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Scalp Blood Flow, Measured by Laser Doppler Flowmetry, and Transcutaneous Po_2 and Pco_2 in the Lamb

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ABSTRACT. To describe the relation between scalp blood flow and transcutaneous Po_2 and Pco_2, these three signals were recorded simultaneously in eight experiments on four healthy lambs in the first weeks after birth. Scalp blood flow was recorded by a laser Doppler flow sensor that was incorporated in the transcutaneous Po_2 electrode. Scalp blood flow was varied by applying a circular pressure on the scalp surrounding the sensors. A decrease in laser Doppler blood flow was associated with a decrease in transcutaneous Po_2 and an increase in transcutaneous Pco_2, according to a hyperbolic curve. The steep parts of the hyperbolic curves were observed at low scalp blood flow, whereas the flat parts were found at high flow values. Even during heat-induced hyperemia only a small part of these hyperbolic curves showed a reasonable independence of the transcutaneous blood gas values of changes in blood flow. In view of the previously observed decrease in intrapartum scalp blood flow, the present data render the transcutaneous measurement of blood gas values doubtful for fetal monitoring during labor. (*Pediatr Res* 27: 442–444, 1990)

Abbreviations

$tcPo_2$, transcutaneous oxygen tension
$tcPco_2$, transcutaneous carbon dioxide tension
LDF, laser Doppler flow
CSP, circular scalp pressure
PVC, polyvinyl chloride

In a previous study, we demonstrated that fetal scalp blood flow, measured by laser Doppler flowmetry, decreases considerably in the course of labor (1). This was most pronounced toward full dilatation of the cervix and in the second stage of labor. The reduction in scalp blood flow sets serious limits to the application of transcutaneous monitoring of fetal blood gases during labor (2–5).

It has been suggested that mechanical factors, *e.g.* circular pressure of the dilating birth canal exerted on the fetal scalp (6), are partly responsible for the impairment of local scalp blood flow (7–10). Previous studies in the fetal lamb have shown that local and circular pressure on the scalp, of a magnitude comparable with that occurring on the scalp of the human fetus during labor, results in a considerable decrease in local blood flow and in $tcPo_2$ (8, 10). However, the xenon washout method used for measuring scalp blood flow in one of these studies (8) is not suitable for investigating the relation between scalp blood flow and $tcPo_2$, because the manipulations required to vary local scalp blood flow interfere with this method. As shown in previous studies, laser Doppler flowmetry can be used for this purpose (1, 4, 5, 11–13).

Therefore, a study was undertaken to investigate the relationship between scalp blood flow, measured by laser Doppler flowmetry, and $tcPo_2$ and Pco_2 in the lamb. Local blood flow changes were brought about by varying the circular pressure exerted on the scalp around the sensors.

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MATERIALS AND METHODS

LDF measurement. Laser Doppler flowmetry allows direct estimation of red blood cell flow in the microvascular bed of translucent tissues (11–15). In brief, monochromatic light from a helium neon laser (Spectra Physics Inc., Mt. View, CA; S105; wavelength = 632.8 nm) is transported to the tissue by a monofilament graded index optical fiber. Light entering the tissue is scattered mainly by static structures. However, some light is scattered by moving particles, *i.e.* red blood cells, and is slightly changed in frequency due to the Doppler effect. This results in a frequency broadening of the remitted light. This light is received by three optical fibers and transported to a photodetector. The frequency spectrum present in the received light results in interference frequencies in the audio range at the surface of the photodetector (11, 13, 15). Appropriate analog processing of this electrical signal produces an LDF index that is linearly related to red blood cell flow (1, 11).

Apart from the interference frequency spectrum resulting from the Doppler shift of the laser light, the electrical signal also contains noise as a result of the use of a silicon photodiode and an amplifier. Consequently, the electrical noise compensation of the laser Doppler flowmeter was adjusted before each experiment on a static white surface, which yielded the same reflected light intensity as the scalp under study.

Transcutaneous blood gas measurement. The oxygen and carbon dioxide partial pressures were measured with a $tcPo_2$ electrode (Radiometer, Copenhagen, Denmark; TCM-1; E5241-0) and a $tcPco_2$ sensor (Radiometer; TCM-3). The four fibers of the LDF meter were incorporated in the heater element of the $tcPo_2$ electrode. The $tcPo_2$ and $tcPco_2$ sensors were prepared according to the instructions of the manufacturer and operated at a temperature of 44°C.

