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The Relationship between Rhythmic Swallowing and Breathing during Suckle Feeding in Term Neonates

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ABSTRACT. Little is known of the development of efficient coordination between suckle feeding and breathing in human infants. To establish baseline data, we recorded breathing and swallowing activity during bottle feeds in 23 infants at 14–48 h postnatal age. Most swallows (overall mean 68%) were organized into runs, with intervals starting at 0.6–0.8 s and slowing to 1–1.3 s after 30–40 s. The proportion of run swallows to total swallows increased significantly with age. Swallow intervals were regular (coefficient of variation = 18–38%) compared with breathing (coefficient of variation = 50%). Both breathing rate and tidal volume were significantly reduced by the onset of suckle feeding, and the pattern of respiratory airflow became markedly irregular. Mild transient desaturation was common, but was not accompanied by changes in heart rate. Swallows could occur in all phases of breathing. Overall, equal numbers of swallows were preceded by expiration and inspiration, but twice as many were followed by expiration compared with inspiration. Swallows were classified by the respiratory phases both preceding and following the swallow. Swallows occurred in all possible classifications in each of the infants studied. The incidence of the most frequent classification (inspiration-swallow-expiration), was 24% overall (individual range 5–50%). The phase relation between swallows and breaths changed frequently but showed occasional short periods of stability during which the breathing became regular and tidal volume increased. We conclude that at <48 h the normal infant has little coordination between swallowing and breathing rhythms and maintains rhythmic swallowing at the expense of eupnea. (*Pediatr Res* 31: 619–624, 1992)

Suckle feeding in infants is a complex activity demanding efficient coordination. The pharynx must rapidly alternate between functioning as an airway, braced open against negative pressure during inspiration, and as a peristaltic pump, able to form and transfer a liquid bolus. During fast, rhythmic feeding, swallowing may occur at 1 Hz or more, and, to avoid aspiration into the lungs, the bolus must be entirely cleared from the pharynx before the airway can reopen. In addition, airway closure during swallow occupies a significant time: the duration of each swallow is typically 5–600 ms (1, 2) and swallow rates are about 1/s (1, 3, 4) so that the airway may be closed for 50% or more of the total time. Maintenance of ventilation under these conditions demands precise coordination of swallows with breaths.

Not all infants are competent suckle feeders, and there are several possible dysfunctions. Penetration of food into the airway is common and may arise from failure to close the airway during swallow or to clear the food bolus from the pharynx. Newborn infants have a poorly developed cough reflex (5). Laryngeal penetration may lead to food entering the lung parenchyma, leading to inflammation and secondary infection. Lung damage may be so severe that surgery is required. Delay in swallowing the bolus prolongs pharyngeal residence time and causes apnea because breathing is inhibited while the pharynx is liquid-filled. There have been several investigations into the coordination of suckle feeding in early life (1–3, 6, 7) but subject numbers have been small, and there is very little quantitative information regarding the phase relation between breathing and swallowing. Coordination between swallows and breaths in suckle feeding may have subtle developmental effects: abnormal coordination between neonatal feeding and breathing has been linked with later difficulties with speech and swallowing (1, 8).

These problems caused by disorders of coordination between swallowing and breathing are easily detectable when they reach clinical significance, but irreversible damage may already have been done by this time. Earlier detection of abnormality could allow preventive treatment. However, early detection of abnormality requires knowledge of the normal condition and time course of development, and this knowledge is not currently available. As a first stage in establishing normative baseline data, we have studied suckle feeding, breathing, and the coordination between them in full-term human neonates.

MATERIALS AND METHODS

Twenty-three newborn, full-term infants awaiting discharge were studied in the nursery of the University of Maryland Hospital during bottle feeds of room-temperature formula at their regular feeding times. The infants had varying numbers of previous feeds, but in no infant was the first feed studied. Mean postnatal age was 33 ± 8 h (range 14–40 h). Infants were all term born (>37 wk) by spontaneous vaginal delivery at birth weights > 2500 g. Exclusion criteria were respiratory distress, known infection requiring antibiotics, congenital abnormality, and maternal drug abuse. Informed parental consent was obtained.

