Pulse oximetry — physiological considerations

Mark A. Hanson a*, Jan G. Nijhuis b

Abstract

Fetal well-being depends on the level of oxygenation in vital organs such as the heart and brain. In this review, we discuss the physiological parameters which underlie the use of pulse oximetry to evaluate fetal conditions intrapartum. Whilst the measurement of haemoglobin oxygen saturation (SaO2) depends on partial pressure of oxygen (Po2), the relation is nonlinear, is relatively insensitive to changes in Po2 at the upper physiological range, and it is affected by the Bohr shift. Oxygen content of the blood cannot be determined without measurement of haemoglobin (Hb) content and this can change quite quickly. In hypoxia for example, oxygen delivery to an organ, e.g. the brain, cannot be assessed without simultaneous measurement of blood flow, which again changes with fetal condition. Lastly, it is not possible to gauge fetal tissue unless some measure of, for example, cytochrome aa3 oxidation is used: tissue oxidation in relation to oxygen delivery can change due to local vascular readjustments and changes in metabolism. We conclude that use of SaO2 to assess fetal well-being is fraught with difficulties, and that much more research is needed before its routine clinical use can be considered. © 1997 Elsevier Science Ireland Ltd.

1. Introduction

Ante- or intrapartum monitoring aims to reduce fetal mortality and morbidity caused by insufficient fetal oxygenation leading to fetal hypoxia/asphyxia. Intrapartum asphyxia causes 10–15% of all cerebral palsy cases [1]. Although insufficient oxygenation has not been uniformly defined, it has become clear that perinatal morbidity is markedly increased if the umbilical artery pH at birth is below 7.00 [2]. If fetal distress is suspected, instrumental delivery (forcipal or vacuum extraction, Caesarean section) will be performed. During labour, electronic fetal monitoring is commonplace. This technique has been introduced into clinical practice without properly randomized studies which showed that the technique indeed reduced fetal morbidity and mortality. As compared to auscultation, the method certainly leads to an increase of obstetric interventions [3], but does not reduce neonatal morbidity. The assessment of acid–base balance in the fetus during labour by obtaining a fetal-blood sample was introduced by Saling in 1962 [4]. However, this technique is in fact traumatic and gives only information on the oxygenation of the fetal scalp at the time of sampling.

Research in this field should be aiming at the development of a technique which measures the fetal condition reliably, continuously and non-invasively. Monitoring methods currently used, have each some disadvantages, the most obvious of which is that none of them measures the degree of oxygenation in the tissues, which is what one really needs to know to assess the extent to which a fetus is threatened. Set against this is the fact that several of the widely used techniques, e.g. fetal heart rate monitoring, measure an aspect of fetal autonomic function which would be expected to change in hypoxia/asphyxia. The problem though arises in interpreting the signal, as from a scientific point of view it is not easy to predict the changes which will occur. For example, changes in fetal heart rate could be viewed either as part of a

*Corresponding author. Tel.: +44 171 209 6058; fax: +44 171 383 7429.
fetal cardiovascular response to hypoxia, or as the result of direct depressant effects of low PO₂ on the brain stem or sinoatrial node. Adequate interpretation in physiology depends on being able to measure both the stimulus and the response to it.

2. Measurement of oxygenation

Pursuance of the theoretical considerations above leads to the question of the most appropriate site for measurement of oxygenation from a practical point of view. Measurement of tissue PO₂ in the brain would be ideal, but it is not currently feasible, and in any event would need to be made alongside measurements of metabolism. Developments in the use of near infrared spectroscopy (NIRS) may ultimately permit this, for NIRS allows simultaneous measurement of the chromophores Hb, HbO₂ and cytochrome O₂ oxidation (cyt O₂). Combination of the Hb and HbO₂ measurement (into total Hb, Hbt) gives an estimate of the blood volume in a part of the brain (see Table 1). Changes in Hb, will reflect changes in blood flow, but the effects of changes in arterial and venous flow cannot be distinguished. At present the method is not sensitive and reliable enough to measure cyt O₂ in neural tissue, which would give a good measure of the redox stage resulting from the combination of O₂ delivery and metabolism.

Cyt O₂ measurement in muscle is easier, because its levels are much greater. However, the correlation between these levels and those in other tissues such as the heart and brain, or indeed with arterial PO₂ (Pao₂), is not known. The fall in tissue PO₂ in muscle is expected to be greater than in the brain during an acute hypoxic challenge, due to the vasoconstriction as part of the redistribution of combined ventricular output [5]. On the other hand, if the hypoxia is prolonged, the initial fall in muscle PO₂ may not be sustained, as metabolism and growth are affected quite fast. Indeed, the effect of local PO₂ on oxygen consumption (VO₂), measured in fetal skeletal muscle in vitro, is large and operates over a higher PO₂ range than reported in the adult (see Fig. 1). Growth in muscle, measured from DNA synthesis, falls after several hours of hypoxia (see Fig. 2). Thus, in the transition from acute to sustained hypoxia, which may occur in prolonged labour, the changes in muscle and tissue cyt O₂ will be hard to interpret with the current state of our knowledge.

In animal experiments, or in neonatal intensive care, where there is access to an arterial line, measurements of Pao₂ are all-important for assessing physiological condition, including placental (or pulmonary) blood flow and the extent of venous admixture. Measurement of the level of Pao₂ (but not SaO₂, CaO₂ or O₂ delivery) is important as it is a potent stimulus to the arterial chemoreceptors, especially the carotid bodies, which initiate the rapid cardiovascular reflexes which occur in the fetus during an episode of acute hypoxia [6]. However, whilst fetal blood samples can be taken by cordocentesis [7], the method is not feasible intra-partum. Fetal blood sampling provides a substitute, but the interpretation needs caution.

