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# Reliability of transcutaneous monitoring of arterial $Po_2$ in newborn infants

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**Huch, R., Lübbers, D. W., and Huch, A. (1974).** *Archives of Disease in Childhood*, **49**, 213. **Reliability of transcutaneous monitoring of arterial $Po_2$ in newborn infants.** Blood $Po_2$ was measured transcutaneously on skin 'arterialized' by means of a heated $Po_2$ electrode. Oxygen diffuses through the relatively thin skin of newborn infants from the outer capillary layer to an electrode fixed to the skin. Arterial changes were registered with approximately a 10-second delay. 41 comparative transcutaneous and arterial $Po_2$ measurements were performed. Transcutaneous $Po_2$ values correlated quite well with arterial values within the whole $Po_2$ range, the correlation being particularly satisfactory in the $Po_2$ range below 100 mmHg. The method is suitable for long-term monitoring of newborn infants, as it is without risk.

Continuous monitoring of arterial $Po_2$ is of major importance in premature babies and in infants with respiratory distress syndrome in order to avoid hyperoxaemia. When applying oxygen therapy, the paediatrician is faced with the problem of avoiding hyperoxaemia, leading to retrolental fibroplasia, without risking hypoxaemia with its damaging consequences.

Many successful experiments have been made with discontinuous (Beutnagel, Gauch, and Fabel, 1972; Veasy *et al.*, 1971) and continuous (Harris and Nugent, 1973; Huch, Huch, and Rooth, 1973c; Parker *et al.*, 1971) monitoring of $Po_2$ in aortic blood by means of a catheter inserted into an umbilical artery. In addition to the technical problems of managing the indwelling catheter and the additional risk to the baby (Cochran, Davis, and Smith, 1968), if there is a pulmonary and/or cardiac shunt, the $Po_2$ found in the abdominal aorta cannot be assumed to be the same as the $Po_2$ in arteries in the head.

The method of polarographic measurement of arterial $Po_2$ through the intact skin of humans, developed in recent years (Huch *et al.*, 1972b, c; Huch, Lübbers, and Huch, 1972d), makes it possible to monitor the arterial $Po_2$ ($Pao_2$) of a child with this transcutaneous $Po_2$ ($tcPo_2$) method for hours or even days. We have already reported the principle of the method (Huch, Huch, and Lübbers, 1972a; 1973b) and its application in adults (Huch *et al.*, 1973a). The data here presented compare transcutaneous and arterial $Po_2$ measurements in newborns.

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## Material and method

The polarographic transcutaneous measurement of blood $Po_2$ is possible when 'arterialization' of a peripheral capillary region can be obtained, so that oxygen diffuses from the superficial capillary layer through the skin, and so to the electrode.

The required local hyperaemia is induced by means of hyperthermia, by heating a modified Clark electrode itself (Clark, 1956; Huch *et al.*, 1972b, d). The heating coil fits into the hollow ring-shaped silver anode, which surrounds three separate 15 $\mu$m platinum cathodes. At the same time we register the heating energy required for keeping the skin temperature constant at the present level. This serves as a measure of local perfusion (Gibbs, 1933) and is a control of perfusion efficiency. A temperature of 43 °C on the surface of the skin is monitored and controlled by a thermistor which fits into the silver anode close to the electrode surface. This temperature produces, within about 10 minutes, an increase in local perfusion, and thereafter $Po_2$ variations registered transcutaneously will reflect arterial changes.

The electrode is fixed to the skin by means of a self-adhesive ring, so that oxygen from the surrounding air cannot diffuse to the cathodes. When monitoring newborn infants, in order to be sure of measuring $Po_2$ above the ductus arteriosus, we apply the electrode to the chest near one of the nipples (Fig. 1).