Before each experiment the $tcPo_2$ electrode was calibrated with room air and the $tcPco_2$ sensor with 5 and 10% CO_2 in nitrogen. The scalp was shaven and thoroughly cleaned before application of the sensors with cyanoacrylate adhesive. A small drop of isotonic saline applied to the $tcPo_2$ electrode surface before fixation assured good optical and chemical contact with the skin, and a contact fluid was applied to the $tcPco_2$ sensor surface before application.

Immediately after each experiment, the calibration of the sensors was checked. The change in sensitivity of the $tcPo_2$ electrode proved to be less than 10%, and the $tcPco_2$ sensor drift was less than 5 mm Hg for the two calibration points during the whole experiment.

Procedures. Eight experiments were done on four healthy lambs in the first weeks of extrauterine life (experiments 1–4: 16–27 d, and experiments 5–8: 5–8 d after birth). Two experiments were done on each lamb. Scalp blood flow was influenced by the application of an increasing circular pressure on the scalp around the sensors. LDF and $tcPo_2$ were recorded in all experiments and $tcPco_2$ was recorded in four experiments (recordings 1–4).

At the beginning of the experiment a PVC ring, shaped to the model of the skull, was applied to the scalp over the parietal and occipital bones, encircling an area with a diameter of 5 cm. A rubber tube between the PVC ring and the scalp distributed the pressure equally over the surface of the scalp, when the PVC ring was pressed to the scalp. The pressure in the tube was measured by connecting the water in the tube with a flexible catheter to a pressure transducer (Hewlett-Packard Co., Palo Alto, CA; HP 1280 C). This pressure approximated the CSP when the PVC ring fit well.

The two sensors were applied to the scalp area encircled by the rubber ring and were allowed to stabilize for 20 min, whereas the pressure transducer was placed at the level of the ring on the scalp. A 5-min control period was followed by a sudden increase of the circular scalp pressure to 10, 20, 30, 40, 50, 60, 70, and 80 mm Hg, randomly chosen (Fig. 1). After 4–9 min, when LDF, $tcPo_2$, and $tcPco_2$ had reached stable values for at least 2 min, the PVC ring was released and the recorded signals were allowed to return to basal levels. The next pressure application followed after a 5-min control period, starting 15–20 min later, when the signals had reached stable values. During the application of pressure, a bluish hue was observed in the scalp indicating venous stasis. Enough recuperation time was allowed between the applications of pressure to prevent the development of scalp edema during the course of the experiment.

During each experiment, the behavioral state of the lamb was observed, because the variability of the LDF and blood gas values was found to be greater during active states. Only data obtained during quiescence (awake or in non-rapid eye movement sleep) were used for analysis of the relation between LDF and the transcutaneous blood gas values. Room temperature and humidity were kept within narrow limits.

The LDF reading at zero blood flow was determined in each experiment by applying pressure on the LDF sensor. This LDF reading amounted to 1 V on the average. Inasmuch as only the flow-dependent part of the LDF signal is of interest for this study, these zero values were subtracted from the recorded LDF values.

The signals (LDF, $tcPo_2$, $tcPco_2$, and CSP) were recorded on a strip chart recorder (Gould 8800 S; Gould Electronics, Cleveland, OH) at a paper speed of 50 mm/min and stored in a microcomputer with a sample interval of 500 ms.

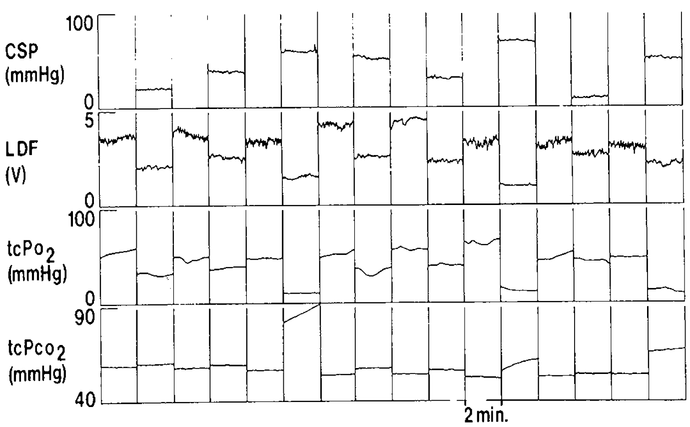

Fig. 1. LDF, $tcPo_2$, and $tcPco_2$ tracing of the last 2 min before and during the application of CSP around the sensors in experiment 4. The sixth pressure application was interrupted after 3 min as the lamb became restless. As a result of the slow response of the $tcPco_2$ it has not yet increased much.

