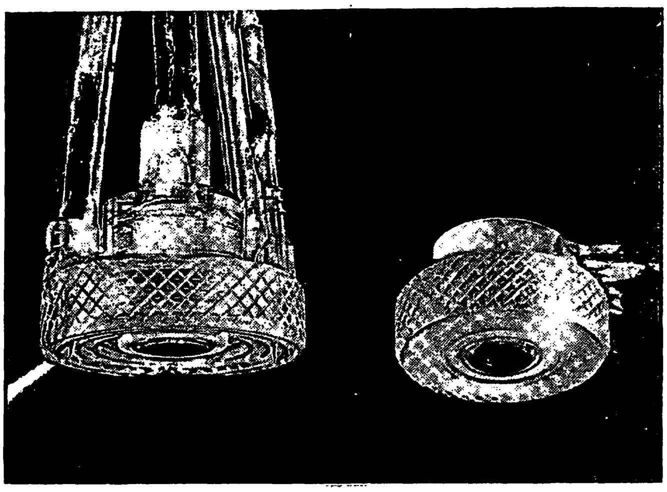

Fig. 2. The two modifications of the Po_2 electrode for transcutaneous measurements. Left: The electrode for application on the fetus (vacuum) during birth. Right: The electrode for fixation on the skin with a self-adhesive ring.

plateau value in the corresponding polarogram) is applied between the anode and the cathode, the resulting current is proportional to the partial pressure of oxygen.

Fig. 1 indicates how oxygen diffuses according to its pressure gradient from the capillary loops through the avascular epidermis towards the skin surface electrode. The tissues between the capillaries and the electrode have an influence on the Po_2 measurements similar to that of the membranes of the Clark-electrode. They prolong the response time of the electrode and influence the calibration [8]. The oxygen consumption of the tissues reduces $tcPo_2$ in comparison to arterial Po_2 (Pao_2), even during maximal vasodilatation. It follows that it is an advantage to measure on skin **where the epidermis is thin,** the oxygen consumption is low and **where the capillary network is dense,** i. e. where perfusion efficiency is at a maximum.

3. The Po_2 electrode for transcutaneous measurements

The Po_2 electrode itself **must not compress the vascular bed,** either by its own weight or by the way it is fixed to the skin. Measurements have shown that the effective pressure of the electrode (Fig. 2) is smaller than 0.01 p/mm². Only if the pressure exceeds 0.2 p/mm², is the $tcPo_2$ value of the vasodilated skin reduced.

Two slightly different Po_2 electrodes were constructed, one for application on the fetal scalp during labor and one for application on the skin of newborn infants or adults. Fig. 3 shows diagrams of these two electrodes. The polarographic part and the part which produces

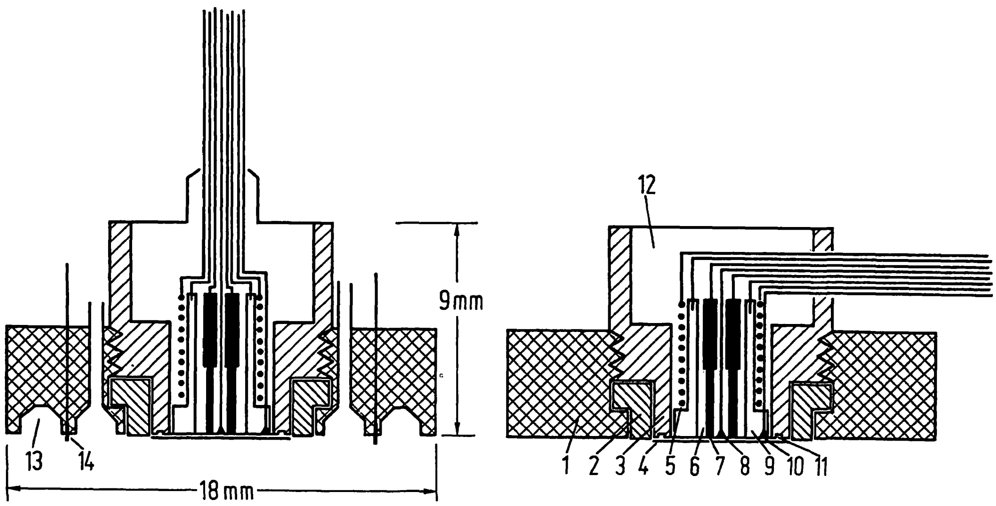

Fig. 3. Schematic drawings of the electrode in Fig. 2. 1 second O-ring, 2 first O-ring, 3 lucite, 4 teflon and cellophane membranes, 5 heating coil, 6 glass, 7 Pt-wire (cathode), 8 NTC, 9 silver anode, 10 NTC, 11 electrolyte chamber, 12 araldite, 13 groove for vacuum, 14 silver tip for ECG or heart rate.

hyperemia are identical. Although in principle only one cathode is needed we have equipped the electrode with three platinum wires. Identical responses of two, if not of all three channels, are proof that the electrode is correctly placed on the skin.