Before and after each test the electrode is calibrated *in vitro* using two gases with known $Po_2$, i.e. pure nitrogen and air at the temperature of the test. The 95% *in vitro*

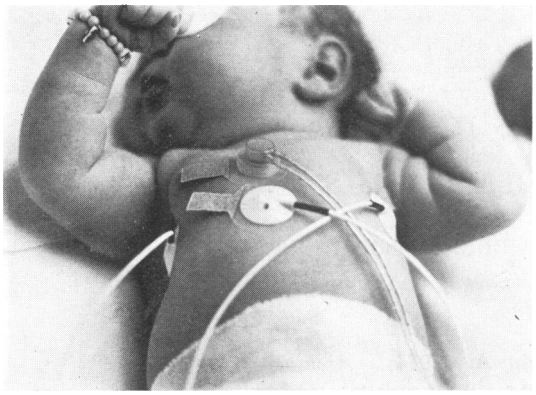

FIG. 1.—*Fixation of the $Po_2$ electrode with a self-adhesive ring above the ECG electrodes.*

response time (electrode covered with 12 $\mu$m cellophane and 12 $\mu$m teflon) was approximately 8–10 seconds. Arterial $Po_2$ changes were observed transcutaneously with a delay of approximately 10 seconds.

Continuous registration of transcutaneous $Po_2$ was performed with a 6-pen Rikadenki recorder (Hellige, Freiburg, Germany). Since four channels were normally required for simultaneous registration of heart rate (beat to beat), respiratory rate, transthoracic impedance, and local perfusion, we could record only 2 of the 3 cathodes. When identical readings of $tcPo_2$ were obtained from 2 cathodes, we judged the electrode to be properly attached to the skin.

Samples of arterial blood were obtained by puncturing the radial artery, usually on the right side, and collecting the blood into a series of 3 or 4 heparinized glass capillaries (100 mm long) connected to each other with short pieces of silicone tube (Huch and Huch, 1973). We always tried to sample blood when the child was sleeping or quiet.

We performed 41 punctures in 25 children, aged 1 to 161 hours. 26 samples were taken from the infant breathing air, and 15 while breathing 100% oxygen. Altogether we determined the arterial $Po_2$ in 116 capillary tubes, and in only three cases was only a single capillary tube used.

Arterial $Po_2$ values were determined in a Combi-analysator (Eschweiler, Kiel, Germany) immediately after sampling. In order to avoid delay, special care was used for samples taken during hyperoxia. The time between sampling and analysis of blood with high $Po_2$ values was noted, and when multiple determinations were performed the values were extrapolated to the time of sampling in order to take into consideration the $O_2$ consumption of the blood itself (Gleichmann and Lübbers, 1960; Lübbers and Windisch, 1963).

All the children were born in the Department of Gynaecology and Obstetrics, University of Marburg.

TABL

*Arterial and transcutaneous $Po_2$ values in 25 infan*

| Case no. | Age (hr) | Weight (g) | No. of capillary tubes | Breathing air | | |
|---|---|---|---|---|---|---|
| | | | | $Pao_2$ (mmHg) mean (range) | $tcPo_2$* (mmHg) | |
| | | | | | Channel 1 mean (range) | Channel 2 mean (range) |
| 1 | 23 | 3930 | 3 | 83 (83) | 99 (98–99) | 99 (99) |
| 2 | 37 | 3100 | 2 | 86 (86) | 99 (97–101) | 95 (92–98) |
| 3 | 2 | 3750 | 3 | 89 (87–92) | 90 (85–96) | 89 (87–92) |
| 4 | 8 | 3580 | 2 | 91 (91) | 110 (110) | 103 (103) |
| 5 | 25 | 3570 | 2 | 94 (94) | 106 (105–106) | 102 (102) |
| 6 | 4 | 2800 | 2 | 53 (53) | 51 (51) | 50 (50) |
| 7 | 15 | 3560 | 2 | 89 (89) | 111 (108–113) | 104 (102–105) |
| 8 | 107 | 3510 | 4 | 77 (74–79) | 78 (75–81) | 78 (75–81) |
| 9 | 152 | 4230 | 3 | 77 (76–77) | 92 (91–92) | 92 (92) |
| 10 | 54 | 3830 | 8 | 78 (76–79) | — | 78 (78) |
| 11 | 60 | 2870 | 5 | 64 (61–68) | 76 (73–79) | 75 (70–75) |
| 12 | 15 | 3590 | 4 | 70 (64–74) | 81 (79–84) | 84 (80–87) |
| 13 | 35 | 3620 | 1 | 81 | 84 | 84 |
| 14 | 12 | 3500 | 1 | 76 | 81 | 83 |
| 15 | 108 | 3320 | 2 | 80 (78–82) | 84 (83–85) | 85 (83–86) |
| 16 | 50 | 3550 | 3 | 69 (69–70) | 72 (70 -75) | 75 (73–77) |
| 17 | 161 | 3590 | 5 | 89 (88–90) | 98 (96–100) | 100 (98–102) |
| 18 | 7 | 3040 | 2 | 62 (62) | 76 (76) | 78 (78) |
| 19 | 133 | 3390 | 4 | 82 (81–83) | 89 (88–91) | 86 (85–88) |
| 20 | 4 | 2890 | 5 | 64 (62–66) | 74 (71–77) | 73 (68–76) |
| 21 | 10 | 4420 | 2 | 62 (57–67) | — | 75 (70–80) |
| 22 | 15 | 3640 | 2 | 73 (73) | 82 (82) | 79 (79) |
| 23 | 18 | 3380 | 7 | 65 (62–70) | 77 (74–87) | 71 (69–76) |
| 24 | 1 | 3730 | 2 | 87 (87) | 85 (85) | 87 (87) |
| ,, | 25 | 3730 | 3 | 70 (69–72) | 77 (76–78) | 75 (73–77) |
| 25 | 24 | 3560 | 2 | 80 | 91 | 92 |

