Evaluation of Response Time of a Transcutaneous Oxygen Tension Electrode

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Summary

Response characteristics of a transcutaneous PO₂ electrode to step changes in PaO₂ were determined. *In vitro* lag time and 95% response time of a transcutaneous PO₂ monitor were compared to *in vivo* response. Release of arterial occlusion was used to produce rapid local PaO₂ changes in human infants and adults. *In vitro* lag time and 95% response time varied according to whether an increment or decrement in PO₂ was produced. *In vivo* 95% response time of this electrode was two to six times slower than previous estimates, and it varied significantly with the magnitude of the step change, subject age, anatomic location, and local hemodynamic factors. Also, we found that *in vivo* lag time is two to three times faster than previously reported.

Speculation

Under steady-state conditions, transcutaneous PO₂ correlates well with PaO₂, but when rapid change is encountered as during oxygen administration or apnea, transcutaneous PO₂ will significantly underestimate PaO₂ change. On the other hand, the relatively short lag time suggests that the transcutaneous PO₂ electrode may be useful in following rapid PaO₂ changes qualitatively.

Monitoring transcutaneous oxygen tension (t.c. PO₂) is a recent but already widely used technique in the care of sick infants. Under steady state conditions, t.c. PO₂ has been shown to correlate well with arterial oxygen tension (PaO₂) (10, 11, 22). Recently, investigators have begun to use this instrument to evaluate rapid changes in PaO₂ (1, 2, 17, 18); however, the usefulness of this technique for estimating PaO₂ in nonsteady state situations is unknown. We have determined the responsiveness of a t.c. PO₂ electrode to arterial PO₂ change and have compared the *in vivo* lag and response times to *in vitro* response. We have observed that the *in vivo* response of this electrode is slower than previous estimates; moreover, the response time is influenced by magnitude of step change, subject age, anatomic location, and local hemodynamic factors.

METHODS AND SUBJECTS

A commercially marketed t.c. PO₂ electrode (Oxymonitor; Litton, Inc., Elk Grove, IL) was used in these studies. It was calibrated in room air and in saturated sodium bisulphite solution at a sensor temperature of 44°C (infants) or 45°C (adults) according to the manufacturer's recommendations.

IN VITRO STUDIES

We produced step changes by applying a drop of the sodium bisulphite solution on the electrode and by removing it with a clean cloth.

IN VIVO STUDIES

Vascular occlusion was used to produce step changes in dermal capillary PO₂ (5-9). Arterial occlusion was achieved by inflating a blood pressure cuff 20 to 30 mm Hg above the systolic pressure, after which there was a gradual fall in t.c. PO₂. The duration of arterial occlusion was varied to change the magnitude of PO₂ reduction. After sudden deflation of the cuff, t.c. PO₂ increased gradually (Fig. 1). The t.c. PO₂, heat flux of the electrode, and the pneumatic cuff pressure were recorded on a Beckman R611 polygraph.

LAG TIME

We defined the lag time (LT) as the time required for t.c. PO₂ to begin to rise after the release of arterial occlusion (Fig. 1).

RESPONSE TIME

The difference between the lowest t.c. PO₂ value produced by arterial occlusion and the steady-state t.c. PO₂ of the pre- and postarterial occlusion was termed the step change in PO₂ (Δ t.c. PO₂). The time interval after the release of arterial occlusion required for the electrode to register 95% of the step change in t.c. PO₂ was termed the 95% response time (95% RT) (Fig. 1).

INFANT SUBJECTS

We examined six infants in the St. Louis Children's Hospital Neonatal Intensive Care Unit. All the infants were medically stable; none was hypotensive, anemic or hypothermic. Informed consent from parents was obtained in each case. Average birth weight was 1438 g (range, 920 to 1871 g); average gestational age was 31 wk (range, 28 to 33 wk). We studied the infants in their warmed isolettes or on an open table under radiant heat. The t.c. PO₂ electrode was placed on the middle third of the right shin. We then applied an infant-size blood pressure cuff proximal to the electrode. In these and other infants, comparison of umbilical artery PaO₂ and t.c. PO₂ showed a correlation comparable to other reports ($r = 0.91$) (10, 22).