Mean values of 10 samples taken every 12 s in a period of 2 min, immediately before and at the end of the circular pressure application, were used for further analysis. Student's t test for paired samples was used to compare the values of LDF, $tcPo_2$, and $tcPco_2$ during each pressure application with those measured before. A p value of <0.05 was chosen as the level of significance. Scatter diagrams were constructed of the data points of LDF and $tcPo_2$ and of LDF and $tcPco_2$. Hyperbolic curves were fitted through the data points of each experiment by a least squares approximation of the distance between the points and the hyperbolic curve. The hyperbolic curves are characterized by a horizontal asymptote, a bending factor, and a vertical asymptote. These three constants as well as the X intercept of the LDF-$tcPo_2$ curve, allow comparison of the different experiments.

RESULTS

When the circular pressure exerted on the scalp was increased, LDF fell rapidly, followed by a decrease in $tcPo_2$ and a slow rise in $tcPco_2$. The effects of varying degrees of circular pressure on the stabilized LDF and transcutaneous blood gas values during one experiment are presented in Figure 1, showing the LDF and blood gas values during the last 2 min of each pressure application in experiment 4. The signals had stabilized at this time, except for the $tcPco_2$ at low LDF levels, which continued to rise until the pressure was released.

With increasing CSP, scalp blood flow and $tcPo_2$ decreased, whereas $tcPco_2$ increased. Table 1 summarizes the changes in LDF at the various CSP values. Figures 2 and 3 show the

Table 1. *LDF (mean ± SD) during CSP (n = 8)*

CSP (mm Hg)	0	10	20	30	40	50	60*	70†	80‡
LDF (V)	2.85	2.0	2.1	1.65	2.0	1.3	0.55	0.6	0.4
(SD)	(0.1)	(0.1)	(0.1)	(0.05)	(0.1)	(0.1)	(0.05)	(0.04)	(0.03)

* $n = 7$.
† $n = 4$.
‡ $n = 3$.

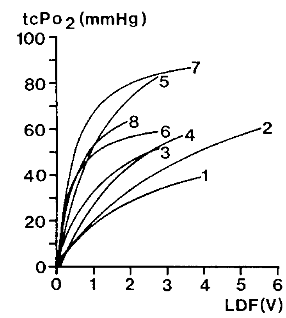

Fig. 2. Hyperbolic curves fitted through the scatter diagrams of the laser LDF and $tcPo_2$ data points of all eight experiments. The numbers are recording identification numbers.

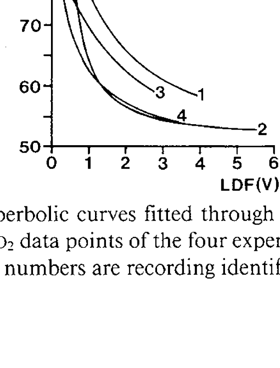

Fig. 3. The hyperbolic curves fitted through the scatter diagrams of the LDF and $tcPco_2$ data points of the four experiments in which $tcPco_2$ was recorded. The numbers are recording identification numbers.

relationship between LDF and the transcutaneous blood gas values as the hyperbolic curves fitted through the scatter diagrams containing the values of LDF *versus* tcP_{O_2} and LDF *versus* tcP_{CO_2}, respectively. At high LDF values, tcP_{O_2} as well as tcP_{CO_2} approximate a level that tends to be independent of LDF. At lower flow levels, however, slight changes in LDF result in pronounced changes in tcP_{O_2} and tcP_{CO_2}. The effect increases with decreasing scalp blood flow.

The hyperbolic curves fitted through each scatter diagram, describing the LDF-tcP_{O_2} relation show pronounced differences in the values of the horizontal asymptote and the bending factor. The LDF value at which tcP_{O_2} is zero, *i.e.* the intercept of the curve with the X axis, is near zero and almost constant (Fig. 2).