*$tcPo_2$, transcutaneous $Po_2$. Correlation channel 1, $r_1 = 0{\cdot}9617$, channel 2, $r_2 = 0{\cdot}9723$. Regression equation (x = arterial $Po_2$, y =

Maternal agreement was obtained in each case for these studies. As shown in the Table, 19 babies were normal after birth, 6 had Apgar scores from 1 to 7 (5 minutes), and one (Case 6) was still distressed at the time of the test.

## Results

Fig. 2 shows part of a typical continuous transcutaneous measurement of arterial $Po_2$ in a 25-hour-old healthy baby (Case 24). The radial artery was punctured first with the baby breathing pure oxygen and then breathing air. The $Po_2$ in 5 capillaries was 440, 441, 435, 441, 438, mean 439 mmHg. The second sampling was made approximately 11 minutes later during air breathing. Here the mean arterial $Po_2$ of 3 capillaries was 70 mmHg (69, 69, 72 mmHg). At the time of the first puncture the child was quiet, whereas he cried loudly during the second; this can be recognized by the increase in the heart rate and in the rapid decrease of $tcPo_2$. As shown in Fig. 2, the sampling times were marked on the skin $Po_2$ curves and the corresponding transcutaneous $Po_2$ values were calculated for both channels of the surface electrode.

The Table shows the mean value of $Pao_2$ obtained for each arterial puncture, together with the values obtained from the individual capillaries. The corresponding mean value of the transcutaneous $Po_2$ of each channel is given.

Fig. 3 is the graphic presentation of the arterial and transcutaneous $Po_2$ values in the Table (average of the two $tcPo_2$ channels).

## Discussion

The results presented show that the local application of heat increases the skin perfusion of newborn infants so that $Po_2$ values obtained transcutaneously prove to be reasonably well correlated with the arterial $Po_2$.

Previous experiments with chemically induced hyperaemia (Evans and Naylor, 1967; Huch *et al.*, 1972d) have shown that this type of arterialization fails to achieve reliable, long-term hyperaemia. Transcutaneous $Po_2$ values obtained after arterialization of the skin with chemical substances were often appreciably lower than the arterial $Po_2$. Using regulated hyperthermia for inducing hyperaemia permits long-term continuous $Po_2$ monitoring, since the preset temperature of 43 °C on skin is well tolerated by newborn infants without having to change the site of the electrode. The simultaneous registration of $Po_2$ and local perfusion also gives some measure of the perfusion efficiency.