The wires are fused into glass and are connected separately to the source of the polarization voltage. The glass cylinder containing the three Pt wires is fitted into one common silver anode. In the anode there is a circular groove for the heating coil. The temperature of the electrode is regulated by means of a miniature thermistor which is situated near the surface of the silver ring. The temperature near the cathodes is controlled by a second thermistor placed centrally in the glass. The surface of the electrode is covered with two 12 μm thick membranes of teflon and cellophane. The 'atter is moistened in an electrolyte with the following composition: 300 ml 0.5 M $NaHCo_3$, 10 ml saturated KCl and 0.215 g agarose. The membranes are fixed to the electrode with one O-ring; a second ring, which has a large circular surface for the fixation of an adhesive ring, is screwed onto the electrode over the first one. The second ring of the fetal electrode (on the left in Fig. 3) has a groove for the application of vacuum and two silver tips to enable simultaneous measurements of fetal ECG or fetal heart rate.

3.1 Instrument and accessories

The 15 μm cathode gives a signal of about 1.0—2.0 x 10^{-9} A at the oxygen tension of air, i. e. at about 150 mm Hg. The current of each channel is read on the three amperemeters (Fig. 4 : 1). Fig. 4 shows the front panel of the Po_2 analyzer as developed in our laboratory. The polarization voltage (Fig. 4 : 2) may be adjusted between 0 and 1000 mV. As the thermistor characteristics differ from electrode to electrode, each one must be calibrated at two temperatures, 25°C and 50°C (Fig. 4 : 3), The temperature for the vasodilatation is preset by means of a potentiometer (Fig. 4 : 4) and may be read on the corresponding scale (Fig. 4 : 5). The current needed for maintaining the temperature of the electrode at the required level is indicated on the "P-Heiz." scale (Fig. 4 : 6) and is used as a relative measurement of the local blood perfusion (inverted Gibbs' technique [3]); increased sensitivity is obtained by zero-point suppression (Fig. 4 : 7).

On the back of the instrument there are six 1 V outputs for registration on recorders or other devices: three are for Po_2, one is for the temperature near the heating coil, one is for the temperature near the cathodes and the last one is for the relative local blood perfusion. Any multipen recorder with a chart speed ranging between 60 mm/h and 60 mm/min may be used for the registration.

3.2 Handling of the electrodes, „in vitro" calibration and response time

After preparing the electrode with the above-mentioned electrolyte, cellophane and teflon membranes, it is connected to the Po_2 analyzer and to the recorder at least **1/2 hour before use in order to allow polarization and stabilization.** During this time the electrode should be kept in a glass tube with distilled water equilibrated with air or another gas with known O_2 tension.

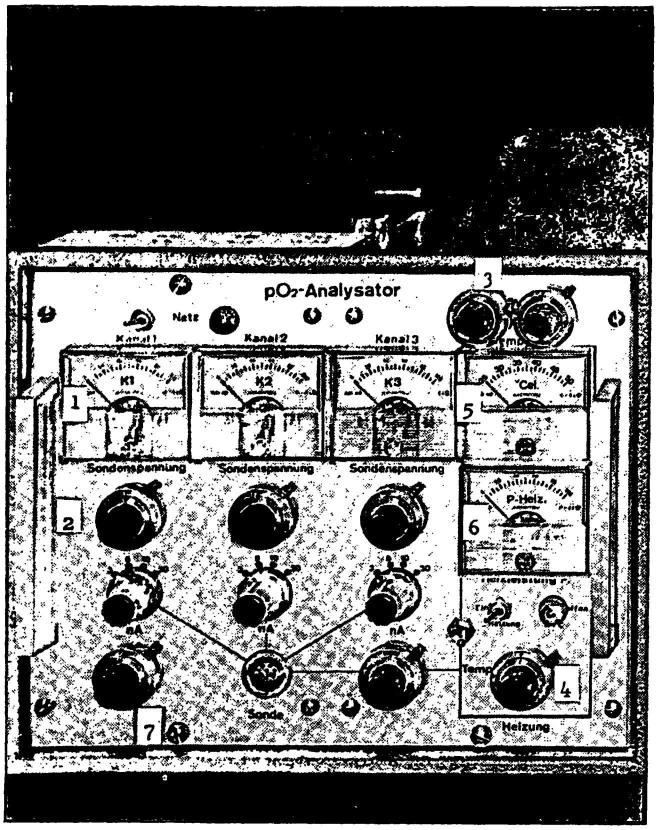

Fig. 4. Po_2-analyzer for transcutaneous Po_2 measurement. 1 nanoamperemeters, 2 polarisation voltage, 3 temperature calibration, 4 heating temperature selection, 5 temperature of the electrode (°C), 6 relatize local blood perfusion (heating power), 7 zero suppression.

