Oxygen transport and utilization during feeding in the young lamb

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1. Five lambs (19–27 days old) were studied to determine the effects of feeding on cardiorespiratory function.

2. Each lamb was instrumented to record cardiac output, aortic and pulmonary artery pressure and arterial and mixed venous oxyhaemoglobin saturations (S_{a,O_2} and S_{v,O_2}).

3. During feeding, arterial haemoglobin desaturated and resaturated sequentially during the periods of sucking and non-sucking. The nadir of these S_{a,O_2} desaturations ($83 \pm 2\%$, mean ± S.E.M.) was significantly lower than the baseline value ($92 \pm 2\%$, $P \leqslant 0{\cdot}05$, ANOVA). S_{a,O_2} returned to the baseline level between periods of sucking. S_{v,O_2} also decreased ($55 \pm 3\%$ baseline, $46 \pm 3\%$ sucking, $P \leqslant 0{\cdot}05$) but, in contrast to S_{a,O_2}, it remained significantly lower than baseline levels in the pauses between periods of sucking.

4. Arterial pressure increased during feeding (94 ± 4 mmHg baseline, 113 ± 6 mmHg feeding, $P \leqslant 0{\cdot}05$), while heart rate and cardiac index did not change.

5. Total body oxygen consumption rose during the pauses between sucking periods ($10{\cdot}9 \pm 1{\cdot}1$ ml O_2 min^{-1} kg^{-1} baseline, $13{\cdot}9 \pm 1{\cdot}2$ ml O_2 min^{-1} kg^{-1} non-sucking, $P \leqslant 0{\cdot}05$) and was provided for by a significant increase in total body oxygen extraction as systemic oxygen transport was unchanged.

6. Our results reveal that during feeding in young lambs oxygen consumption increases and body stores of oxygen (e.g. S_{v,O_2}) become depleted; this combination may promote rapid arterial desaturation and cyanosis during feeding.

An infant's ability to feed and maintain adequate ventilation demands successful co-ordination of three complex motor skills: sucking, swallowing and breathing. While feeding can lead to marked alterations in cardiorespiratory function in full-term human infants (Mathew, Clark, Pronske, Luna-Solarzano & Peterson, 1985) and in newborn animals (Harding, Johnson, McClelland, McLeod, Whyte & Wilkinson, 1978; Harding & Titchen, 1981), the co-ordination of sucking, swallowing and breathing can be particularly troublesome for the preterm infant. Feeding in the preterm infant often results in irregular respiration, bradycardia, apnoea, aspiration and cyanosis (Shivpuri, Martin, Carlo & Fanaroff, 1983; Guilleminault & Coons, 1984; Rosen, Glaze & Frost, 1984; Koenig, Davies & Thach, 1990; Mathew, 1991). Significantly, feeding (Templeman, 1892; Camps & Carpenter, 1972) and the abnormalities in cardiorespiratory function associated with feeding (Steinschneider, Weinstein & Diamond, 1982) have also been implicated in the sudden infant death syndrome (SIDS).

A feeding epoch typically begins with a period of continuous sucking during which breathing frequency, tidal volume and arterial oxygen tension (P_{a,O_2}) are substantially reduced and arterial carbon dioxide tension (P_{a,CO_2}) is substantially increased (Harding *et al.* 1978; Harding & Titchen, 1981; Shivpuri *et al.* 1983; Mathew *et al.* 1985; Mathew, 1991). Subsequently, sucking and breathing occur concurrently, minute ventilation recovers, and P_{a,O_2} and P_{a,CO_2} return to baseline levels (Harding *et al.* 1978; Harding & Titchen, 1981; Shivpuri *et al.* 1983). As the most prolonged interruption of ventilation occurs early in the feeding epoch during the period of continuous sucking, one might predict that the propensity for marked arterial

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oxyhaemoglobin desaturation, and subsequently cyanosis and bradycardia, would be greatest during this first phase of feeding. However, in a seeming paradox, the most pronounced arterial desaturation may occur later in feeding when ventilation and arterial blood gases should normally have recovered to baseline levels. Continuous recordings of arterial oxyhaemoglobin saturation (S_{a,O_2}) reveal that arterial haemoglobin undergoes a succession of desaturations and resaturations during feeding (Mok, McLaughlin, Pintar, Hak, Amaro-Galvez & Levison, 1986). Surprisingly, however, the rate and magnitude of these desaturations appear to increase near the end of the feeding epoch, the period of feeding normally associated with intermittent sucking – a phenomenon that is as yet unexplained.

