Technical Communication

In vivo response time of transcutaneous oxygen measurement to changes in inspired oxygen in normal adults

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We examined the in vivo response time of transcutaneous oxygen measurement (PtcO₂) to a step increase (100 per cent oxygen) or decrease (air) of inspired oxygen in five normal adults (age 27 ± SD 4.5 years). The PtcO₂ electrode was placed on the upper chest (sensor temperature 44°C). The mean ± SEM 63 and 95 per cent response times of PtcO₂ to a step increase in inspired oxygen were 2.9 ± 0.2 and 6.8 ± 0.2 and to a step decrease were 2.4 ± 0.2 and 5.1 ± 0.3 minutes. The 63 and 95 per cent response times for the pulmonary washin of oxygen were 1.0 and 2.6 minutes and washout were 0.8 and 2.3 minutes.

We conclude that the in vivo response time of the PtcO₂ is reproducible but substantially longer than that of the pulmonary washin and washout times and inadequate to

monitor rapid changes in arterial oxygenation during anaesthesia, perioperative period or sleep in adults.

Key words

MONITORING: oxygenation, transcutaneous oxygen tension; MEASUREMENT TECHNIQUES: transcutaneous oxygen, dynamics, time constant, response times.

Physiologic variables which may vary rapidly and impair oxygenation of the brain and myocardium should ideally be measured continuously. Invasive methods of continuous measurement of oxygen tension or haemoglobin saturation or periodic blood sampling are not without risks and periodic sampling may not provide the necessary information at the appropriate time. Transmittance or transcutaneous measurements have the advantage of being continuous and non-invasive. Ear oximetry¹ which depends on light transmittance through the ear lobe is extensively used in human sleep studies,² and measurement of the ventilatory response to progressive hypoxaemia.³ However, the ear piece is cumbersome and is not suitable for paediatric patients. Measurements of transcutaneous oxygen tension (PtcO₂) correlate with the arterial oxygen tension (PaO₂) in neonates,⁴⁻⁶ children^{6,7} and in adults^{8,9} except in the presence of circulatory abnormalities.⁶⁻⁸ Therefore the PtcO₂ has been

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recommended not only as a trend indicator in critically ill patients where the PtcO₂ measurement is combined with the heating power required to maintain a constant electrode temperature¹⁰ but also to monitor acute changes in oxygenation. However, no data are available in adults on the *in vivo* response time of the PtcO₂ to a step change in inspired oxygen concentration or to reduced alveolar ventilation as a result of respiratory depression or upper airway obstruction.

In order to evaluate the potential of the PtcO₂ in monitoring acute changes in adult patients perioperatively or during sleep, we examined the response times of PtcO₂ to a step change in inspired oxygen concentration in normal adults. The advantages of studying normal volunteers in a controlled laboratory environment are minimization of the influence of perturbations such as pain, anxiety, drugs and cold environmental temperature which occur during anaesthesia and surgery or in the recovery room and which alter cutaneous blood flow.

Methods

Studies were performed on five healthy laboratory staff (four males and one female), mean age $27 \pm$ SD 4.5 years who gave their informed consent. All subjects were four hours postprandial and seated comfortably in a chair. The PtcO₂ electrode system (HP78850A) was calibrated (sensor temperature 44°C) and placed on the upper chest (after cleaning with alcohol) and stabilized for 30 minutes. The PtcO₂ was recorded on the instrument strip chart and the respired oxygen and carbon dioxide (Perkin Elmer Anesthesia/Respiratory Mass Spectrometer MGA 1100, Pomona, CA), minute ventilation (measured by pneumotachography) and an electrocardiogram (HP bioelectric amplifier) were recorded by a Honeywell Visicorder (Honeywell, Denver, CO) and monitored on an oscilloscope. The respiratory circuit consisted of a gas mixture source, flow meters, reservoir bag, three-way switch valve to oxygen or air, one-way respiratory valve, and pneumotachograph (Fleisch 3, Validyne MP 45 $\pm$ 2 cm H₂O). The response times of the PtcO₂ electrode from air to 100 per cent oxygen and from 100 per cent oxygen to air were measured in duplicate for each subject. Oxygen was breathed for ten minutes.

The Hewlett Packard oxygen monitor 78850A (Böblingen, Germany) combines a PtcO₂ sensor

and dual micro fuel cells to measure gaseous oxygen. The active elements of the PtcO₂ sensor are three platinum cathodes each 15 microns in diameter polarized at 800 mV, heated to 42–45°C and used with a teflon membrane (25 microns).¹¹ The heating power after stabilization is 400 mW. The linearity from 0 to 160 mmHg is $\pm$ 3 mmHg. The PtcO₂ electrode is zeroed chemically (sodium bisulphite) and calibrated in air. The time to achieve 63 and 95 per cent of a maximum or minimum oxygen tension *in vitro* are 3 and 15 seconds respectively (one and three time constants).