ADULT SUBJECTS

We performed similar arterial occlusion tests in eight healthy young adults (four females and four males). Tests were performed on the flexor surface of the arm with the electrode sensor temperature 45°C. Arterial occlusion in the mucous membrane of the lower lip was achieved by applying pressure with a ring clamp (padded with cotton) circling the electrode. To test the effect of changes in local blood pressure, the arm was elevated from a dependent position, 28 ± 5 cm ($\bar{x} \pm$ S.D.) below the shoulder to a level of 28 ± 5 cm above the shoulder. Twenty-four to 40% oxygen by mask was given to six adults to detect the effect of hyperoxemia.

The unpaired Student *t* test was used for statistical analysis.

RESULTS

IN VITRO STUDIES

For step reductions in PO_2 (Δ 157 torr), the LT was 0.2 ± 0.06 ($x \pm S.D.$) sec, and the 95% RT was 22 ± 4.14 sec ($N = 16$). For step elevations in PO_2 (Δ 157 torr), LT was 0.8 ± 0.15 sec, whereas the RT was 10 ± 1.44 sec ($N = 16$). Differences between LT and RT for PO_2 reduction and elevation are statistically significant ($P < 0.001$).

INFANT STUDIES

Thirty-three arterial occlusion and release maneuvers were performed in infants. Occlusion duration was 26.8 ± 3.9 sec ($x \pm S.D.$). A positive linear correlation between the Δ t.c. PO_2 and 95% response time was seen (Fig. 2). The average correlation coefficient between these two variables in individual infants was $r = 0.90$. The mean lag time was 3.9 ± 1.1 sec (Table 1).

ADULT STUDIES

Thirty-five arterial occlusion tests were done with the electrode on the flexor surface of the right arm of eight adults. Occlusion

Fig. 1. *In vivo* determination of a transcutaneous PO_2 electrode (t.c. PO_2) LT and 95% RT after arterial occlusion release. Upper panel, t.c. PO_2 ; middle panel, electrode relative heat flux; lower panel, pressure in the pneumatic cuff around the arm. Arrows at A and B show when the cuff pressure was raised and released. C is the point when t.c. PO_2 started to rise, and D is when it reached 95% of the t.c. PO_2 steady-state value. Time intervals between B and C and B and D represent LT and 95% RT, respectively.

duration was 52.3 ± 28.4 sec ($x \pm S.D.$). As in infants, RT showed a linear correlation with the size of step change. The average correlation coefficient between these two variables in the adult subject was $r = 0.96$. The adult response and lag times were greater than those in infants (Table 1); differences were statistically significant ($P < 0.001$ for both).

Effect of the Electrode Site. Eight tests in the palm and eleven tests in the mucosa of the lower lip of two adults were done. RT and LT were much longer in the palm and shorter in lip mucosa than the flexor surface of the arm (Table 1). Differences between arm versus palm and arm versus lip mucosa LT and RT in each individual were statistically significant ($P < 0.01$).

Effect of Local Blood Pressure. In two subjects, ten tests were done in the flexor surface of the arm when the whole limb was in dependent position (mean local blood pressure, 120/80 mm Hg) and after elevation above the shoulder (mean local blood pressure, 80/50 mm Hg). LT and RT increased after elevation of the arm. In each subject, differences from the dependent position were statistically significant ($P < 0.05$). The steady state t.c. PO_2 tended to decrease after each elevation of the arm and increased to the previous level when the arm was back in the dependent position.

Fig. 2. Correlation between step change in transcutaneous oxygen tension (Δ t.c. PO_2) and 95% response time in six infants. Different symbols represent values for different subjects.

Table 1. t.c. PO_2 electrode lag and 95% RTs for step changes in PO_2 (Δ t.c. PO_2) in vivo and in vitro studies

Site and maneuver	No. of subjects	Change in t.c. PO_2 /torr	LT/sec	95% RT/sec
<i>In vivo studies</i> ¹				
Infant leg	6	16.4 ± 2.9^2	3.9 ± 1.1	76.5 ± 20.3
Adults flexor surface of the arm	8	18.8 ± 2.8	9.2 ± 2.5	121.5 ± 38.4
Adults palm	2	19.0 ± 4.2	44.4 ± 14.4	1032.5 ± 24.8
Adults mucosa of the lip	2	19.5 ± 4.0	4.8 ± 1.1	51.0 ± 1.4
Adults arm dependent	2	19.6 ± 3.1	6.7 ± 0.9	96.2 ± 16.9
Adults arm elevated	2	24.0 ± 0.0	11.6 ± 2.0	174.0 ± 24.9
Adults arm breathing 40% oxygen	6	22.3 ± 4.9	10.6 ± 2.2	126.8 ± 30.7
<i>In vitro studies</i>				
Descending change		157 ± 0	0.2 ± 0.06	22.00 ± 4.14
Ascending change		157 ± 0	0.8 ± 0.15	10.00 ± 1.44

¹ *In vivo* LT and RT for 15 to 25 torr step changes in t.c. PO_2 postarterial occlusion release.