*eathing air and in 15 infants breathing 100% oxygen*

| No. of capillary tubes | Breathing 100% $O_2$ | | | Clinical remarks |
|---|---|---|---|---|
| | $Pao_2$ (mmHg) mean (range) | $tcPo_2$* (mmHg) | | |
| | | Channel 1 mean (range) | Channel 2 mean (range) | |
| | | | | Caesarean section; Apgar 6 |
| | | | | Surviving twin; Apgar 3 |
| 2 | 342 (336–348) | 356 (348–364) | 333 (327–338) | |
| | | | | Caesarean section; Apgar 1 |
| 4 | 394 (390–412) | 390 (390) | 400 (400) | |
| 3 | 385 (382–390) | 286 (286) | 297 (297) | |
| 3 | 353 (338–370) | 397 (374–390) | 358 (354–362) | |
| 3 | 344 (320–372) | 398 (374–420) | 410 (385–410) | |
| 2 | 277 (268–285) | 279 (275–283) | 312 (306–318) | |
| 2 | 390 (376–404) | 372 (365–379) | 373 (370–375) | |
| 6 | 316 (310–323) | 309 (308–314) | 298 (293–302) | |
| 1 | 399 | 365 | 330 | |
| 4 | 367 (352–384) | 312 (312) | 339 (334–344) | Apgar 4 |
| 2 | 347 (341–352) | — | 391 (382–400) | Apgar 7 |
| 2 | 397 (393–401) | — | 396 (396) | |
| 3 | 492 (482–504) | 505 (505) | 497 (497) | |
| 4 | 344 (334–351) | 165 (160–170) | 197 (192–202) | Apgar 1 |
| 5 | 439 (435–441) | 364 (364) | 376 (376) | |

:ranscutaneous $Po_2$) (for channel 1, $y_1 = 0{\cdot}8827x + 17{\cdot}65$; for channel 2, $y_2 = 0{\cdot}9043x + 15{\cdot}49$).

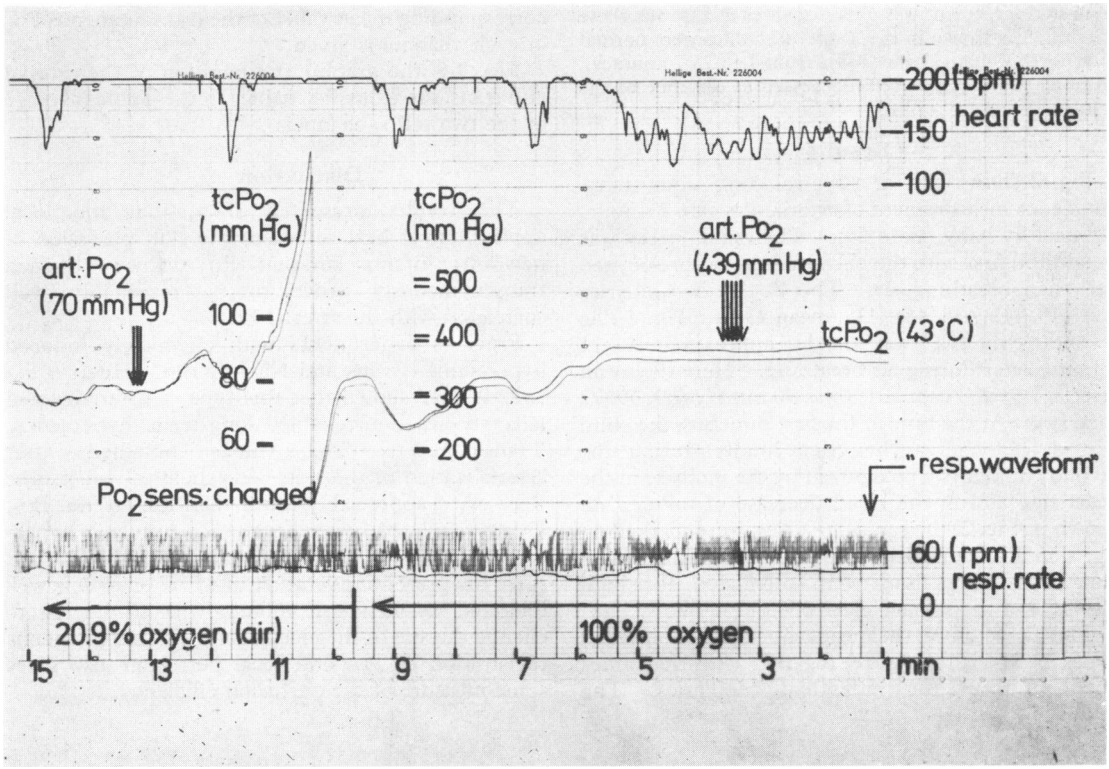


FIG. 2.—*Part of a continuous transcutaneous $Po_2$ registration (Case 24, 25 hours old). Time scale reads from right to left. From top to bottom: heart rate (beat to beat); transcutaneous $Po_2$ (two channels of the same electrode); 'respiratory waveform'; respiratory rate. The right radial artery was punctured when the infant breathed 100% oxygen, indicated by 5 arrows (= 5 capillary tubes), and then during air breathing (3 arrows).*