The *in vivo* response times following change in inspired oxygen of PtcO₂ were calculated from the 63 per cent (one time constant) and 95 per cent (three time constants) of the time to reach a plateau.¹² The average of duplicate measurements in each direction are reported. The results are expressed as the mean $\pm$ SEM and the coefficient of variation (SD/Mean%). Paired student's *t* tests were used to compare the differences between duplicate measurements in each direction and between each response time in different directions. In order to compare the *in vivo* response time of the PtcO₂ with the pulmonary oxygen washin or washout the end tidal oxygen partial pressure (P_{ET}O₂) was also plotted against time and the 63 and 95 per cent response times calculated. In normal lungs during steady state conditions the P_{ET}O₂ will approximate the mean alveolar partial pressure of oxygen (PAO₂).

In order to examine the relationship between PtcO₂ and arterial oxygen tension (PaO₂) during steady state conditions we calculated the alveolar oxygen tension (PAO₂) for breathing air and 100 per cent oxygen from the alveolar gas equation assuming a PaCO₂ of 40 mmHg and a respiratory quotient of 0.9. Normal alveolar–arterial oxygen tension differences (AaO₂D) for breathing air (5 mmHg) and 100 per cent oxygen (50 mmHg) were then used to calculate PaO₂. Least squares linear regression analysis were used to examine the relationship between PtcO₂ and PaO₂, and PtcO₂–PaO₂ and PaO₂.

Results

The mean $\pm$ SEM (coefficient of variation) of the 63 and 95 per cent response times of the PtcO₂ to a step increase in inspired oxygen were 2.9 ± 0.2 (16 per cent) and 6.8 ± 0.2 (11 per cent) minutes,

FIGURE 1 Time course of response of PtcO₂ in an individual subject to a step increase and decrease in inspired oxygen showing the reproducibility in each direction and the difference between a step increase and decrease in inspired oxygen.

respectively and to a step decrease were 2.4 ± 0.2 (19 per cent) and 5.1 ± 0.3 (15 per cent) minutes, respectively. The differences between step increase and decrease were significantly different, and at 63 and 95 per cent response times were $p < 0.02$ and $p < 0.001$, respectively. The differences between duplicate measurements in the same direction were not significantly different ($p > 0.05$) (Figure 1).

The 63 and 95 per cent response times for the pulmonary washin of oxygen measured from the time for the $P_{ET}O_2$ to reach a plateau were 1 and 2.6 minutes and for the washout were 0.8 and 2.3 minutes (Figure 2).

During steady state conditions in five subjects breathing air the mean $\pm$ SEM PtcO₂ was 76 ± 2 mmHg and breathing 100 per cent oxygen was 467 ± 23 mmHg. There was a direct relationship between PtcO₂ mmHg and the predicted PaO₂ mmHg which was $PtcO_2 = 0.78 PaO_2 + 1.65$, $r = 0.99$, $p < 0.01$ ($n = 20$). The difference between PtcO₂ and PaO₂ was also directly related to the PaO₂ and was $PtcO_2 - PaO_2 = 0.22 PaO_2 - 1.65$, $r = 0.93$, $p < 0.01$ ($n = 20$).

Discussion

The response times of the PtcO₂ to a step change in

inspired O₂ include the instrument (*in vitro* response time), alveolar change in partial pressure of oxygen, circulation time, the cutaneous microcirculation and diffusion across the skin. The *in vitro* response times of the majority of PtcO₂ instruments are similar and the 95 per cent response times range from 15 to 30 seconds. The majority of *in vivo* examinations of the PtcO₂ response times have been in infants.^{4,5,13-17} Although the majority have shown a prompt change in PtcO₂ with a change in inspired oxygen concentration,^{13,15,16} onset of controlled ventilation,^{5,14} disconnection of ventilator,¹⁴ tracheal suctioning,⁵ and motor activity¹⁷ there are few quantitative estimates of the response times. In addition insufficient time was allowed from the onset of the physical perturbation for equilibration and the development of a plateau. In newborn infants the 50 per cent response times to an increase in inspired oxygen ranged from 78–84 seconds (different electrodes) with large coefficients of variation (25 per cent), and a 50 per cent response time to a decrease in oxygen of 45–53 seconds with similar large variations.¹⁵ However in Jacobsen and Lofgren's study the 95 per cent response time to an increase in inspired oxygen was approximately seven minutes and to a decrease was three minutes.¹⁶ In *in-*