The calibration curve of the Clark-electrode is linear and may therefore be obtained by measuring two points. We determine the lower point with **pure nitrogen** (= 0 mm Hg). This has one further advantage, that if undesired zero currents occur they can be detected. The zero currents of our electrodes should not be greater than 0.1 × 10^{-9} A. The second calibration point is usually about 140—150 mm Hg as obtained by pumping **air** through distilled water. The equilibration of the distilled water with the two gases is performed **at 44°C.**

The 95% response time is **8—12 sec.**

3.3 Application of the electrode to the skin

The electrode is fixed on to the skin of newborn infants or adults by means of a self-adhesive ring which is commercially available for ECG electrodes. For fetal measurements the electrode is fixed to the scalp by vacuum. Vacuum fixation may also be used for measurements on parts of the body where the adhesive ring may not be applied, such as the earlobe of adults. **The $tcPo_2$ reading is not influenced by suction.**

A suitable zone for transcutaneous measurements in the newborn infant is the skin of the forehead, but this irritates some infants. We therefore apply the **electrode to**

the chest when monitoring is expected to last for hours. The $tcPo_2$ electrode is placed between the electrodes for the registration of the heart and respiratory rates.
Measurements on mothers during labor were done with the **electrode placed on the sternum,** which allows stable readings even in restless women.

3.4 Influence of temperature on $tcPo_2$ levels

As the electrode is heated and the temperature rises, the recorded $tcPo_2$ increases gradually. This is due to the following three factors:

1. There is **an increase in local Po_2 because of higher local blood flow,** i. e. better arterialization,

2. Given the same total oxygen content within the range of the oxygen dissociation curve, **a temperature increase of 1°C produces a Po_2 increase of approximately 5%,**

3. There is a **temperature effect on the electrode itself.**

The heating temperature of the electrode is chosen so that maximal vasodilatation is obtained; at the same time the skin must tolerate this temperature for several hours.
In order to obtain an effective temperature **of 43°C on the skin** we preset the temperature of the **electrode at 45°C;** this temperature range is well tolerated both by newborn infants and by adults. We measured the actual surface temperature by placing a thin thermistor between the electrode and the skin. Consequently we perform in vitro calibration of the electrode at a temperature lying between these two values, namely 44°C. The subepidermal capillary network, from which O_2 diffuses towards the electrode, also has a temperature of 43°C, provided the skin is thin enough. This temperature produces a remarkable increase in the local Po_2. On the other hand the thickness of the skin and its O_2 consumption induce a decrease in Po_2, so that these factors compensate each other partially.
In newborn infants the skin is relatively thin and consequently the influence of the temperature factor is most important und results in tcP_{O_2} values which are higher than the arterial Po_2 at 37°C. **Simultaneous measurements of $tcPo_2$ and Pao_2 have shown that the $tcPo_2$ level (43C) is approximately 10—15% higher than Pao_2.** In adults transcutaneously measured Po_2 values seem to be of the same order of magnitude as the arterial Po_2, because here the different factors tend to cancel each other.

3.5 Test procedure

At first in vitro calibration is performed at two points. The electrode is then placed on the skin. As Fig. 5 shows, **about 10 minutes are needed until the skin under the electrode is homogeneously heated and the arterialization is adequate.** During this period the $tcPo_2$ reading increases, but provided Pao_2 is stable $tcPo_2$ is also stable after that. Initially the relative blood flow reading is as high as the heat required for the increase in temperature but after the 10 minutes, blood perfusion readings are stable. Any variation in $tcPo_2$ will now, as stated, be due to changes in Pao_2 and this may be tested by hyperventilation, voluntary breath holding or admin-