The transcutaneous $Po_2$ value (43 °C, 12 μm membrane) obtained is the sum of the effects of various factors that influence the true local $Po_2$. Firstly, after *in vitro* calibration and covering of the electrode with a 12 μm thick teflon membrane, the $tcPo_2$ found is approximately 10% less than the 'true' value. Our experiments (Huch *et al.*, 1972d) have shown that for the 15 μm cathodes which we use, a teflon membrane of approximately 50 μm thickness would be more suitable for measuring absolute values on skin. However, we prefer to use the 12 μm membrane since it has a faster response time (95% response time for a 12 μm membrane, 8–10 seconds; for a 50 μm membrane, 55–60 seconds).

Secondly, local $tcPo_2$ is lowered by the $O_2$ consumption of the avascular epidermis layer. It is therefore advantageous to choose a site where the epidermis is very thin and well capillarized to obtain fast and accurate reactions.

Thirdly, $Po_2$ in the arterialized region is increased by the hyperthermia from the heated electrode. It is known (Bradley, Stupfel, and Severinghaus, 1956; Lübbers and Windisch, 1963) that $Po_2$ in the blood, in a closed system, and in the range of the haemoglobin binding curve shows an increase of approximately 5% per degree of temperature increase. If we assume that the temperature in the outer capillary layer is the same as on the skin surface, namely 43 °C, the $Po_2$ of the blood at body temperature is significantly increased locally. In the high $Po_2$ range, $> 100$ mmHg, where the amount of $O_2$ physically dissolved in the blood is predominant, the temperature increase affects $Po_2$ only about 1% per °C; the $O_2$ coefficient of solubility decreases with increasing temperature (Altman and Dittmer, 1970).

These factors which influence the true local $Po_2$ sometimes tend to cancel each other. In newborn infants, whose thin skin is ideal for transcutaneous monitoring, the predominant influence is raised skin temperature.