FIGURE 2 Comparison of the time course of change in $P_{tc}O_2$ and end-tidal oxygen ($P_{ET}O_2$) following a step increase in inspired oxygen from air to 100 per cent oxygen and a step decrease in inspired oxygen from 100 per cent oxygen to air.

infants and children Brouillette and associates observed that during obstructive sleep apnoea although the PtcO₂ gave an indication of the direction of change the response time was too long to accurately estimate the magnitude of hypoxaemia.¹⁸ In adults although there is an apparent prompt change in PtcO₂ with a change in inspired oxygen concentration the data on response times were not quantitative.¹⁹

We have therefore measured the *in vivo* response times of the PtcO₂ and have demonstrated substantially longer response times to a step change in inspired oxygen than in the above studies. Therefore in adults the *in vivo* PtcO₂ response time is substantially longer than that of the ear oximeter.²⁰ Knill *et al.*²¹ and Hutchison *et al.*²² also reported qualitatively that the response time of the PtcO₂ measurements were prolonged however Knill also remarked that the response times were not reproducible.²¹ Our data show that for the same direction of change that both within subjects and between subjects the PtcO₂ response times were reproducible. The reason for the reproducibility of our data in comparison to Knill may be that our study was performed on normal subjects in the carefully controlled environment of a laboratory without the perturbations of anaesthesia and surgery on cutaneous microcirculation. The *in vivo* response times of PtcO₂ measurements are not accounted for by the duration of pulmonary washin or washout, and therefore are probably the result of the combination of circulation time and diffusion within the skin.

Abu-Osba *et al.*²³ measured the response time in infants and adults of the PtcO₂ to a step change in arterial blood flow following release of occlusion. They also concluded that the *in vivo* response time of the PtcO₂ electrode was longer than previously reported and was influenced by the magnitude of step change (direct correlation between change in PtcO₂ and 95 per cent response time, $r = 0.96$ adults), age, anatomic location and local haemodynamic factors.

As a result of our data and supported by similar evidence,²¹⁻²³ we conclude that the *in vivo* response time of the PtcO₂ electrode systems in adults is too long to provide reliable measurement of acute changes in oxygenation as a result of changes in inspired O₂ and possibly alveolar ventilation. We also suggest that the disparity between PaO₂ and PtcO₂ is increased by a wide range of factors during anaesthesia and in the postoperative period which alter cutaneous blood flow. These include cold environ-

mental temperatures, pain, anxiety, hypocapnia as a result of hyperventilation and haemorrhage, therefore the PtcO₂ may provide unhelpful or misleading data. Therefore the ear oximeter which has a shorter *in vivo* response time²⁰ and is not influenced by cutaneous blood flow except in shock remains a potentially useful monitor for postoperative arterial oxygenation. Satisfactory technology for accurate, rapid, reliable and convenient non-invasive monitoring of oxygenation in adults and possibly paediatric patients is not yet available.

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References

- 1 Saunders NA, Powles ACP, Rebuck AS. Ear oximetry: Accuracy and practicability in the assessment of arterial oxygenation. *Am Rev Respir Dis* 1976; 113: 745-9.
- 2 Garay SM, Rapoport D, Sorkin B, Epstein H, Feinberg I, Goldring RM. Regulation of ventilation in the obstructive sleep apnea syndrome. *Am Rev Respir Dis* 1981; 124: 451-7.
- 3 Rebuck AS, Campbell EJM. A clinical method for assessing the ventilatory response to hypoxia. *Am Rev Respir Dis* 1974; 109: 345-50.
- 4 Huch R, Huch A, Lübbers DW. Results of clinical and physiologic investigations with the transcutaneous PO₂ technique. IV. Transcutaneous PO₂. New York: Thieme-Stratton (1981), p. 108-151.
- 5 Huch R, Huch A, Albani M *et al.* Transcutaneous PO₂ monitoring in routine management of infants and children with cardiorespiratory problems. *Pediatrics* 1976; 57: 681-90.
- 6 Peabody JL, Gregory GA, Willis MM, Tooley WH. Transcutaneous oxygen tension in sick infants. *Am Rev Respir Dis* 1978; 118: 83-7.
- 7 Venus B, Patel KC, Pratap KS, Konchigeri H, Vidyasagar D. Transcutaneous PO₂ monitoring during pediatric surgery. *Crit Care Med* 1981; 9: 714-6.
- 8 Yahav J, Mindorff C, Levison H. The validity of the transcutaneous oxygen tension method in children with cardiorespiratory problems. *Am Rev Respir Dis* 1981; 124: 586-7.
- 9 Rafferty TD, Marrero O, Nardi D, Schachter EN, Mentelos RA, Ngeow YF. Transcutaneous PO₂ as a trend indicator in arterial PO₂ in