² Mean $\pm$ S.D.

Table 2. Published values for *in vitro* and *in vivo* response of t.c. PO_2 electrode

References	Electrode type	Electrode placement	Subjects	RT (sec)	LT (sec)	Method
Huch <i>et al.</i> (10, 11)	Huch	<i>In vitro</i>		8-12 (95%)		Not described
Rooth (20, 21)	Huch	<i>In vitro</i>		8-10 (-)		Not described
Dennhardt <i>et al.</i> (3)	Huch	<i>In vitro</i>		6-9 (-)		Not described
Versmold <i>et al.</i> (24)	Huch, Litton	<i>In vitro</i>		16.8 (95%)		Step change FIO_2 (140 to 0 torr)
Peabody <i>et al.</i> (18)	Huch	<i>In vivo</i>	Infants	30 (95%)		Not described
Dennhardt <i>et al.</i> (3)	Huch	<i>In vivo</i>	Unspecified	20-30 (-)		Step change FIO_2
Litton (16)	Huch	<i>In vivo</i>	Unspecified	<25 (95%)		Not described
Rooth (20, 21)	Huch	<i>In vivo</i>	Infants		10	Not described
Lesouöf <i>et al.</i> (15)	Huch	<i>In vivo</i>	Infants		10	Step change FIO_2
Huch and Huch (10)	Huch	<i>In vivo</i>	Unspecified		10	Step change FIO_2
Swanstrom <i>et al.</i> (23)	Huch	<i>In vivo</i>	Infants?		20-30	Step change FIO_2
Rooth (20)	Huch	<i>In vivo</i>	Adult		20-30	Not described
Jacobsen and Löfgren (12)	Radiometer	<i>In vivo</i>	Infants	20-25 (-)		Step change FIO_2
Krauss <i>et al.</i> (13)	Eberhard	<i>In vivo</i>	Infants	60-90 (-)		Step change FIO_2
Versmold <i>et al.</i> (24)	Huch, Litton	<i>In vivo</i>	Infants	82.5 (50%)		Step increase in FIO_2
			Infants	51.1 (50%)	16.7	Step decrease in FIO_2

Effect of Breathing Oxygen. When 24 to 40% oxygen by mask was given to six adults, the lowest t.c. PO_2 postarterial occlusion was more than 70 torr. The RT showed the same relationship with size of Δ t.c. PO_2 . Results are shown in Table 1.

DISCUSSION

IN VITRO RESPONSE

Our *in vitro* 95% response time for increases in PO_2 is comparable to previously reported values although the methodology used in previous reports is not described (Table 2). We found *in vitro* response of the t.c. PO_2 electrode to depend on the direction of the PO_2 step change. This difference probably reflects differences in the techniques used to produce the step changes because response in liquid which we used to produce a step reduction in PO_2 might be expected to be slower than response in gas, which we used to produce a step increment in PO_2 . The values obtained during reduction of PO_2 , *i.e.*, the longer of the two *in vitro* response times, are probably more applicable to the expected performance of the electrode when measuring t.c. PO_2 because a liquid film is interposed between the skin surface and the electrode membrane.

IN VIVO RESPONSE

We used arterial occlusions to reduce skin PO_2 and occlusion release to produce a sudden increment in local Pao_2 ("step change"). The rationale for using this technique is provided by the studies of Evans and Naylor (5-9). They found that t.c. PO_2 is determined by oxygen tension in the venous arm of the superficial dermal capillary loops. They concluded that increasing skin blood flow by warming the skin or stopping blood flow altogether greatly reduces the A-V PO_2 difference between arterial and venous ends of the capillary loop. During vascular occlusion, intradermal O_2 tension falls as a result of local tissue metabolism. In the present studies, the electrode was positioned within 2 cm of the blood pressure cuff; therefore, we estimate that arterial blood from above the cuff reached the skin capillaries in a fraction of the subject's circulation time. This assumption is supported by our observations that LT was as short as 2 sec. Only part of that interval would be due to blood flow transit time because the intrinsic LT of the electrode was 0.2 sec and also because oxygen diffusion time across the avascular epidermal layer would account for part of the LT. Hence, we believe that arterial occlusion release approximates a true step change in Pao_2 . Other investigators have assessed *in vivo* response of the electrode by changing inspired oxygen concentration (Table 2). However, changes in inspired oxygen require time both for alveolar mixing and transit from lung to arm, and consequently, the change in Pao_2 is relatively slow using this

method. Aside from the obvious disadvantage of the present technique which does not allow step decreases in arterial PO_2 , we believe that it is superior to the previously described method.

