Changes in Transcutaneous Oxygen Tension During Capillary Blood-Gas Sampling

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With a Radiometer TCM-1 oxygen monitor, we followed the fluctuations in transcutaneous oxygen tension (p_{tcO_2}) during capillary blood collection from a heel prick. Thirty premature infants who presented with some respiratory compromise showed unpredictably increased (43 of 125 observations) or decreased (82 of 125 observations) values during this blood-sampling process. The fluctuation exceeded 10 mmHg in 61 observations and represented as much as −67% relative change. In general, p_{tcO_2} values exceeded capillary p_{O_2} values determined by standard blood-gas analysis. We investigated several aspects of capillary blood sampling to explain these observations. Because the induced response is a dynamic change, which continues throughout the collection process, we conclude that successive specimens will have different O_2 tensions. Even if the capillary blood p_{O_2} truly reflected p_{aO_2}, the magnitude and direction of deviation from the patient's uncompromised O_2 tension could lead to inappropriate management. We conclude that capillary blood specimens should not be used for p_{O_2} determinations in newborns.

Clinical management of the sick premature infant frequently includes blood-gas analysis (*1, 2*). The specimen of choice for blood-gas determination is arterial blood. In the newborn, umbilical artery catheterization provides convenient access to a specimen. However, because of the risks of arterial catheterization (*3*) and the complications of repeated arterial punctures (*4*), "arterialized" (i.e., local hyperemia induced by heat or chemicals) capillary blood from the heel is frequently substituted as the specimen for blood-gas analysis. There are conflicting reports on the suitability of this specimen for p_{O_2} determinations (*5–20*). Several investigators have reported that the use of capillary blood for p_{O_2} determinations is particularly contraindicated for the newborn population. Koch and Wendel (*5*) and Gandy et al. (*6*) have suggested that poor arterial pressure and perfusion of a newborn's heel are possible sources of discrepancy in the blood-gas measurement. Compounding these physiological limitations, capillary p_{O_2} analysis may be compromised by incomplete "arterialization" before sampling (*7*) and by the mechanics of the sampling itself (*8–10*). Nevertheless, the Committee on Pediatric Clinical Chemistry of the American Association for Clinical Chemistry states that p_{O_2} determinations on capillary blood

may be useful if they are "judiciously ordered, obtained by highly skilled personnel, and interpreted cautiously" (*21*).

Here, we present evidence that the arterial oxygen tension (p_{aO_2}) changes during the capillary blood-sampling process. Such a change alone could explain the reported discrepancies between arterial and capillary blood p_{O_2} measurements. Transcutaneous oxygen measurements (p_{tcO_2}) were used to follow the p_{aO_2} changes. Although some investigators question the identity of p_{tcO_2} and p_{aO_2} (*22, 23*), studies in this laboratory and elsewhere (*24–28*) have established the equality of p_{tcO_2} with arterial O_2 tensions determined by conventional measurements.

Materials and Methods

The transcutaneous p_{O_2} measurement system used in this study consisted of a Radiometer TCM-1 oxygen monitor, a Radiometer TCM101 calibrating unit (The London Co., Cleveland, OH 44145), and a modified Omniscribe Model B5217-5 dual-pen recorder (Houston Instruments, Austin, TX 78753). The recorder was set up so that p_{tcO_2} was continuously displayed on the lower half of the chart and the heater power output on the upper. The heater power output is an indicator of blood-flow changes (*29*), so we used a modified recorder (*28*) to enhance this channel's signal.

All of the above items were transported on a laboratory cart especially equipped with hospital-grade electrical receptacles and a single 3-meter power cord. In practice, this system is easily transported, requires little space, and is operated from a single electrical outlet in the intensive-care unit.

The p_{tcO_2} equipment was used according to the manufacturer's instructions, except for contact-gel composition and instrument calibration, as described elsewhere (*28*). All transcutaneous measurements were made at 44 °C.

Specimens for comparative studies were transported to the laboratory within 5 min of collection and were analyzed within 10 min. The IL 213 blood-gas analyzer (Instrumentation Laboratory, Inc., Lexington, MA 02173) was used in these experiments. Its performance and quality control have been described elsewhere (*30, 31*).

The patients (n = 30) ranged in gestational age from 24 to 38 weeks and weighed 595 to 3300 g at birth. The most frequent primary diagnosis of these patients was prematurity. Blood-gas measurements were performed for the following reasons: respiratory distress, bronchopulmonary dysplasia, hyaline membrane disease, apnea of prematurity, or Wilson–Mikity syndrome.