This pattern of a normal arterial oxyhaemoglobin saturation, interspersed by desaturations that increase in rate and extent during bouts of feeding, is reminiscent of the pattern seen during repetitive apnoea. When apnoea occurs in a series the rate and extent of desaturation commonly increases with each succeeding apnoeic event even though S_{a,O_2} may return to normal between apnoeas. In explanation of the apnoeic desaturation pattern, Fletcher *et al.* (Fletcher, Kass, Thornby, Rosborough & Miller, 1989) and Wilkinson *et al.* (Wilkinson, Berger, Blanch & Brodecky, 1995) have shown that it is the body oxygen stores, and in particular the mixed venous oxyhaemoglobin saturation level (S_{v,O_2}), that are pivotal in determining the rate of arterial desaturation during repeated apnoea. Other factors important in determining oxygen storage and utilization include the initial S_{a,O_2} (Strohl & Altose, 1980), lung volume (Henderson-Smart, 1980; Bradley *et al.* 1985; Findley, Ries, Tisi & Wagner, 1986), and the rate of oxygen consumption and transport. How each of these factors may contribute to arterial desaturation and the development of cyanosis during feeding is not known. Nor is it known how body oxygen stores, in particular venous oxygen stores, are affected by feeding. As a step towards furthering our understanding of how feeding may lead to rapid desaturation and cyanosis we sought to define the cardiorespiratory alterations which occur during feeding in the lamb. Specifically, we sought to determine whether the venous oxygen store (S_{v,O_2}) is substantially and continuously decreased during feeding, thereby creating a condition which favours rapid S_{a,O_2} desaturations.

METHODS

Five newborn lambs were separated from their ewes at 1 day of age and housed, with companion lambs, in a Plexiglass cage located within an environmental chamber (25 °C, 40% humidity, 12 h light–dark cycle). Each lamb was taught to feed independently and had continuous access to milk (Lamb Milk Replacer, Land O'Lakes, Fort Dodge, IA, USA; mean weight gain, 230 ± 30 g day^{-1}).

Surgical instrumentation

We instrumented each lamb at 2 days of age using sterile surgical techniques. Atropine sulphate (0·2 mg kg^{-1}, subcutaneously) was administered and then general anaesthesia was induced by allowing the lambs to breathe 5% halothane in oxygen. The lambs were then intubated with a cuffed endotracheal tube and ventilated with 0·5–1·0% halothane in oxygen. Ventilatory rate and volume were adjusted to ensure adequate ventilation as assessed by blood gas analysis.

We performed a left thoracotomy at the level of the third or fourth intercostal space. The pericardium was widely incised and the pulmonary artery exposed. An ultrasonic flow probe (Transonic Systems Inc., Ithaca, NY, USA) was placed around the main pulmonary artery to measure pulmonary artery blood flow. A fibre-optic catheter oximeter (Intravascular Optical Catheter Model U440, Abbott Critical Care Systems, Mountain View, CA, USA) was inserted through a purse-string suture into the pulmonary artery distal to the flow probe. From this catheter we measured pulmonary artery pressure and S_{v,O_2}. A similar catheter oximeter was positioned in the descending aorta, via the femoral artery, to measure arterial pressure and S_{a,O_2}. The chest was closed in layers and air evacuated from the chest with 3–5 cmH_2O suction. For a series of unrelated studies stainless-steel electrodes were implanted as previously described (Grant, Davidson & Fewell, 1995) to record the electrocorticogram, electro-oculogram and electromyogram of the neck muscles.

Following surgery we placed the lambs in a Shor-Line intensive care unit for small animals (Schroer Manufacturing Company, Kansas City, MO, USA) to recover from anaesthesia. After recovery, the lambs were returned to their cage. Each day following surgery catheters were flushed with heparinized saline (1000 units ml^{-1}). Antibiotics (penicillin G and dihydrostreptomycin; 125 mg of each) were administered daily for 5 days following surgery. The lambs were not studied in the present protocol until a minimum of 17 days had elapsed (age of lambs in study, 19–27 days; body weight at time of study, 8·2 ± 0·6 kg), providing ample time for full recovery of normal cardiorespiratory function.

Conditions of study

On the day prior to the study, the cage was partitioned to prevent the lamb from turning around. The lambs continued to have access to food and could walk forward and backward, as well as stand or lie down. We connected the flow probe to the flow meter (Model T101 Ultrasonic Blood Flow Meter, Transonic Systems Inc., Ithaca, NY, USA). The pulmonary artery and aortic catheters were connected to calibrated strain gauge manometers (Gould P23ID) located outside the environmental chamber. Vascular pressures were referenced to the mid-plane of the heart. In addition to these physiological signals we recorded the pressure within the tube leading from the milk supply to the feeding nipple. Deflections in feeding tube pressure signalled the occurrence of feeding.