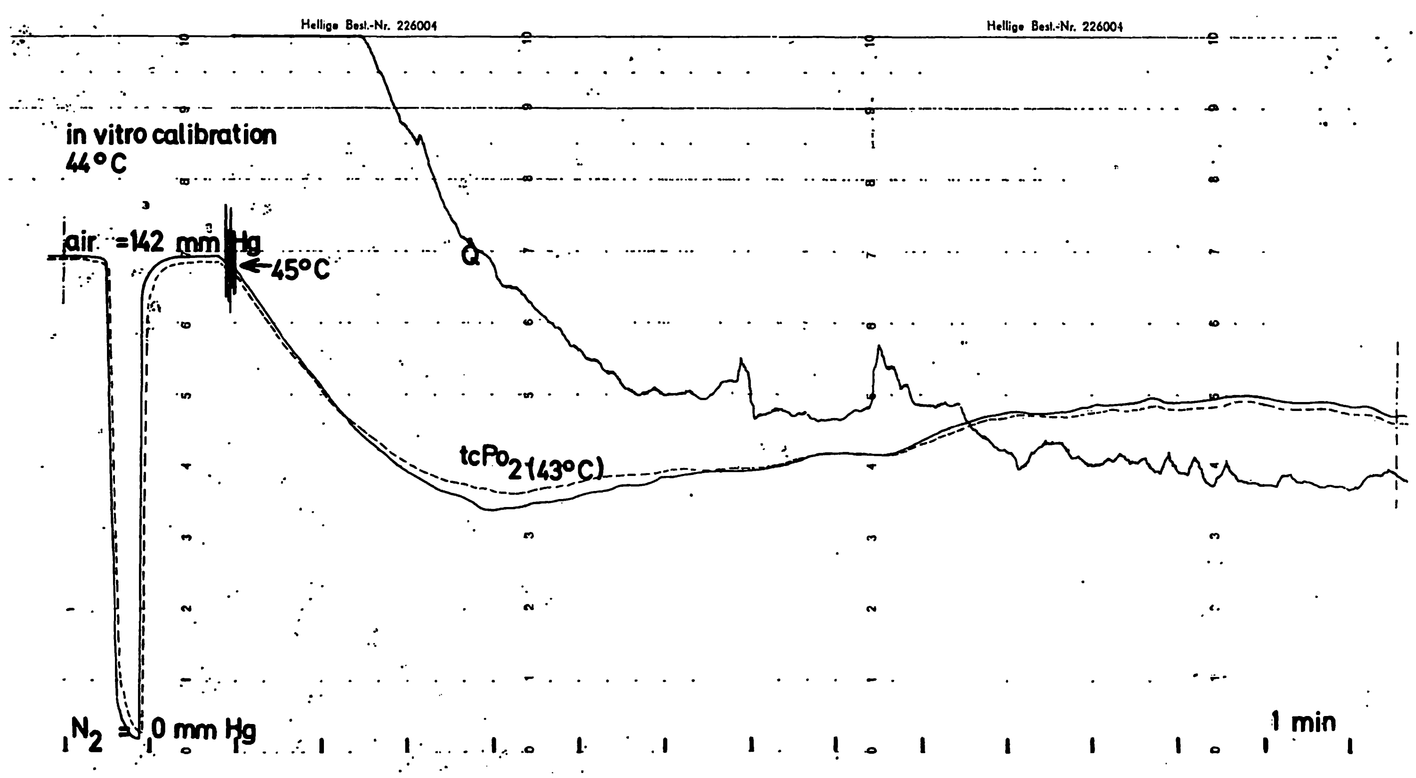

Fig. 5. Calibration and unstable initial phase of transcutaneous measurements of Po_2 (two channels) and blood perfusion ($\dot{Q}$).