The capillary blood-sampling procedure was performed by the Neonatal Intensive Care Unit nursing staff. So that the capillary bed might be arterialized, the infant's heel was wrapped with a warm cloth 10 min before the blood was sampled. The lateral aspect of the heel was punctured to start a good flow of blood, from which three 120-μL heparinized capillary tubes (Sherwood Medical Industries, St. Louis, MO 63103; no. 8889-307008) were filled. Both ends of the capillaries were plugged with "Critoseal" (Sherwood Medical In-

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dustries, no. 8889-215003) after visual inspection to be sure no air bubbles were present.

Results

Figure 1 shows the p_{tcO_2} and heater power consumption recorded during a typical blood-sampling. p_{tcO_2} changes were unremarkable during the interval A–B while the infant's heel was warmed. p_{tcO_2} rarely changes at A, but usually there was a significant change at B when the heel was lanced. The last of the three capillary tubes was filled at point D. The "sampling interval" is therefore defined as the interval B–D, which averaged 2.8 min. Approximately 30 s after point B, the p_{tcO_2} began to decline. The initial rate of change was 20 mmHg/min.[3] Such a rate of change is commonly observed, although the magnitude and direction of change varies.

The patient contact was terminated before E, by which point the p_{tcO_2} had returned to the pre-intervention values (A–B). Point C is defined as the point of maximum change. Sometimes the pressure changes associated with capillary blood-sampling were positive rather than negative; i.e., p_{tcO_2} increased, and C exceeded B. The heater power always increased during the capillary sampling process.

In the instance illustrated, the variations in heater power consumption shown here do not coincide with opening the incubator or other activities that could disturb the incubator temperature. (Environment-associated temperature changes may not be significant because the ambient temperature of the patient-care area is about 32 °C.)

Sampling-induced changes in p_{tcO_2} (similar to those shown in Figure 1) were simultaneously measured with the monitor's electrodes placed against the upper right chest and against the inside of the lower left calf (approximately 3.5 cm above the heel) of a 30-hour-old infant. (The results from the extremity were all lower than those measured on the chest.) The range of differences between sites was 4–24 mmHg. The p_{tcO_2} depression associated with capillary blood sampling occurred simultaneously at both sites, but the magnitude and rate of change were not as pronounced in the extremity as on the chest. Arterial blood-gas specimens from an umbilical artery catheter (high placement) were taken before and during (at point C of Figure 1) capillary blood-specimen collection. The ratio of the p_{aO_2}/p_{tcO_2} observed before specimen collection was used to predict the p_{aO_2} from the observed p_{tcO_2} during this procedure. The predicted p_{aO_2} was 50 mmHg; the observed p_{aO_2} was 49 mmHg.

Studies of several subjects confirm that changes at the chest and leg sites parallel one another during sampling. However, statistical analysis of results did not confirm a consistent bias between measurement sites, and this inconsistency was not ascribable to interinstrument bias, because the calibration points and control-gas determinations were identical before and after the test was performed.

In separate experiments, no significant changes in chest and leg p_{tcO_2} were caused by elevating the patient's leg 10 cm above the heart (the average elevation during capillary blood-sampling) without blood sampling.

The variation in p_{tcO_2} associated with capillary blood sampling can be seen in Figure 2, in which the measured capillary p_{O_2} is compared to the range of p_{tcO_2} observed during the interval B–C. The bias toward p_{tcO_2} values higher than capillary p_{O_2} is apparent. The magnitude of variations did not correlate with p_{tcO_2}. At a given capillary p_{O_2}, the range of measured p_{tcO_2} was not consistent (i.e., at 48 mmHg capillary p_{O_2}, observed p_{tcO_2} ranges were 71–78, 42–48, 62–80, 52–78, and 48–64 mmHg in five different individuals). The mean value for the midpoints of observed p_{tcO_2} ranges was 55

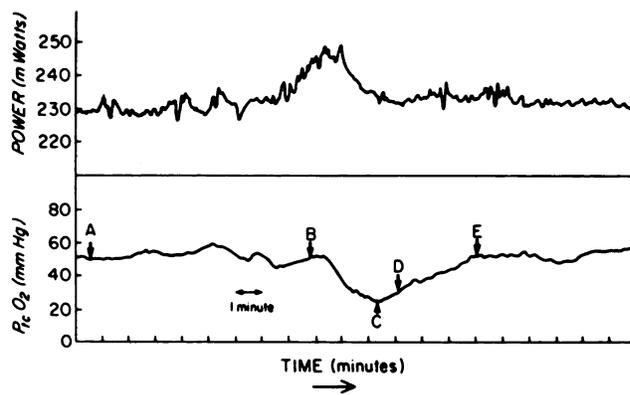[3] 1 mmHg $\simeq$ 133 Pa = 133 N/m².