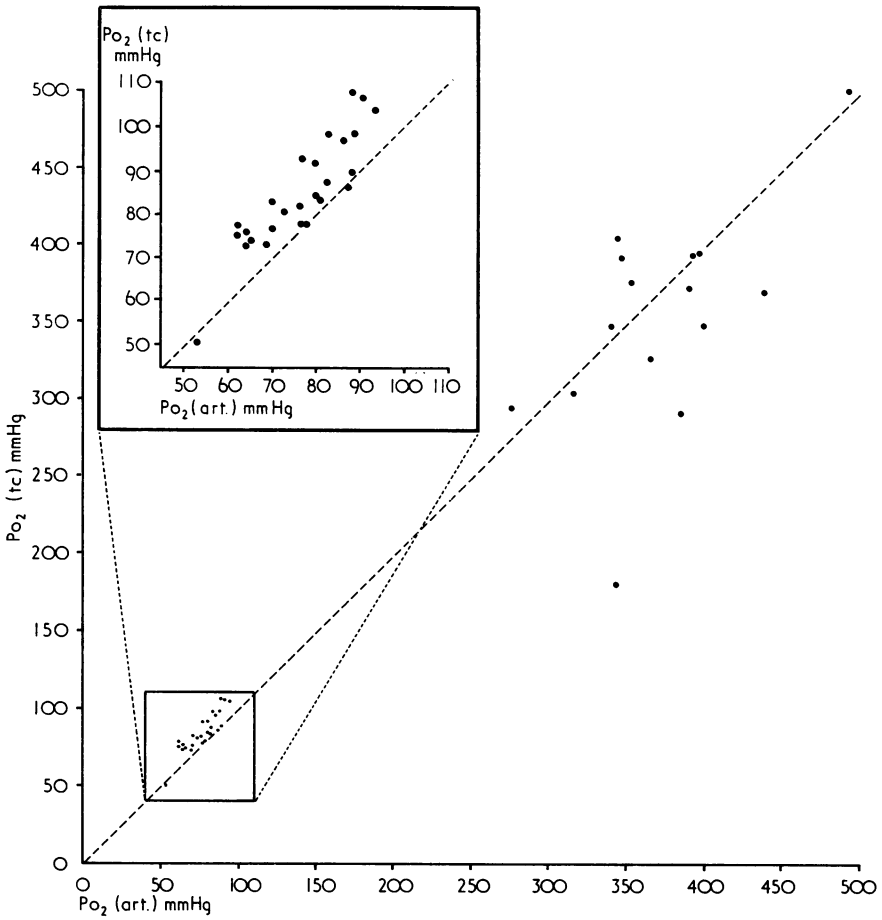


FIG. 3.—*Comparison of arterial $Po_2$ (horizontal axis) and corresponding transcutaneous $Po_2$ (43 °C, 12 μm membrane) (vertical axis) in 41 arterial punctures.*

The correlation with arterial $Po_2$ is good throughout the whole physiological range of $Po_2$, particularly in the range of the haemoglobin binding curve. As shown in the Table and in Fig. 3, a measurement made when blood $Po_2$ is $<100$ mmHg gives $tcPo_2$ values (43 °C, 12 μm membrane) which average 11% higher than the arterial levels, for the reasons mentioned. When measuring at high $Po_2$ values, $>270$ mg,Hm the deviation of $tcPo_2$ is not so systematic, and the transcutaneous values are distributed on both sides of the ideal correlation curve. However, at high partial pressures the possibility of error in both arterial and transcutaneous $Po_2$ determinations increases with the increase of blood $Po_2$. $O_2$ consumption of blood in the time between sampling and measurement is also an important factor.

By use of the capillary tube method (Huch and Huch, 1973) we can minimize all errors concerning sampling, transfer of the blood sample, mistakes caused by dead space in the syringe, and dilution with heparin, and the same heparinized capillaries used for sampling are applied directly to the $Po_2$ analyser.

Regarding the precision of transcutaneous measurements, calibration with nitrogen and air is optimal only when $tcPo_2$ is also within this range. Higher precision at $Po_2$ values above 150 mmHg can be obtained by calibrating the electrode with a correspondingly higher oxygen concentration. Our previous experiments have shown that, as with all Clark electrodes, the calibration curve of the heated surface electrode is linear, so that calibration can be performed with two gases. Ideally, one should

calibrate the electrode with gases covering the range of the expected $Po_2$ values on the skin. In fact, when we measured $Po_2$ transcutaneously, the 2 channels differed from each other by only about 2·7% with the baby breathing air, whereas when the baby breathed 100% $O_2$ they showed a difference of about 6·9%. Any slight difference in the steepness of the calibration curves of the two cathodes in the low $Po_2$ range produces a large difference at high oxygen levels.

The correlation between arterial and transcutaneous $Po_2$ was good in Case 6, where the infant had respiratory distress after a complicated delivery. The low arterial $Po_2$, 53 mmHg, corresponded well to the transcutaneous values. This is our only experience with infants with respiratory distress, but successful results in such cases have been obtained by others with our equipment (G. Rooth and A. Fenner, personal communication, 1972).

The difference we observed between $tcPo_2$ (43 °C, 12 μm membrane) and $Pao_2$ during hyperoxaemia in Case 24 cannot easily be explained. This child was born distressed, but showed no particular clinical symptom when we tested it at age 1 hour. Breathing air, arterial $Po_2$ was 87 mmHg and corresponded to the transcutaneous values. We were more surprised about the difference when breathing 100% $O_2$, especially because both arterial $Po_2$ values were normal and did not allow explanations such as possible centralization, etc., for the too low $tcPo_2$. A second test performed at age 25 hours, however, gave results which agreed.

In summary, transcutaneous $Po_2$ measurement is satisfactory for monitoring arterial $Po_2$. Clinically, the most important $Po_2$ range is $<100$ mmHg, and it was here that correlation was best. In this range avoidance of hypoxia without risking hyperoxia is mandatory.

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## References

Altman, P. L., and Dittmer, D. S. (Eds.) (1970). *Respiration and Circulation*, p. 18. Federation of American Societies for Experimental Biology, Bethesda, Maryland.