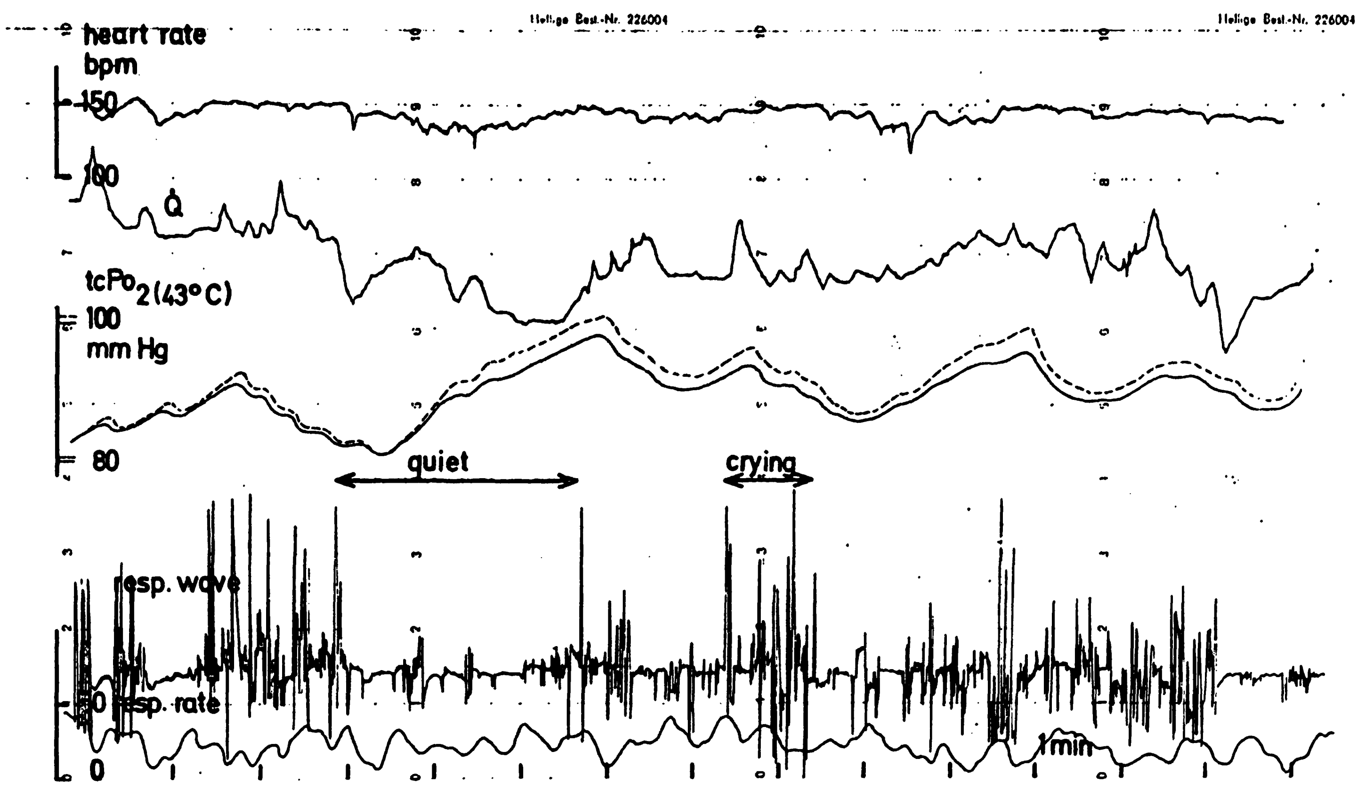

Fig. 6. Part of continuous $tcPo_2$ measurements (two channels) in a 45 minute old infant delivered by Caesarian section. Also registered are heart rate, blood perfusion (Q̇), respiratory wave and respiratory rate.

istration of supplementary oxygen. **In the newborn infant there is a delay in the response of about 10 seconds and in the adult of about 20—30 seconds.**

4. Examples of applications in perinatal medicine

Fig. 6 shows part of a continuous $tcPo_2$ recording in a 45 minute old infant delivered by Caesarean section. Simultaneous registrations of heart rate, respiratory impedance and respiratory rate were also performed. There is a loss in the beat-to-beat variation in the heart rate, which is probably a pathological sign in the newborn infant also. Otherwise the different variables were within normal range. The undulations in the $tcPo_2$ curve are due to variations in the respiration of the infant and are particularly related to its crying. **Brief but intense crying results in a decrease in $tcPo_2$ as a consequence of ineffective breathing and/or increased shunting.**

This technique is intendid for **recognizing or preventing dangerous levels of hypoxemia as well as for avoiding too high Po_2 values during the administration of supplementary oxygen.** Hyperoxemia may cause, among other things, retrolental fibroplasia in the premature infant. Fig. 7 shows the $tcPo_2$ monitoring of a healthy newborn infant to which pure oxygen was administered through a funnel. It can be seen that already **after about two minutes** Po_2 was dangerously high. Only by continuous $tcPo_2$ measurements is it possible to select an appropriate O_2 concentration in an incubator.

Fig. 8 is part of a $tcPo_2$ monitoring of a IV parous woman during her painful second stage of labor. The picture illustrates how Po_2 also varies rapidly in the adult. Intense hyperventilation occurred at the beginning of each contraction (see the increase in respiratory rate and the increased amplitude of the impedance curves). During the period of relaxation there was an almost apnoic phase when Po_2 dropped to about 60 mm Hg from the 100 mm Hg after hyperventilation.

5. Conclusions

As illustrated in some perinatal examples the Po_2 which can be monitored through the intact skin after the induction of a local thermal hyperemia correlates closely with the arterial Po_2.