Fig. 1. p_{tcO_2} and heater power consumption, simultaneously recorded during collection of a capillary blood specimen for blood-gas determination.

During interval A–B, the heel was lanced and specimen collection was initiated. Specimen collection (three capillary tubes) was concluded at D. C is the point of maximum p_{tcO_2} change. Patient contact was terminated at E

mmHg. The mean value for the capillary p_{O_2} data was 43 mmHg.

When 125 cases were examined for the maximum percentage change associated with capillary specimen collection, i.e., $[(C - B)/B] \times 100$, the results ranged from −67 to +63% relative change. The overall mean was −8%, the SD +23.5%. The mean of positive changes was +17%; the mean of negative changes was −21%. In only one observation was there no change. The change $(C - B)$ was negative in 66% of these observations, positive in 34% of them. The direction of change in a given patient was unpredictable. In 61 of 125 cases, the observed change exceeded 10 mmHg. The maximum absolute p_{tcO_2} change observed was a drop from 88 to 34 mmHg.

Discussion

The blood-gas response of sick newborns to capillary blood sampling described here seems to be unique and not associated with on-going dynamic changes. This response was readily identified in all cases except those of extreme p_{tcO_2} instability when frequent or rapid variations mask these changes, or in instances of limited responsiveness associated with moribund infants. The parallelism of leg and chest p_{tcO_2} determinations with coincidentally determined p_{aO_2} and the predictability of p_{aO_2} from p_{tcO_2} determinations indicate that transcutaneous O_2 sensors are monitoring true physiological
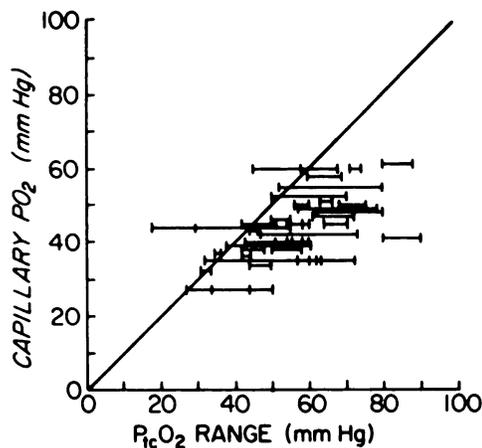

Fig. 2. Comparison of the p_{tcO_2} range (———) observed during capillary sampling (interval B to C in Figure 1) and of the p_{O_2} determined on the capillary blood specimen. n = 58

The theoretical line of identity is illustrated, for comparison

changes in O_2 tension. Distinct p_{tcO_2} changes have been described to occur with other patient manipulations such as suctioning, feeding, etc. (32). Thus, this report and others point to the very labile O_2 status of sick newborns.

As indicated in Figure 1, the p_{tcO_2} changes throughout the collection of a capillary blood specimen. The p_{O_2} determined on any given capillary blood specimen by conventional analysis would be the average of changing O_2 tensions in circulating blood during its collection interval. Moreover, two or more capillary blood specimens taken during the total interval would be expected to have different O_2 tensions.

Because of these differences, the analysis of two or more samples of capillary blood with different blood-gas instruments is ineffective as a quality-control technique in this circumstance, even though it is a powerful technique otherwise.

The observation illustrated in Figure 1 also suggests that arterial vs capillary p_{O_2} comparisons made by earlier investigators (5–20) may be compromised, because an overall negative bias could be obtained if specimens were not collected simultaneously.