All signals were low-pass filtered at 75 Hz and recorded on polygraph (Grass model 7 Polygraph). Signals were also stored on computer (Zenith AT 286) at a sampling rate of 167 Hz using an analog-to-digital converter (Data Translation 2801A A/D and DATAQ WFS-200 Hardware Scroller) and data acquisition software (Codas Data Acquisition Software; DATAQ Instruments Inc., Akron, OH, USA). Data were subsequently analysed off-line (CVSOFT, Odessa Computer Systems Inc., Calgary, Canada).

Experimental protocol

Prior to beginning the study arterial and venous blood samples were drawn and analysed for blood gas values, pH, oxyhaemoglobin saturation and haemoglobin (Hb) concentrations. Fibre-optic catheter oximeter systems were calibrated using the collected S_{a,O_2} and S_{v,O_2} values. Subsequently, we recorded data from each lamb for a maximum period of 6 h. During this time the lambs were allowed

Table 1. Characteristics of feeding epochs ($n = 5$ lambs)

	Mean ± S.E.M.	Range
Number of periods of sucking	7 ± 2	3–14
Duration of periods of sucking (s)	12 ± 4	2–59
Duration of pause between periods of sucking (s)	6 ± 2	1–13
Duration of longest period of sucking (s)	28 ± 8	12–59
Duration of last period of sucking (s)	7 ± 2	2–14

to cycle spontaneously through behavioural states and to feed at will. One feeding epoch from each lamb was randomly selected from these 6 h data files (the only selection criterion was that the epoch contain three or more periods of sucking, the greatest common number of sucking epochs observed in all lambs; see Table 1 – the number of feeding epochs meeting this criterion ranged between 1 and 3 epochs per lamb; mean, 2 ± 0·5). These data were analysed to determine continuous values for each of the physiological variables recorded, as well as for the calculated variables: arterial and venous oxygen contents ($C_{a,O_2} = [Hb] \times S_{a,O_2} \times 0{\cdot}0136$, $C_{v,O_2} = [Hb] \times S_{v,O_2} \times 0{\cdot}0136$), total body oxygen extraction ($TBOE = 100(C_{a,O_2} - C_{v,O_2})/C_{a,O_2}$), total body oxygen consumption ($\dot{V}_{O_2}$ = cardiac index × $(C_{a,O_2} - C_{v,O_2})/100$), and systemic oxygen transport (SOT = cardiac index × $C_{a,O_2}/100$).

Data analysis and statistics

Baseline data were calculated as the mean for each variable over the 30 s prior to the onset of the first period of sucking in a feeding epoch. Data for each variable were also averaged over three heart beats at the time points corresponding to the sequential minimal and maximal values observed on the S_{a,O_2} recording (see Fig. 1; trough and peak values, respectively). Analysis of variance for repeated measures was performed to determine if statistically significant differences existed between means. A Dunnet's analysis was then used to isolate those data which differed significantly from the baseline values. A probability of $P \leqslant 0{\cdot}05$ was assumed to be statistically significant. All values are presented as means ± S.E.M. The surgical preparation and experiments described herein were approved by the Animal Care Committee of the Faculty of Medicine of The University of Calgary whose standards conform to the guiding principles of the American Physiological Society.

RESULTS

The feeding pattern (Table 1, Fig. 2) demonstrated by our lambs closely resembles the pattern previously reported for the newborn lamb (Harding *et al.* 1978; Harding & Titchen, 1981). An epoch of feeding was composed of periods of sucking separated by pauses during which no sucking was observed. The longest periods of sucking occurred early in each feeding epoch, being either the first or the second

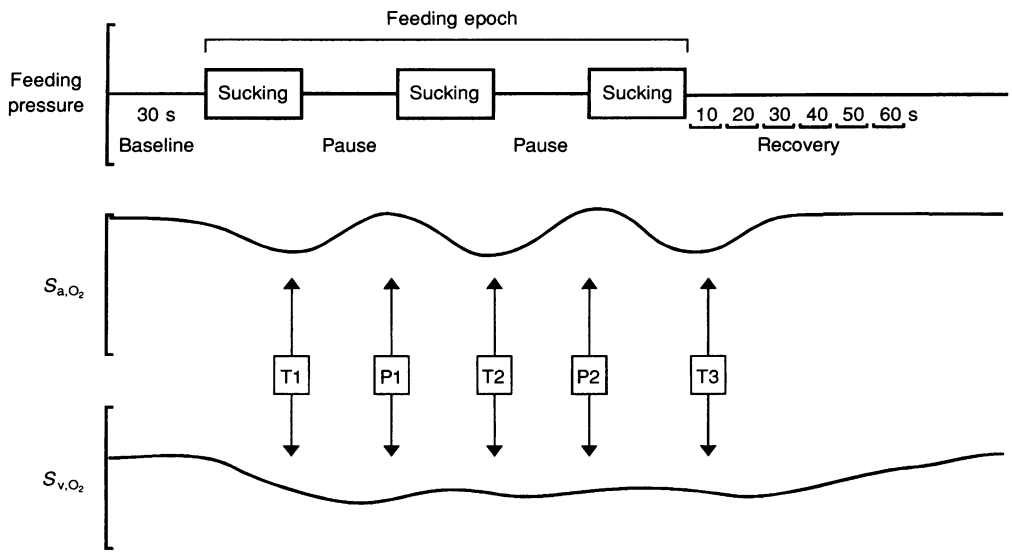

Figure 1. Analysis performed to assess the effect of feeding on cardiorespiratory function