- normal anesthetized adults. *Anesth Analg* 1982; 61: 252-5.
- 10 Tremper KK, Waxman K, Bowman R, Shoemaker WC. Continuous transcutaneous oxygen monitoring during respiratory failure, cardiac decompensation, cardiac arrest and CPR. *Crit Care Med* 1980; 8: 377-81.
 - 11 Hewlett Packard - Model 78850A oxygen monitor. Service manual number 78850-9000. Hewlett Packard GmbH. D-7030. Boblingen, 1981.
 - 12 Nunn JF. *Applied Respiratory Physiology*. London: Butterworths (1969), p. 392-403.
 - 13 Huch R, Huch A, Lübbers DW. Transcutaneous measurement of blood PO_2 (tc PO_2)-method and application in perinatal medicine. *J. Perinat Med* 1973; 1: 183-91.
 - 14 Swanström S, Villa Elisaga I, Cárdena L, Cárdenes A, Méndez-Bauer C, Rooth G. Transcutaneous PO_2 measurements in seriously ill newborn infants. *Arch Dis Child* 1975; 50: 913-9.
 - 15 Versmold HT, Linderkamp O, Stuffer KH, Holzmänn M, Riegel KP. Vivo vs in vitro response time of transcutaneous PO_2 electrodes. *Acta Anaesthesiol Scand Suppl* 1978; 63: 40-8.
 - 16 Jacobsen L, Löfgren O. Transcutaneous monitoring of PO_2 in different skin areas in the neonate and in the scalp of the fetus during labor - methodological and physiological observations. *Acta Obst Gynecol Scand* 1977; 66: 55-68.
 - 17 Abu-Osba Y, Brouillette RT, Wilson SL, Thach BT. Breathing pattern transcutaneous oxygen tension during motor activity in preterm infants. *Am Rev Respir Dis* 1982; 125: 382-7.
 - 18 Brouillette RT, Fernbach SK, Hunt CE. Obstructive sleep apnea in infants and children. *J Pediatrics* 1982; 100: 31-40.
 - 19 Dennhardt R, Fricke M, Mahal S, Huch A, Huch R. Transcutaneous PO_2 monitoring in anaesthesia. *Eur J Intensive* 1976; 2: 29-33.
 - 20 Douglas NJ, Brash EM, Wraith PK et al. Accuracy, sensitivity to carboxyhemoglobin and speed of response of the Hewlett-Packard 47201A ear oximeter. *Am Rev Respir Dis* 1979; 119: 311-3.
 - 21 Knill RL, Clement JL, Kiersaszewicz HT, Dodgson BG. Assessment of two noninvasive monitors of arterial oxygenation in anesthetized man. *Anesth Analg* 1982; 61: 582-6.
 - 22 Hutchison DCS, Rocca G, Honeybourne D. Estimation of arterial oxygen tension in adult subjects using a transcutaneous electrode. *Thorax* 1981; 36: 473-7.
 - 23 Abu-Osba YK, Thach BT, Brouillette RT. Evaluation of response time of a transcutaneous oxygen tension electrode. *Pediatr Res* 1981; 15: 143-6.

Résumé

Nous avons mesuré le temps de réaction de l'oxymètre trans-cutané ($PtcO_2$) à l'augmentation en palier de l'oxygène inspiré (FiO_2 1.0) et à la diminution en palier (air libre) chez cinq adultes normaux d'âge moyen de 27 ans. L'électrode était placée sur la partie supérieure du thorax. Le temps nécessaire pour obtenir 63 et 95 pour cent de la réponse maximale à une augmentation en palier d'oxygène inspiré était de 2.9 plus ou moins 0.2 min. et de 6.8 plus ou moins 0.2. Ces mêmes temps, pour une diminution en palier de l'oxygène inspiré étaient de 2.4, plus ou moins 0.2 et 5.1 plus ou moins 0.3 min.

Les temps nécessaires pour atteindre 63 et 95 pour cent de la dénitrégénéation totale étaient de 1.0 et 2.6 minutes. Pour la rénitrogénéation ces mêmes temps étaient 0.8 et 2.3 min.

On conclut de ces mesures que le temps de réponse de l'oxymètre trans-cutané est passablement plus long que les temps d'équilibration alvéolaire des gaz inspirés; de ce fait, l'oxymétrie transcutanée n'apparaît pas tout à fait adaptée pour déceler les changements rapides dans l'oxygénation du sang artériel durant l'anesthésie, la période péri-opératoire et même durant le sommeil.