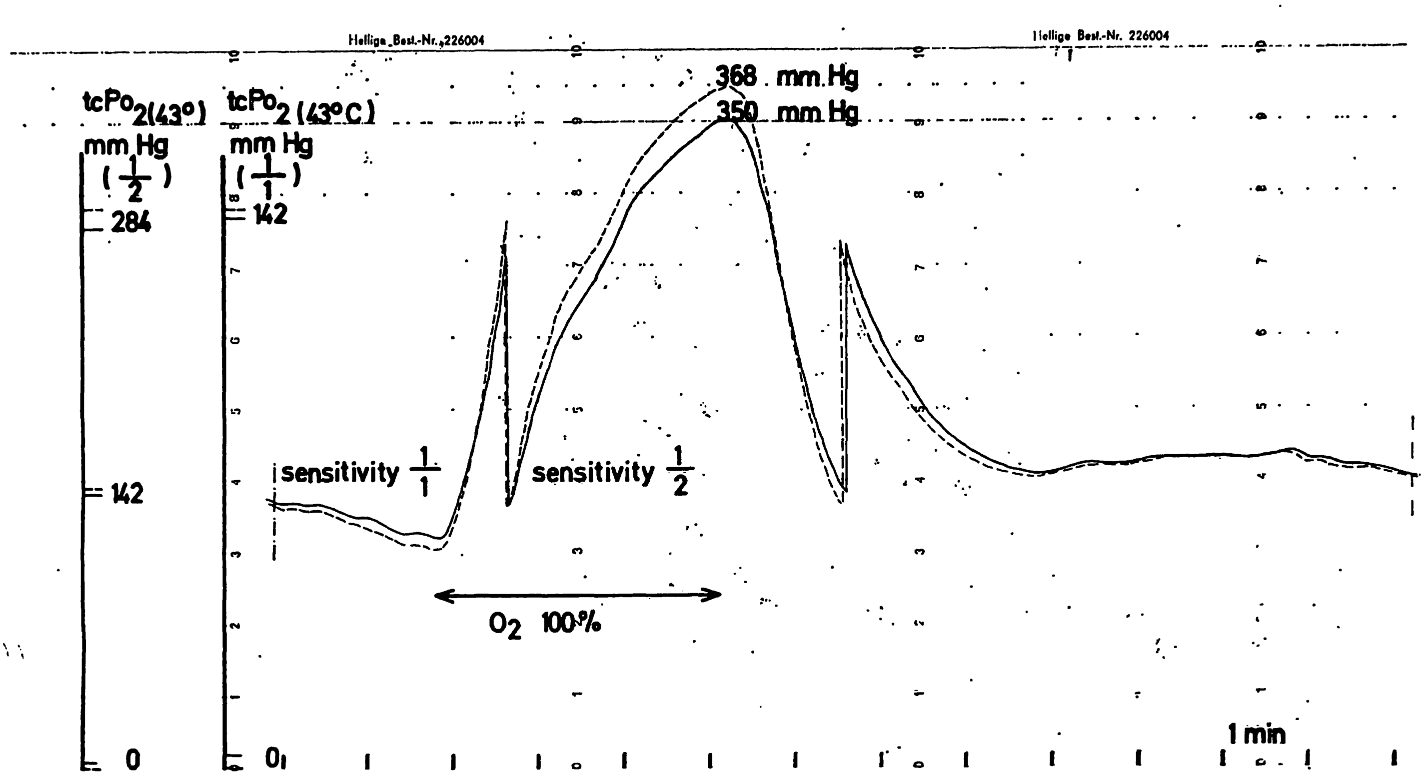

Fig. 7. Part of continuous $tcPo_2$ measurements (two channels) in a healthy 27 hours old infant. The inhalation of O_2 for about three minutes through a funnel produces a rapid increase in Po_2 up to about 350 mm Hg. The sensitivity of the recorder was halved during the O_2 inhalation.

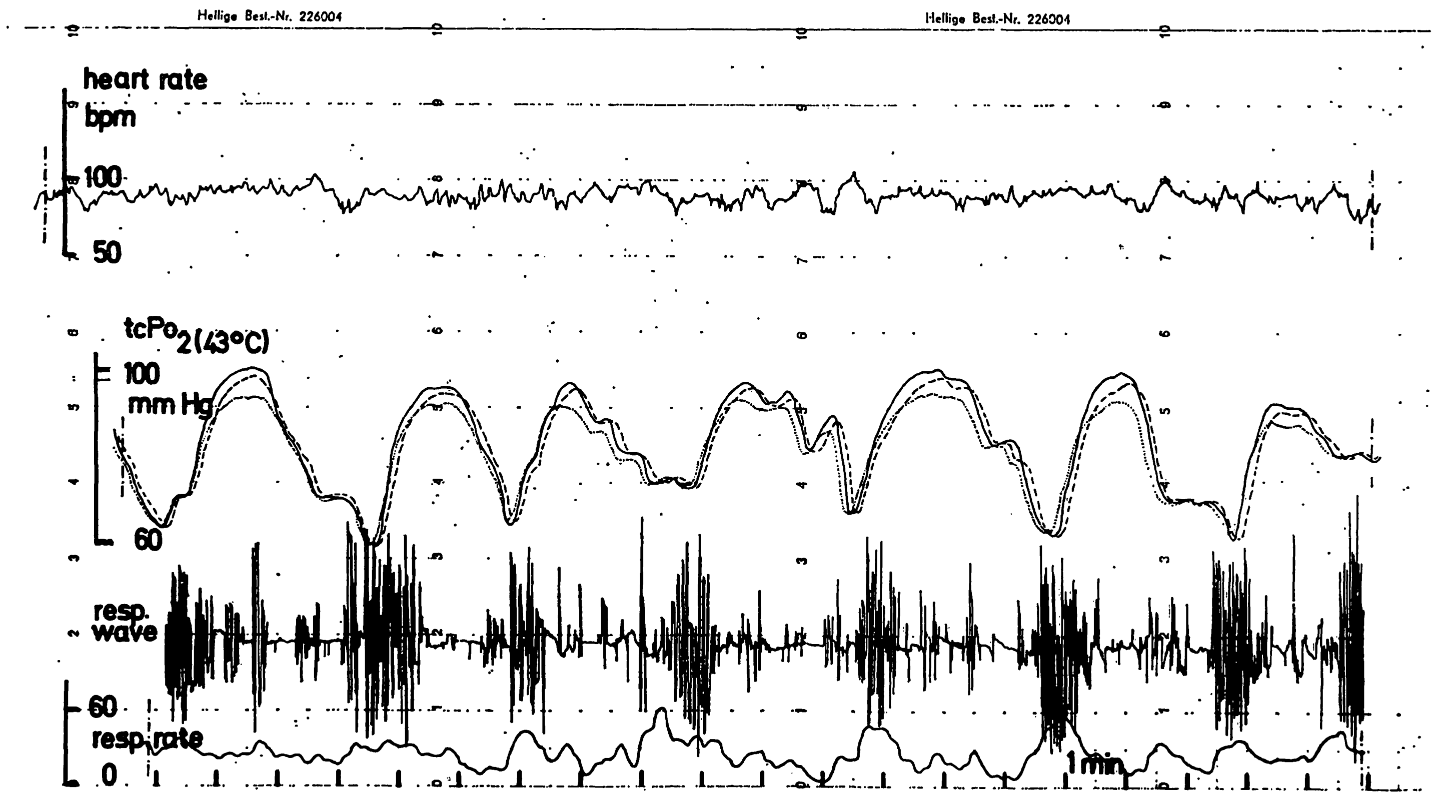

Fig. 8. Part of continuous $tcPo_2$ measurements (three channels) in a multiparous woman during labor with simultaneous monitoring of her heart rate, respiratory rate and respiratory wave. The beginning of each contraction is indicated by a sudden increase in the respiratory rate and in the amplitude of the respiratory wave curve.