Feeding epochs were partitioned into periods of sucking and non-sucking based upon analysis of the pressure recorded from the feeding supply system. Subsequently, baseline data were obtained as the 30 s mean of each variable immediately preceding the onset of the first period of sucking. Data for each variable were also averaged over three heart beats (approximately 1 s) at the time points corresponding to the sequential minimal (T, trough) and maximal (P, peak) values observed on the S_{a,O_2} recording. Recovery data were recorded as 10 s means for the first 60 s following the final period of sucking.

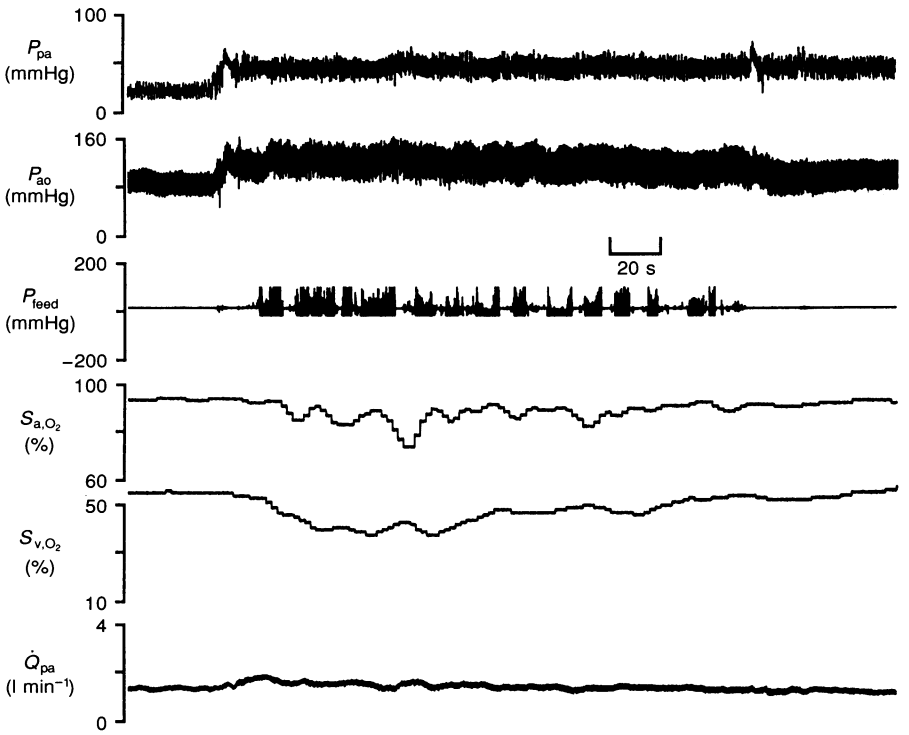

Figure 2. Physiological recordings during an epoch of feeding in a lamb

Arterial and mixed venous oxyhaemoglobin saturations (S_{a,O_2} and S_{v,O_2}) decreased during the first period of sucking (indicated by deflections in the pressure in the feeding system, P_{feed}). With the interruption of feeding S_{a,O_2} returned to the baseline level while S_{v,O_2} remained below baseline. Subsequent periods of sucking again produced cyclic desaturations of S_{a,O_2} while S_{v,O_2} remained below baseline. (P_{pa}, pulmonary artery blood pressure; P_{ao}, aortic blood pressure; $\dot{Q}_{pa}$, mean pulmonary artery blood flow.)