The LDF-tcP_{CO_2} relationship (Fig. 3) shows tcP_{CO_2} values between 53 and 63 mm Hg when blood flow is undisturbed and increasing values up to 95 mm Hg at lower LDF values. In contrast to tcP_{O_2}, the constants characterizing the relationships between tcP_{CO_2} and LDF do not show considerable differences between the experiments (Fig. 3). TcP_{CO_2} failed to stabilize during three prolonged applications of 60 mm Hg and one of 50 mm Hg. Frowning and bleating resulted in significant short-term fluctuations of the LDF signal, while tcP_{O_2} and tcP_{CO_2} remained unaffected.

DISCUSSION

In our study, scalp blood flow was influenced by applying a circular pressure around the sensors. This method was chosen to obtain an obstruction of the blood flow in the encircled scalp area via a mechanism similar to that supposedly occurring during labor. Obviously in several younger lambs complete obstruction was only attained at higher CSP values because the CSP ring did not fit precisely on the smaller skull of these lambs. As the signals stabilized during the application of pressure, analysis of the relation between blood flow and transcutaneous blood gas values remains justified.

The presented data showed a nonlinear relation between scalp blood flow as measured by laser Doppler flowmetry and transcutaneous blood gas values, tcP_{O_2} and tcP_{CO_2}, in the lamb. Such a relationship has been described previously in a theoretical study (16) and has also been demonstrated for tcP_{O_2} and heating power in an experimental study (17). Although, in our study, the scalp under the LDF sensor was heated to 44°C and thus thermally vasodilated, the LDF-blood gas relations show only a small part in which the transcutaneous blood gas values are fairly insensitive to changes in scalp blood flow (Figs. 2 and 3).

As long as scalp blood flow remains undisturbed, the transcutaneous blood gas values are mainly determined by the carotid arterial ones. Changes in the latter will have contributed to the spread of the data points around the hyperbolic curves describing the LDF-blood gas relations. However, changes in LDF of a magnitude as observed during human labor, *i.e.* a reduction in scalp blood flow of approximately 50% (1), are associated with profound changes in the transcutaneously measured P_{O_2} as well as P_{CO_2}. The latter have a much larger amplitude than those normally observed in tcP_{O_2} and tcP_{CO_2} monitoring of the neonate (18). This, combined with the immediate onset of the LDF and blood gas change resulting from the CSP application, indicates the presence of a causal relation between the changes in LDF and transcutaneous blood gas values.

It has been shown that in human labor a circular pressure profile is generated over the scalp surface, which is the result of the expulsive forces exerted by the fetal head on the maternal cervix and vaginal wall (6). Our experiments demonstrate that a circular pressure, small in comparison with that observed during uterine contractions, is associated with considerable changes in LDF and transcutaneously measured blood gas values. Consequently, a disruption of the relation between the carotid arterial and the transcutaneous blood gas values is, contrary to previous assumptions (19), likely to occur during labor. This makes transcutaneous blood gas measurement unreliable for fetal monitoring during labor.

Of the differences between the constants characterizing the hyperbolic curves fitted through the LDF-tcP_{O_2} data points of each experiment, the difference between the horizontal asymptote and bending factors of each experiment is most apparent. The lambs that were studied in the first 5 to 8 d after birth, showed significantly higher tcP_{O_2} values than those studied on the 16th to 27th d (Fig. 2). This could be the result of decreased O_2 diffusion to the scalp surface with advancing age. In contrast to the tcP_{O_2}, the tcP_{CO_2} values at high blood levels show only minor differences between the experiments, possibly as a result of the higher diffusibility of CO_2. The latter is presumably also the explanation of the greater uniformity of the constants characterizing the LDF-tcP_{CO_2} relation, in comparison with the LDF-tcP_{O_2} relation.

The X intercepts of the hyperbolic curves, describing the LDF-tcP_{O_2} relations, show only small differences between the experiments and almost correspond with the zero flow value. Inasmuch as oxidative metabolism in the cells continues until almost all oxygen has been consumed, CO_2 production goes on, resulting in CO_2 accumulation in the encircled scalp area. Consequently, tcP_{CO_2} increased until the pressure was released.

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