Absolute values may be obtained by blood gas analysis. In order to avoid blood sampling we developed a non-invasive calibration method [8, 9] which is now being tested in routine work. **The transcutaneous Po_2 method is ready for clinical application and the described in vitro calibration is sufficient for routine use.** It is now possible to monitor asphyxiated newborn infants in order to evaluate the effect on Po_2 of various systems used for resuscitation such as buffering, administration of drugs and supplementary oxygen. This can be done continuously and without any blood sampling. The method may also be applied in research for studying the physiology of circulatory and respiratory adaptation of the newborn infant. The monitoring of the Po_2 of the mother will increase our knowledge about the action of different drugs. It will now also be possible to observe which breathing technique is most suitable for the mother in order to avoid too low Po_2 levels.

There are still practical problems to be solved before the fetal scalp electrode may be applied routinely to any fetus, but our first measurements have already shown that the continuous monitoring of the fetal Po_2 will improve the diagnosis asphyxia and will make it possible to study the influence of maternal factors on fetal oxygenation.

Summary

The development of a polarographic method by means of which it is possible **to monitor arterial Po_2 continuously through the skin of patients** is described **(Fig. 1)** and some examples of its **application in perinatal medicine** are reported.

In order to obtain satisfactory results optimal dimensions of the electrode itself, of the cathodes and of the oxygen diffusible membranes had to be found. **Consistent and reproducible values** were obtained when the **required local arterialization** was achieved by **heating the oxygen electrode** itself. **Measurement may be done for several hours.**

The oxygen electrode is a modified Clark-cell **(Figs. 2 to 3)**. The cathode is a 15 μm platinum wire. The anode is a silver cylinder, with a groove containing a heating coil. The temperature may be preset at the desired level. The heating energy needed for maintaining the temperature at a constant level is used as a relative measurement of **local blood perfusion** (inverted Gibbs' method) **(Fig. 4)**.

The electrode is fixed to the skin with a **self-adhesive ring.** It is also possible to fix the electrode by means of **suction,** for instance ot the fetal scalp during delivery. Before use the electrode is **calibrated in distilled water with two gases of known Po_2.**

The electrode heated to 45°C induces a temperature of about **43°C** on the skin and this temperature is well tolerated for several hours even in infants.

If due regard is paid to the influence of hyperthermia on the Po_2 of the blood this method makes it possible to measure arterial Po_2 through the skin of newborn infants. Also in adults, where conditions are less favorable because of the thickness of the skin, we obtain values which are significantly correlated to the arterial levels and which change in accordance with arterial changes.

Examples of continuous transcutaneous Po_2 measurements in newborn infants and in women during labor **(Figs. 5 to 8)** illustrate that such Po_2 values give much more detailed information about the Po_2 of the patient than earlier intermittent measurements of blood samples. Changes in the respiratory rate or amplitude of the impedance are reflected in the transcutaneous Po_2 curves. **Hypoxemia or hyperoxemia induced by O_2 inhalation is readily recognizable.**

Keywords: Blood gas analysis, Electrodes (Po_2), Hyperoxemia, Hypoxemia, Intensive care unit, Labor (maternal Po_2), Monitoring systems (continuous), Newborn infant (Po_2), Respiration, Transcutaneous Po_2 measurement.

Zusammenfassung

Transkutane Messung des Blut-Po_2 — Methode und Anwendung in der Perinatal-Medizin

Es wird über die Entwicklung einer polarographischen Methode berichtet, mit der es möglich ist, über **die Haut von Patienten (Schema Abb. 1) den arteriellen Po_2 fortlaufend** zu kontrollieren. Beispiele der **Anwendung der Methode in der Perinatalogie** werden demonstriert.