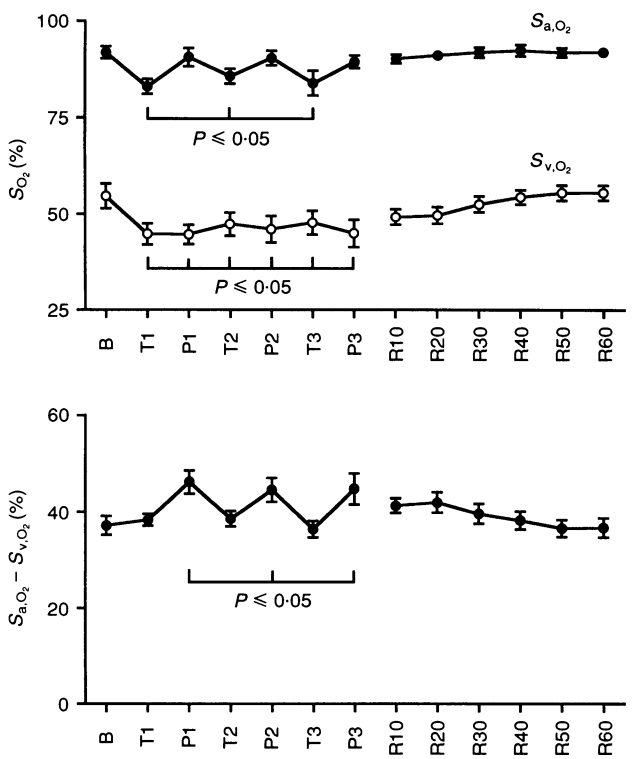

Figure 3. Arterial and venous oxyhaemoglobin saturation during feeding

Feeding produced repetitive cyclic decreases and increases in arterial oxyhaemoglobin saturation (●, S_{a,O_2}), while mixed venous oxyhaemoglobin saturation (○, S_{v,O_2}) decreased significantly ($P \leqslant 0{\cdot}05$) and remained decreased throughout. The persistent depression of S_{v,O_2} and the cyclic desaturation and resaturation of arterial blood lead to an increase in the difference between arterial and venous oxyhaemoglobin saturations during the non-sucking periods ($S_{a,O_2} - S_{v,O_2}$). Values represent the means ± S.E.M. B, baseline; T, trough value; P, peak value (see Fig. 1); R, 10 s means of data recorded after the final period of sucking. Data indicated by the vertical bars differ statistically from baseline values ($P \leqslant 0{\cdot}05$).

period of sucking, and were significantly longer than that of the final period of sucking ($P \leqslant 0{\cdot}05$). Because the number of periods of sucking within a given epoch of feeding varied between lambs (Table 1), all further analysis was limited to the initial three periods of sucking (the range of sucking epochs common to each lamb) plus 60 s immediately following the end of feeding.

With the onset of sucking both S_{a,O_2} and S_{v,O_2} decreased significantly below baseline values (Fig. 2). When sucking briefly ceased S_{a,O_2} returned to baseline levels; however, S_{v,O_2} recovered less quickly and remained significantly decreased from the baseline values. With the onset of the next period of sucking S_{a,O_2} again decreased before S_{v,O_2} had returned to the baseline level. This pattern of sucking and non-sucking leading to arterial desaturation and resaturation and maintained venous desaturation was repeated throughout the early portion of each feeding epoch. Later in the feeding epoch, beyond the third period of sucking, both S_{a,O_2} and S_{v,O_2} returned towards baseline even though sucking continued (Fig. 2). These later portions of the feeding epoch were not analysed because of the difficulty of comparing feeding epochs of differing lengths.

When analysed at points temporally related to the peaks and troughs of S_{a,O_2} (Fig. 1) both S_{a,O_2} and S_{v,O_2} were significantly reduced from baseline levels during the periods of sucking (troughs, Fig. 3, $P \leqslant 0{\cdot}05$). At the peaks of S_{a,O_2}, which reflect the pauses between periods of sucking where normal breathing occurred, S_{a,O_2} returned to baseline levels while the S_{v,O_2} remained significantly decreased (Fig. 3, $P \leqslant 0{\cdot}05$). There was no significant difference between the minimal S_{a,O_2} attained during the initial sucking period ($83 \pm 2\%$) and those attained in the second ($86 \pm 2\%$) and third period of sucking ($84 \pm 3\%$). Because of the sinusoidal-like pattern of S_{a,O_2} and the maintained decrease in S_{v,O_2} the difference in arterial–venous oxyhaemoglobin saturation increased significantly during the pauses between periods of sucking in each feeding epoch (Fig. 3, $P \leqslant 0{\cdot}05$). To minimize the effect that a change in feeding pattern (as discussed below) would have upon the analysis of the rate of arterial desaturation during sucking we compared the rate of arterial desaturation in the first period of sucking to that in the second using Student's paired t test. The rate of arterial desaturation was greater in the second period of sucking ($1{\cdot}1 \pm 0{\cdot}1\%\ s^{-1}$) than in the initial period ($0{\cdot}6 \pm 0{\cdot}1\%\ s^{-1}$, $P \leqslant 0{\cdot}05$).