Beutnagel, H., Gauch, D., and Fabel, H. (1972). Der arterielle Sauerstoffpartialdruck beim Neugeborenen in den ersten Lebensminuten. *Zeitschrift für Geburtshilfe und Perinatologie*, **176**, 117.

Bradley, A. F., Stupfel, M., and Severinghaus, J. W. (1956). Effect of temperature on $PCo_2$ and $Po_2$ of blood in vitro. *Journal of Applied Physiology*, **9**, 201.

Clark, L. C., Jr. (1956). Monitor and control of blood and tissue oxygen tensions. *Transactions. American Society for Artificial Internal Organs*, **2**, 41.

Cochran, W. D., Davis, H. T., and Smith, C. A. (1968). Advantages and complications of umbilical artery catheterization in the newborn. *Pediatrics*, **42**, 769.

Evans, N. T. S., and Naylor, P. F. D. (1967). The systemic oxygen supply to the surface of human skin. *Respiration Physiology*, **3**, 21.

Gibbs, F. A. (1933). A thermoelectric blood flow recorder in the form of a needle. *Proceedings of the Society for Experimental Biology and Medicine*, **31**, 141.

Gleichmann, U., and Lübbers, D. W. (1960). Die Messung des Sauerstoffdruckes in Gasen und Flüssigkeiten mit der Platin-Elektrode unter besonderer Berücksichtigung der Messung im Blut. *Pflügers Archiv für die Gesamte Physiologie des Menschen und der Tiere*, **271**, 431.

Harris, T. R., and Nugent, M. (1973). Continuous arterial oxygen tension monitoring in the newborn infant. *Journal of Pediatrics*, **82**, 929.

Huch, A., and Huch, R. (1973). A new method for arterial blood sampling in newborn infants and adults. *Archives of Disease in Childhood*, **48**, 982.

Huch, A., Huch, R., Arner, B., and Rooth, G. (1973a). Continuous transcutaneous oxygen tension measured with a heated electrode. *Scandinavian Journal of Clinical and Laboratory Investigation*, **31**, 269.

Huch, A., Huch, R., and Lübbers, D. W. (1972a). Überwachung des Neugeborenen durch transcutane $Po_2$-Messung. Vortrag 5. Deutsches Kongress für Perinatale Medizin, Berlin.

Huch, R., Huch, A., and Lübbers, D. W. (1973b). Transcutaneous measurement of blood $Po_2$ ($tcPo_2$)—method and application in perinatal medicine. *Journal of Perinatal Medicine*, **1**, 183.

Huch, A., Huch, R., Meinzer, K., and Lübbers, D. W. (1972b). Eine schnelle, beheizte Pt-Oberflächenelektrode zur kontinuierlichen Überwachung des $Po_2$ beim Menschen. Elektrodenaufbau und -eigenschaften. Vortrag Medizin-Technik, Stuttgart.

Huch, R., Huch, A., Meinzer, K., and Lübbers, D. W. (1972c). Eine schnelle, beheizte Pt-Oberflächenelektrode zur kontinuierlichen Überwachung des $PO_2$ beim Menschen. Messergebnisse. Vortrag Medizin-Technik, Stuttgart.

Huch, A., Huch, R., and Rooth, G. (1973c). Monitoring the intravascular $Po_2$ in newborn infants. *Journal of Perinatal Medicine*, **1**, 53.

Huch, R., Lübbers, D. W. and Huch, A. (1972d). Quantitative continuous measurement of partial oxygen pressure on the skin of adults and newborn babies. *Pflügers Archiv für die Gesamte Physiologie des Menschen und der Tiere*, **337**, 185.

Lübbers, D. W., and Windisch, E. (1963). Die Messung hoher Sauerstoffdrucke in kleinen Gas- oder Flüssigkeitsmengen mit der Pt-Elektrode. *Pflügers Archiv für die Gesamte Physiologie des Menschen und der Tiere*, **276**, 429.

Parker, D., Key, A., Davies, R., and Scopes, J. W. (1971). A disposable catheter-tip transducer for continuous measurement of blood oxygen tension in vivo. *Bio-Medical Engineering*, **6**, 313.

Veasy, L. G., Clark, J. S., Jung, A. L., and Jenkins, J. L. (1971). A system for computerized automated blood gas analysis. Its use in newborn infants with respiratory distress. *Pediatrics*, **48**, 5.

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