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.

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 μm 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 μ m cellophane and 12 μ 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.

Arterial and transcutaneous PO_2 values in 25 infants

Case no.	Age (hr)	Weight (g)	No. of capillary tubes	PaO_2 (mmHg) mean (range)	Breathing air	
					$tcPO_2^*$ (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, $r_1 = 0.9617$, channel 2, $r_2 = 0.9723$. Regression equation (x = arterial PO_2 , y = $tcPO_2$)

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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.

breathing 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)	
4	394 (390–412)	390 (390)	400 (400)	Caesarean section; Apgar 1
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)	

transcutaneous Po_2) (for channel 1, $y_1 = 0.8827x + 17.65$; for channel 2, $y_2 = 0.9043x + 15.49$).

FIG. 2.—Part of a continuous transcutaneous P_{O_2} registration (Case 24, 25 hours old). Time scale reads from right to left. From top to bottom: heart rate (beat to beat); transcutaneous P_{O_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 P_{O_2} value (43 °C, 12 μ m membrane) obtained is the sum of the effects of various factors that influence the true local P_{O_2} . Firstly, after *in vitro* calibration and covering of the electrode with a 12 μ m thick teflon membrane, the tcP_{O_2} found is approximately 10% less than the 'true' value. Our experiments (Huch *et al.*, 1972d) have shown that for the 15 μ m cathodes which we use, a teflon membrane of approximately 50 μ m thickness would be more suitable for measuring absolute values on skin. However, we prefer to use the 12 μ m membrane since it has a faster response time (95% response time for a 12 μ m membrane, 8–10 seconds; for a 50 μ m membrane, 55–60 seconds).

Secondly, local tcP_{O_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, P_{O_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 P_{O_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 P_{O_2} of the blood at body temperature is significantly increased locally. In the high P_{O_2} range, > 100 mmHg, where the amount of O_2 physically dissolved in the blood is predominant, the temperature increase affects P_{O_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 P_{O_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 ($43^\circ C$, $12\ \mu m$ 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 ($43^\circ C$, $12\ \mu m$ membrane) which average 11% higher than the arterial levels, for the reasons mentioned. When measuring at high PO_2 values, >270 mmHg, 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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