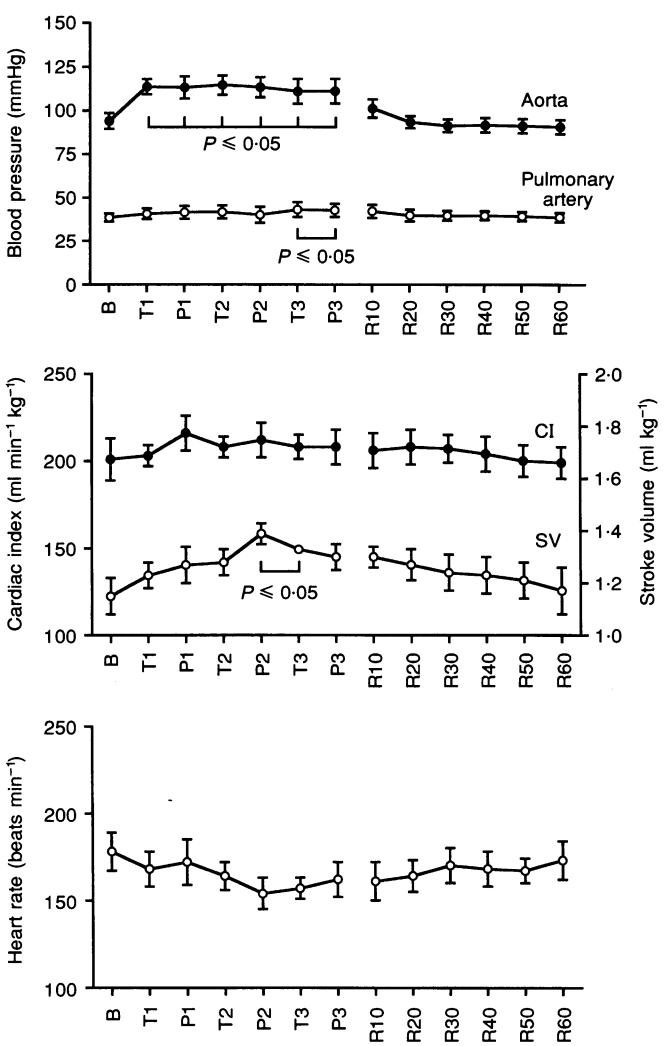

Figure 4. Cardiovascular function during feeding
Mean arterial pressure (aortic) increased significantly ($P \leqslant 0{\cdot}05$) throughout the epoch of feeding. Subsequently, mean pulmonary artery pressure also increased significantly ($P \leqslant 0{\cdot}05$). Heart rate and cardiac index (CI) were not altered during feeding. Stroke volume (SV, right ventricular) increased significantly late in feeding ($P \leqslant 0{\cdot}05$). Values represent means ± S.E.M. B, baseline; T, trough value; P, peak value (see Fig. 1); R, 10 s means of data recorded after the final period of sucking. Data indicated by the vertical bars differ statistically from baseline values ($P \leqslant 0{\cdot}05$).

Mean aortic pressure was significantly increased during the feeding epoch, both during sucking and non-sucking periods (Fig. 4, $P \leqslant 0{\cdot}05$). Mean pulmonary artery pressure was also significantly elevated in the later portion of the feeding epoch (Fig. 4, $P \leqslant 0{\cdot}05$). Feeding had little effect upon the other cardiovascular variables recorded; heart rate and cardiac index were unchanged while right ventricular stroke volume was significantly increased relative to baseline late in the feeding epoch (Fig. 4, $P \leqslant 0{\cdot}05$).

In terms of oxygen delivery and consumption, systemic oxygen transport remained unchanged during feeding (Fig. 5) while total body oxygen consumption was significantly increased during the pauses between periods of sucking and remained elevated into the recovery period (Fig. 5, $P \leqslant 0{\cdot}05$). This increase in oxygen consumption was provided for by a significant increase in total body oxygen extraction (Fig. 5, $P \leqslant 0{\cdot}05$).

Baseline blood gas and pH data were similar to those reported for neonatal lambs (pH, $7{\cdot}42 \pm 0{\cdot}19$; [Hb], 11 ± 1 g dl^{-1}; P_{a,CO_2}, 33 ± 1 mmHg; P_{a,O_2}, 82 ± 3 mmHg; and base excess, $-1{\cdot}0 \pm 1{\cdot}0$ mmol l^{-1}) (Fewell, Williams & Hill, 1984).

DISCUSSION

Feeding in the young lamb significantly alters cardiorespiratory function resulting in a marked change in oxygenation, oxygen utilization, and haemodynamic status. Of particular note was our observation that feeding affected S_{a,O_2} and S_{v,O_2} differently. S_{a,O_2} cycled between a low level during the periods of sucking and the baseline level during the pauses between sucking, while S_{v,O_2} (and thus body stores of oxygen) decreased with the onset of a feeding epoch and remained decreased even during the pauses between sucking. This decrease in body oxygen stores, in conjunction with the observed increase in total body oxygen consumption and increased total body oxygen extraction, may, as we argue below, be a key predisposing factor in the onset of rapidly developing cyanosis during feeding.