Eine wesentliche Voraussetzung neben der optimalen Größe der gesamten Elektrode, der Kathoden und der Membranen für die Überwachung der arteriellen Po_2-Werte über die Haut ist, daß das periphere Hautareal so hyperämisiert wird, d. h. "arterialisiert" wird, daß es hinsichtlich der Blutgase arterielles Blut repräsentiert. **Wir erzielen diese Hyperämie durch lokale umschriebene Hyperthermie, die über Stunden zu applizieren ist.**

Die Sauerstoffelektrode ist eine modifizierte Clark-Elektrode **(Abb. 2 und 3).** Ein ringförmig ausgehöhlter Silberzylinder dient einmal als Anode und zum anderen zur Aufnahme einer Heizspirale, die die gewünschte Hyperthermie regelbar erzeugt. Die aufgewandte Heizleistung zur Aufrechterhaltung der vorgegebenen Temperatur kann gleichzeitig als Maß für die **relative lokale Perfusion** (umgekehrtes Gibbssches Verfahren) registriert werden **(Abb. 4).**
Die Elektrode ist mit einem **selbstklebenden Ring** einfach auf der Haut zu fixieren. Sie kann auch durch **Vakuum** angesaugt werden, zum Beispiel für die Messung am vorangehenden Teil während der Geburt. Vorher wird die Elektrode **in destilliertem Wasser bei zwei bekannten Gasdrucken geeicht.**
Mit der mit 45°C innen geheizten Elektrode wird eine Übertemperatur von **43°C** auf der obersten Hautschicht erzeugt, was über Stunden gut von der Haut toleriert wird. Berücksichtigt man den Einfluß dieser Hyperthermie auf den Po_2, ist es auf diese Weise möglich, beim Neugeborenen arterielle Po_2-Werte auf der Haut zu messen bzw. beim Erwachsenen solche, die in strenger Korrelation zum arteriellen Po_2 stehen.
Beispiele der kontinuierlichen transkutanen Po_2-Messung am Neugeborenen und an der Kreißenden **(Abb. 5 bis 8)** zeigen, daß solche Po_2-Werte detailliertere Informationen über den Po_2 erbringen als früher die stichprobenartige Messung in Blutproben.
Veränderungen der Atemfrequenz oder -tiefe wirken sich in charakteristischer Weise auf den transcutan registrierten Po_2 aus. **Hypoxämie und Hyperoxämie bei Beatmung mit O_2 sind umgehend und sicher zu erkennen.**

Schlüsselworte: Atmung, Blutgasanalyse, Elektroden (Po_2), Hyperoxämie, Hypoxämie, Intensivüberwachung, Neugeborenes (Po_2), Transkutane-Po_2-Messung, Überwachung (kontinuierliche), Wehen (mütterlicher Po_2)

Résumé

Mesure transcutanée de la Po_2 sanguine ($tcPo_2$) — Méthode et application en périnatalogie

Nous décrivons le développement d'une méthode polarographique avec laquelle il est **possible de faire des mesures continues de la Po_2 artérielle à travers la peau (Fig. 1).** Nous reportons aussi des **exemples d'application en périnatalogie.**
En dehors de l'optimalisation de la dimension de l'électrode complète, des cathodes et des membranes,**il est absoluement nécéssaire d'hyperémiser la peau, c'est à dire d'«artérialiser» la zone capillaire pour la mesure âfin d'obtenir des valeurs de Po_2 correspondantes aux artérielles.** Nous obtenons l'hyperémie par hyperthermie localisée qui peut **être appliquée pour plusieurs heures.**
Le transducer est une électrode construite selon le principe modifié de Clark **(Fig. 2 et 3).** Le cylindre d'argent creux est l'anode et en même temps comprend la spirale de chauffage qui produit une hyperthermie réglable. L'énergie de chauffage nécéssaire pour maintenir la température au niveau désiré peut être aussi employée comme **mesure relative du flux sanguin** (inversion de la méthode de Gibbs) **(Fig. 4).**
L'électrode est appliquée post-partum par un anneau **auto-adhesif,** et chez le foetus pendant l'accouchement avec **vacuum.** Avant l'emploi l'électrode est **calibrée dans l'eau distillée** équilibrée **avec deux gaz dont on connaît la tension de Po_2.** L'électrode chauffée produit une température effective sur la peau d'environ **43°C,** une température bien tolérable pour plusieurs heures. Considérant l'influence de l'hyperthermie sur la Po_2, cette méthode permet de mesurer des valeurs artérielles de la Po_2 sur la peau du nouveau-né et chez l'adulte d'obtenir des niveaux très proches des vraies valeurs artérielles.
Des mesures par tielles transcutanées de la Po_2 chez le nouveau-né et chez le femme pendant l'accouchement **(Fig. 5—8)** montrent que ces mesures de la Po_2 obtenues à travers la peau donnent une information continue et optimale sur l'approvisionnement en O_2 du malade. Les changements en respiration/min. et en profondeur ont une influence typique sur la Po_2 transcutanée. **L'hypoxémie et l'hyperoxémie induite par l'inhalation de O_2 peuvent être rapidement et facilement découvertes.**

Mots-clés: Accouchement (Po_2 maternelle), Analyses des gaz du sang, Electrode (Po_2), Hyperoxémie, Hypoxémie, Mesure transcutanée de la Po_2, Nouveau-né, Respiration.

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Dr. Renate Huch
Universitäts-Frauenklinik
D-3550 Marburg
Pilgrimstein 3
Germany

and

Max-Planck-Institut für Arbeitsphysiologie
D-4600 Dortmund
Rheinlanddamm 210
Germany