3. Saturation measurement and its physiological problems

The search for a measure of fetal well-being in relation to oxygenation has led to sustained research over many years into the use of oximetry. From a physiological point of view, the problems with interpreting the results are summarised in Fig. 3. HbO₂ is, of course, related to the PO₂ by the well known Hb dissociation curve, the position of which is shifted to the left in the fetus in relation to the adult and which shifts if PCO₂/pH change (the Bohr effect). The sigmoid shape of the curve means that the relation between SaO₂ and Pao₂ depends on the level of the Pao₂ — SaO₂ being relatively unaffected by changes in Pao₂ when it is high and linearly related when Pao₂ is lower. The relation also becomes allinear at very low Pao₂ values, which may be problematic if this is the area over which monitoring is clinically important.
Fig. 1. Relationship between oxygen tension in the hypoxic perfusate entering the Petri-dish ('entry PO2') and the change of oxygen consumption of fetal skeletal muscle cells in monolayer culture as % of control ($y = 5.17 - 0.54x + 0.03x^2 - 0.00016x^3$, $r = 0.97$, $n = 54$, $P < 0.0001$). Experiments in which the flow rate was 60 ml/h (●) and 120 ml/h (O, $n = 3$) are marked differently. The values correlate closely over a wide range so that not only during fetal hypoxia but also during recovery and on transition from fetal to postnatal life when oxygen delivery increases, optimal cell function may be warranted at any given state of oxygenation [8].

Extrapolating from $Sao2$ to $CaO2$ requires measurement of Hb, which would necessitate taking a blood sample. Moreover, there is the problem that plasma Hb can change relatively fast during an episode of hypoxaemia (see Fig. 4) due to changes in fluid transfer across capillaries, so that prediction of $CaO2$ values from minute to minute is not easy.

$O2$ delivery to tissues depends on a further variable, namely blood flow. This of course cannot be measured intra-partum and will also change over time.

Fig. 2. Tissue DNA synthesis rates collected from fetuses after either 10-day period of daily fetal placental embolization (closed bars) or 10-day control period (open bars). Asterisks, DNA synthesis rates in tissues from embolized fetuses that are significantly less than control ($P < 0.05$) [9].
Fig. 3. Physiological determinants of tissue $P_O_2$, considered as a flow diagram to highlight the problems of interpreting the $SaO_2$ signal.

Fig. 4. Effects of 1 h of acute isocapnic hypoxia on carotid arterial blood of late gestation sheep fetuses in utero. Note particularly that the fall in haemoglobin during hypoxia in these experiments produces a larger fall in $O_2$ content than predicted from $SaO_2$ values (unpublished data of Green LR, Bennet L, Crowe C, and Hanson MA).
The pressure of contractions could be one factor which alters blood flow and the effects of changes in PO₂ and PCO₂ on cerebral blood flow are well known. The problem is exacerbated if the oximetry probe is applied to the scalp or cheek, as is usual intrapartum, for the signal will be derived at least partially from cutaneous blood. This flow is particularly sensitive to neural and endocrine-mediated vasoconstriction which occurs in hypoxaemia [6], and indeed the linear relation between skin blood flow and plasma catecholamines has been used as a measure of fetal stress responses to hypoxaemia [8] (see Fig. 5). This poses a potentially serious problem for the use of externally applied oximetry for measurement of the oxygenation of the blood at a time when changes in cutaneous blood flow are likely to occur. However, it is said that scalp and face cutaneous blood flow change less than those of other cutaneous beds during adrenergic stimulation [5].

It is thus clear that physiological considerations cast serious doubt on the use of SaO₂ measurement, as in pulse oximetry, to assess fetal condition. This is further emphasised if, finally, we consider the determinants of fetal tissue oxygenation upon which well-being ultimately depends.

As indicated in Fig. 3, the relation between arterial and venous PO₂ and tissue PO₂ is not simple. Tissue PO₂ must always be less than venous PO₂: oxygen is consumed by metabolism as it diffuses down its concentration gradient from capillaries to cells. Thus the arrangement of capillaries and any arterio-venous anastomosis, intercapillary distance and tissue metabolism rate all affect the level of tissue PO₂. Rapid changes in the distribution of vessels perfused and in metabolism can occur, for example in hypoxia. For this reason, progress in this area may ultimately depend on the development of methods for measurement of tissue oxygenation which can be used intrapartum.

However, before such a new method is introduced into clinical practice, multi-centered randomized studies need to be performed. Only if such studies show that the method is more sensitive than the currently used techniques and indeed reduce both perinatal morbidity and unnecessary obstetric interventions, one can advocate its use in daily clinical practice.

**Fig. 5.** Relationship between log catecholamine concentrations and mean transcutaneous PO₂ (upper) and mean skin blood flow (lower). Mean transcutaneous PO₂ and mean skin blood flow were calculated by averaging all maximum and minimum points of inflection (n = 23) of the respective tracings throughout the experiment and are expressed as percent of control. (tcPO₂, mean = 151 - 40.0 × log [NE], r = -0.81, 2α < 0.001; tcPO₂, mean = 89 - 15.3 × log [E], r = -0.76, 2α < 0.001) (blood flow skin, mean = 193 - 34.8 × log [NE], r = 0.97, n = 9, 2α < 0.001; blood flow skin, mean = 151 - 19.7 × log [E], r = -0.94, 2α < 0.001) [10].
Acknowledgements

M A Hanson’s work is supported by The Wellcome Trust.

References