In the present study, the *in vivo* LT was less in infants than in adults. This likely results from the infant's thinner epidermal layer allowing a shorter path for oxygen diffusion. This age-related difference is also consistent with our observation of short LT in nonkeratinized skin (lip) and long LT in areas with extremely thick epidermis (palm). Our values are one-sixth to one-half those reported by others (Table 2). This disagreement is likely accounted for by the alveolar gas mixing time and lung to arm transit time inherent in previously used methods.

We have shown that RT to a rise in PO_2 is a function of the magnitude of the Pao_2 step change. This conclusion seems valid even though the precise size of the step change was unknown because fall in dermal PO_2 after occlusion was detected by the fall in t.c. PO_2 . Taking the electrode RT into account, we have underestimated the actual capillary PO_2 postarterial occlusion in each case. For equivalent step changes in t.c. PO_2 , response time in infants was shorter than in adults. In adults, response was fastest in nonkeratinized areas (lip) and slowest in areas with thickest epidermis (palm). These observations appear to be consistent with those of Purvis (19) who found that thick membranes used in making PO_2 electrodes lengthened response time.

Our values for *in vivo* RT are two to six times longer than previously reported values (Table 2). Precise comparison is difficult because detailed description of methods has been lacking in these reports. In some cases, it appears that LT and RT have been used interchangeably. Also, the relation of RT to magnitude of step change was not evaluated in previous studies. It seems unlikely that our long RT is due to change in skin circulation produced by hypoxia because similar RTs were noted in individuals breathing 40% oxygen and room air. A potential problem with the present techniques is postocclusion hyperemia. However, for periods of ischemia of less than 5 min, the change in skin circulation is quite small (4). Furthermore, with an electrode temperature of 44°C in infants and 45°C in adults, a maximal vessel dilation is expected. However, our results showing that limb elevation affects RT suggest that local vascular influences can be important.

Krauss *et al.* (13) monitored t.c. PO_2 simultaneously with ear oxymetry. Their published polygraphic records suggest that t.c. PO_2 response to changes in arterial PO_2 is slow compared to change in arterial saturation suggesting that damping of the t.c. PO_2 signal will occur during rapid Pao_2 change. The amount of damping would depend on the rate of Pao_2 change. In studies of newborn animals, Pao_2 has been observed to fall at a rate of 2 to 3 torr/sec after airway obstruction (14). In other animal studies, using an

intravascular electrode with extremely rapid response (95% response, 0.3 sec), Purves (19) noted similar rates of change in P_{aO_2} after step change in inspired oxygen tension or spontaneous deep breaths. Considering the present RT determinations, we conclude that significant divergence of P_{aO_2} from t.c. PO_2 can be expected in human subjects in a variety of circumstances where rapid changes in P_{aO_2} are encountered. That is t.c. PO_2 will be a highly damped measure of P_{aO_2} , and when used to follow rapid transient P_{aO_2} changes, such as occur during apneic spells, it would significantly underestimate the true P_{aO_2} change. This suggests limited use for t.c. PO_2 as an apnea alarming device. These are limitations which have previously received little comment (17, 22). On the other hand, our observations do not detract from the established value of the t.c. PO_2 electrode in relatively steady state situations. Also, our observations of a short LT for reflecting P_{aO_2} change suggest that the t.c. PO_2 electrode may be useful as a noninvasive technique for following rapid P_{aO_2} changes qualitatively.

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25. Robert Brouillette was a recipient of an American Lung Association Training Fellowship.
26. The authors are indebted to Drs. D. Dietzler, R. Marshall, and C. Smith for their help and suggestions and to the St. Louis Children's Hospital Neonatal Intensive Care Unit nursing staff for assistance.
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28. This research was supported in part by a grant from The Life Seekers and by NIH grant HD-10993-03.
29. Received for publication February 8, 1980.
30. Accepted for publication August 4, 1980.