The cyclic pattern of S_{a,O_2} desaturation and resaturation, coupled with a sustained decrease in S_{v,O_2} during feeding, closely resembles the pattern of S_{a,O_2} and S_{v,O_2} observed during repetitive apnoea (Fletcher *et al.* 1989; Poets & Southall, 1991; Samuels, Poets, Stebbens, Alexander & Southall, 1992; Poets, Stebbens, Samuels & Southall, 1993; Wilkinson *et al.* 1995). When apnoeas occur in a sequence

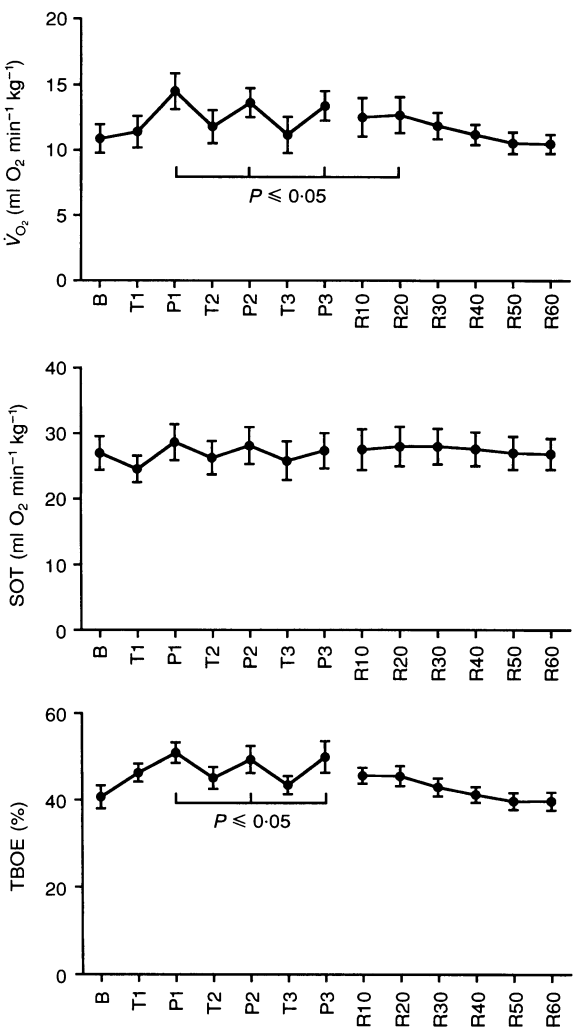

Figure 5. Oxygen delivery and consumption during feeding

Total body oxygen consumption ($\dot{V}_{O_2}$) increased during the non-sucking periods of feeding and remained elevated into the recovery period ($P \leqslant 0{\cdot}05$). Systemic oxygen transport (SOT) was unchanged while total body oxygen extraction (TBOE) increased significantly ($P \leqslant 0{\cdot}05$). A portion of the increase in $\dot{V}_{O_2}$ during the periods of non-sucking reflects a true increase in the metabolic O_2 utilization, as illustrated by the maintenance of a significant increase in $\dot{V}_{O_2}$ into the early recovery period. Superimposed upon this increase are transient increases in $\dot{V}_{O_2}$ that reflect increases in O_2 uptake from the lung as detailed by Wilkinson *et al.* (1995). Values represent means ± S.E.M. B, baseline; T, trough value; P, peak value (see Fig. 1); R, 10 s means of data recorded after the final period of sucking. Data indicated by the vertical bars differ statistically from baseline values ($P \leqslant 0{\cdot}05$).

the rate of desaturation in the second and subsequent apnoeas increases as preapnoeic S_{v,O_2} decreases, even though S_{a,O_2} may return to normal between apnoeas (Fletcher *et al.* 1989; Wilkinson *et al.* 1995). Just as in apnoea, where S_{v,O_2} is of key importance in determining the rate at which arterial desaturation occurs (Fletcher *et al.* 1989; Wilkinson *et al.* 1995), S_{v,O_2} may similarly be important in determining the rate at which S_{a,O_2} decreases during an epoch of feeding. Rapid arterial desaturation would be predicted to occur during feeding if apnoea develops, while body O_2 stores (S_{v,O_2}) are decreased. Based upon the relationship that exists between the rate of S_{a,O_2} desaturation and the preapnoeic level of S_{v,O_2} (see Fig. 5 in Wilkinson *et al.* 1995) and upon the mean minimal S_{v,O_2} we observed in the feeding epochs, arterial desaturation rates of up to 4% s^{-1} are predicted if apnoea were to occur. When we analysed the rate of arterial desaturation during feeding we found that the rate almost doubled as S_{v,O_2} decreased from the first to the second period of sucking. Thus, the rate of arterial desaturation increased in the second period of sucking as predicted by the model proposed by Wilkinson *et al.* (1995). That it did not reach the predicted levels does not exclude S_{v,O_2} as a critical component for the development of cyanosis during feeding. While feeding does produce changes in S_{a,O_2} and S_{v,O_2} that resemble those observed during repetitive apnoea, feeding differs significantly from apnoea in that feeding is not necessarily associated with total cessation of breathing.