In theory, the induced physiological phenomena described here should have been equally reflected in capillary p_{O_2} and p_{tcO_2} values, but Figure 2 demonstrates that p_{tcO_2} results are consistently greater than capillary p_{O_2} results, irrespective of the direction of change. We initially hypothesized that the capillary p_{O_2} vs p_{tcO_2} bias identifiable in Figure 2 would be the sum of peripheral perfusion (chest to leg) bias plus orthostatic (leg elevation) bias plus methodology-associated bias. In the small series described here, the existence of a peripheral perfusion bias could not conclusively be demonstrated by simultaneous transcutaneous O_2 measurements on the chest and leg. This agrees with the findings of Jacobson and Lofgren (33), who measured no difference between the thigh and the chest in infants. In other investigations we have shown that infants less than 24 h old may constitute a peculiar subpopulation and that such a bias may exist for them (28). The suspected orthostatic bias was not demonstrable but may be present under some circumstances of low blood pressure or aortic atresia. Because the hypothesized perfusion and orthostatic biases were not supported by our data, we conclude that methodology-associated phenomena are responsible. One methodology-associated bias which could account for these observations is incomplete "arterialization" before capillary-blood collection. Only a detailed investigation of arterialization mechanisms that directly measure heel-skin temperature and coincidentally determine p_{tcO_2} will elucidate the origin of the bias.

Perhaps the most serious limitation to the use of capillary blood specimens for p_{O_2} determinations is the potential for misinterpreting a patient's O_2 status by over-reliance on results that have been compromised by the collection process. Even if the capillary p_{O_2} truly reflected the p_{aO_2}, the magnitude and direction of deviation from the patient's uncompromised O_2 tension could lead to inappropriate management. In these studies, 66% of capillary blood specimens represent falsely lower p_{O_2} values. In 49% of our observations, p_{tcO_2} changes exceeded 10 mmHg. In our hospital, changes of this magnitude in values below 50 mmHg or above 75 mmHg would make a difference in the management of the case. The most extreme change noted (from 88 to 34 mmHg) would clearly change the patient's evaluation. We conclude that capillary blood specimens from the heel should not be used for p_{O_2} determinations in newborns. We believe that, under most circumstances, the transcutaneous measurement of O_2 tension is a valid alternative to the p_{O_2} analysis of a capillary blood specimen.

References

1. Klaus, M. H., and Faranoff, A. A., *Care of the High-Risk Neonate*, W. B. Saunders Co., Philadelphia, PA, 1973, pp 133—135.

2. Durbin, G. M., Reasons for monitoring arterial oxygen in the neonate. In *Oxygen Measurements in Biology and Medicine*, J. P. Payne and D. W. Hill, Eds., Butterworths, London, 1975, pp 259–268.

3. Cochran, W. D., Heather, T. D., and Smith, C. A., Advantages and complications of umbilical artery catheterization in the newborn. *Pediatrics* 42, 769–777 (1968).

4. Siggaard-Anderson, O., Acid-base and blood-gas parameters—arterial or capillary blood? *Scand. J. Clin. Lab. Invest.* 21, 289–292 (1968).

5. Koch, G., and Wendel, H., Comparison of pH, carbon dioxide tension, standard bicarbonate and oxygen tension in capillary blood and in arterial blood during the neonatal period. *Acta Paediatr. Scand.* 56, 10–16 (1967).

6. Gandy, G., Grann, L., Cunningham, N., et al., The validity of pH and pCO2 measurements in capillary samples in sick and healthy newborn infants. *Pediatrics* 34, 192–197 (1964).

7. Koch, G., Comparison of carbon dioxide tension, pH and standard bicarbonate in capillary blood and in arterial blood. *Scand. J. Clin. Lab. Invest.* 17, 223–229 (1965).

8. Gambino, S. R., Collection of capillary blood for simultaneous determinations of arterial pH, CO2 content, pCO2, and oxygen saturation. *Am. J. Clin. Pathol.* 35, 178–183 (1961).

9. Hunt, C. E., Capillary blood sampling in the infant: Usefulness and limitations of two methods of sampling, compared with arterial blood. *Pediatrics* 51, 501–506 (1973).

10. Christoforides, C., and Miller, J. M., Clinical use and limitations of arterialized capillary blood for PO2 determination. *Am. Rev. Resp. Dis.* 98, 653–657 (1968).

11. Oxygen therapy in the newborn infant. Statement by the Fetus and Newborn Committee of the Canadian Paediatric Society. *Can. Med. Assoc. J.* 113, 750 (1975).

12. Corbet, A. J. S., and Burnard, E. D., Oxygen tension measurements on digital blood in the newborn. *Pediatrics,* 46, 780–782 (1970).