Towards the end of a feeding epoch the magnitude of arterial desaturation during periods of sucking appeared to lessen and S_{v,O_2} appeared to recover (Fig. 2). This gradual recovery of oxygenation may correspond to a transition from a feeding pattern of continuous sucking and swallowing early within the epoch to one of intermittent sucking, reduced swallowing and simultaneous ventilation late in the feeding epoch. While sucking and breathing can occur simultaneously, it is the frequency of swallowing that limits ventilation (Koenig *et al.* 1990). In the continuous phase of feeding, sucking and swallowing occur in a 1:1 ratio (Koenig *et al.* 1990). Subsequently, with a switch to the intermittent phase of feeding, sucking continues apparently uninterrupted, although the frequency of swallowing is reduced and normal minute ventilation is resumed.

While it is known that feeding markedly alters respiratory control and function (Durand, Leahy, MacCallum, Cates, Rigatto & Chernick, 1981; Shivpuri *et al.* 1983), and it is known that many factors interact to control food intake and the duration of a meal (Woods, Taborsky & Porte, 1986), those factors which interrupt sucking, re-establish breathing and lead to the cyclic pattern of sucking and non-sucking observed within a feeding epoch before satiety is achieved are not completely understood. A combination of peripheral and central chemoreceptor inputs probably play key roles. Although the level of hypoxaemia observed in our study is a potent respiratory stimulus in sleeping lambs (Henderson-Smart & Read, 1979), hypoxaemia alone is not the sole mechanism by which ventilation interrupts sucking. Since feeding continues as a series of periods of sucking and non-sucking near the end of a feeding epoch (Fig. 2), even though oxygenation returns to normal (Harding *et al.* 1978), other mechanisms must be involved. Hypercapnia may be the stimulus as P_{a,CO_2} progressively increases during a feeding epoch (Harding *et al.* 1978; Timms, Difiore, Martin & Miller, 1993).

We believe that our observation of a significantly elevated $\dot{V}_{O_2}$ during the periods of non-sucking reflects two components. First, there is a significant, though modest, increase in the metabolic O_2 utilization associated with the physical requirements of sucking and feeding. Second, as argued for the case of repeated apnoea by Wilkinson *et al.* (1995), there is an increase in O_2 uptake from the lung which replenishes the blood oxygen stores (both S_{a,O_2} and S_{v,O_2}). The increase in metabolic O_2 utilization is evidenced by the maintenance of a significant increase in the baseline of $\dot{V}_{O_2}$ in the early recovery period. Superimposed upon this increase are transient increases in $\dot{V}_{O_2}$ following periods of sucking that reflect transient increases in O_2 uptake from the lung; as detailed by Wilkinson *et al.* (1995), these elevations in $\dot{V}_{O_2}$ are promoted by a reduced S_{v,O_2} and thus an increased alveolar–arterial gradient for O_2 uptake.

A reduced S_{v,O_2} may, in itself, not be dangerous when ventilation is maintained. However, if a disruption of ventilation, such as may occur with airway obstruction or aspiration during feeding, is superimposed upon a low S_{v,O_2}, rapid hypoxaemia and cyanosis are predicted to occur. The rate and extent of arterial desaturation during feeding would be expected to be exacerbated by factors such as increased or decreased ambient temperature or the presence of a fever, each of which increase metabolic rate and thus would reduce S_{v,O_2} prior to the onset of feeding. Further studies are required to determine if such an increased metabolic rate, when coupled with cardiorespiratory difficulties during feeding, may be an important factor in precipitating SIDS.

Our results have important implications for the management of infants in hospital settings. Nursing staff often briefly interrupt feeding if arterial desaturation occurs and subsequently resume feeding once S_{a,O_2} recovers. This practice, proposed to lessen the severity of hypoxaemia during feeding (Rosen *et al.* 1984), may, in fact, do exactly the opposite by reducing S_{v,O_2} and predisposing the infant to rapid arterial desaturations should aspiration or apnoea occur. Our results suggest that following arterial desaturation sufficient time should be allowed for S_{v,O_2} to return to baseline levels before feeding is reinitiated.

In summary, our study has revealed that significant changes in oxygenation, oxygen utilization, and haemodynamics occur during feeding in the lamb. Our observation that S_{v,O_2}, an important body store of oxygen, is substantially and continuously reduced during the early period of feeding

is of particular relevance to understanding the genesis of cyanosis during feeding. In the presence of venous haemoglobin desaturation, superimposition of apnoea or aspiration, common occurrences during feeding, may trigger the onset of rapid arterial desaturation and cyanosis.

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