13. Duc, G. V., and Cumarasamy, N., Digital arteriolar oxygen tension as a guide to oxygen therapy of the newborn. *Biol. Neonate* 24, 134–137 (1974).

14. Hofford, J. M., Pell, S., and Dowling, A. S., The clinical usefulness and limitations of arterialized capillary bloods. *Del. Med. J.* 45, 8–11 (1973).

15. Bannister, A., Comparison of arterial and arterialized capillary blood in infants with respiratory distress. *Arch. Dis. Child.* 44, 726–728 (1969).

16. Mountain, K. R., and Campbell, D. G., Reliability of oxygen tension measurements on arterialized capillary blood in the newborn. *Arch. Dis. Child.* 45, 134–138 (1970).

17. Winquist, R. A., and Stamm, S. J., Arterialized capillary sampling using histamine iontophoresis. *J. Pediatr.* 76, 455–458 (1970).

18. Garg, A. K., "Arterialized" capillary blood. *Can. Med. Assoc. J.* 107, 16 (1972).

19. Glasgow, J. F. T., Flynn, D. M., and Swyer, P. R., A comparison of descending aortic and "arterialized" capillary blood in the sick newborn. *Can. Med. Asssoc. J.* 106, 660–662 (1972).

20. Hofford, J. M., Dowling, A. S., and Pell, S., More about arterialized capillary blood measurements. *J. Am. Med. Assoc.* 224, 1297 (1973).

21. Meites, S., and Levitt, M. J., Skin-puncture and blood collecting techniques for infants. *Clin. Chem.* 25, 183–189 (1979).

22. le Souëff, P. N., Morgan, A. K., Soutter, L. P., et al., Comparison of transcutaneous oxygen tension with arterial oxygen tension in newborn infants with severe respiratory illnesses. *Pediatrics* 65, 692–697 (1978).

23. Soutter, L. P., and Parker, D., A comparison of transcutaneous and arterial PO2 in sick neonates. In *Advances in Experimental Medicine and Biology: Oxygen Transport to Tissue*, J. Grote, D. Reneau, and G. Thews, Eds., Plenum Press, New York, NY, 1976, pp 747–752.

24. Duc, G., Bucher, H. U., and Mitcheli, J. L., Is transcutaneous PO₂ reliable for arterial oxygen monitoring in newborn infants? *Pediatrics* 55, 566–567 (1975).

25. Swanstrom, S., Villa Elisaga, I., Cardona, L., et al., Transcutaneous PO₂ measurements in seriously ill newborn infants. *Arch. Dis. Child.* 50, 913–919 (1975).

26. Huch, R., Lübbers, D. W., and Huch, A., Reliability of transcutaneous monitoring of arterial PO₂ in newborn infants. *Arch. Dis. Child.* 49, 213–218 (1974).

27. Eberhard, P., Mindt, W., Jann, F., and Hammacher, K., Continuous PO₂ monitoring in the neonate by skin electrodes. *Med. Biol. Eng.*, May, 436–442 (1975).

28. Graham, G., and Kenny, M. A., Assessment of transcutaneous oxygen measurements in a neonatal intensive care unit. *Clin. Chem.* 26, 629–633 (1980).

29. Huch, R., Lübbers, D. W., and Huch, A., The transcutaneous measurement of oxygen and carbon dioxide tensions for the deter-

mination of arterial blood-gas values with control of local perfusion and peripheral perfusion pressure. Theoretical analysis and practical application. In *Oxygen Measurements in Biology and Medicine*, J. P. Payne and D. W. Hill, Eds., Butterworths, London, 1975, pp 121–138.

30. Delaney, C. J., Teng Leary, E., Raisys, V. A., and Kenny, M. A., Proficiency testing for blood-gas quality control. *Clin. Chem.* 22, 1675–1684 (1976).

31. Teng Leary, E., Delaney, C. J., and Kenny, M. A., Use of equilibrated blood for internal blood-gas quality control. *Clin. Chem.* 23, 493–503 (1977).

32. Emmrich, P., Transcutaneous oxygen tension measurements in pediatrics. *Monatsschr. Kindersheilkd.* 124, 504–510 (1976).

33. Jacobson, L., and Löfgren, O., Transcutaneous monitoring of PO₂ in different skin areas in the neonate and in the scalp of the fetus during labor—methodological and physiological observations. *Acta Obstet. Gynaecol. Scand.*, Suppl. 66, 55–68 (1977).