Data collection. The swallow recording methods were based on those of Wilson *et al.* (9) and Pierantoni *et al.* (10). Respiratory recording used standard polysomnography techniques. Before feeding, each infant was fitted with *1*) ECG electrodes (chest and left leg) for heart rate and to provide a synchronizing signal for the pulse oximeter; *2*) a mercury-in-rubber chest strain gauge to monitor chest movements (This method is lightweight and nonintrusive. Although it does not measure absolute tidal volume, it allows accurate observation of breath times and gives a useful indication of relative changes in tidal volume when used with a thermistor to detect air flow.); *3*) a nasal thermistor bead assembly, taped below one nostril, to detect air temperature (high on

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expiration, low on inspiration) (This system has a rapid response to flow changes, but care is needed to distinguish respiratory air flow from artifact caused by temperature equilibration of the bead if airflow stops. In regular breathing, the thermistor wave form is strongly correlated with the chest strain gauge signal.); *4*) a pulse oximeter probe (Nellcor, Hayward, CA) on one foot for oxygen saturation recording; and *5*) an open-ended vinyl catheter (5 Fr whistle-tip suction tube) introduced transnasally to lie with the tip at the back of the pharynx and connected to a Statham P23ID (Statham Instruments, Hato Rey, Puerto Rico) pressure transducer to record pharyngeal pressure. Catheter insertion occasionally evoked a sneeze, but the catheter had no apparent effect once in place. The high-frequency response of the entire recording system was tested using a 20-mm Hg instantaneous pressure change (balloon burst). There was no significant attenuation up to 50 Hz.

A second pressure transducer was connected via 1-mm inner diameter catheter tubing to the lumen of a full-term nipple (Mead Johnson, Evansville, IN) attached to a bottle of room-temperature formula (Enfamil, Mead Johnson). Catheters and pressure transducers were open and water-filled. When preparation was complete, a short period of baseline breathing was recorded and the bottle was offered. Recording then continued until the end of the feed. All signals (nipple and pharyngeal pressure, nasal airflow and chest movements, O_2 saturation, and heart rate) were displayed on an eight-channel oscillograph (Grass Instrument Co., Quincy, MA) at a paper speed of 1 cm/s and recorded on an FM tape recorder (TEAC XR310) at a tape speed of 9.5 cm/s (bandwidth 0–2400 Hz). The taped data were used for detailed analysis. After the feed, the infant was returned to normal care.

Data analysis. The tape-recorded wave forms were digitized (CODAS, Dataq Corporation; Akron, OH), and graphic displays of the data files reviewed frame by frame. The amplitude of respiratory movements was often low and extremely variable during feeding, so it was necessary to establish a minimum amplitude of movement to be accepted as a breath. The amplitude of the most recent series of uninterrupted breaths was taken as baseline, and a movement 20% or more of this amplitude was regarded as a valid breath. Peaks of inspiration, expiration, and pharyngeal pressure were marked manually on the screen display by positioning a cursor, whose position was then recorded automatically in a worksheet file for calculation of intervals between events and for statistical and graphic treatment.

RESULTS

Swallows were organized into rhythmic sequences. Casual observation of infant suckle feeding gives the impression that swallowing is organized and repetitive. This impression was confirmed by analysis of the feeding records. A run was defined as three or more swallows occurring at intervals < 2 s. A swallow-swallow interval of 2 s or more was considered to mark the end of a run. Over the observation period, the total number of swallows and the number occurring in runs were counted for each infant. The fraction (run swallows/total swallows) was calculated for each infant ($n = 17$, total of 2613 run and 1238 nonrun swallows). Values ranged from 35 to 92%: the mean for all infants was 68 ± 15 (SD)%. In only two infants was the ratio below 50%. Runs were never continuous for the entire feed. Sixty-one percent of all runs were between 5 and 15 s, and the longest continuous run was 100 s.

Swallowing was regular during suckle feeding runs. For each infant, the swallow-swallow intervals during runs were measured and the mean and SD calculated. The overall mean was 1.22 s. Mean values ranged between 1.02 and 1.46 s, and individual values for the coefficient of variation [100 × (SD/mean)] were between 18 and 38% (mean value, 26%). In each infant, the initial swallow-swallow interval was 0.6–0.8 s, and the interval increased over the first 30–40 s of the swallow run to a maintained value of 1.1–1.3 s with no upward or downward trend. The variability given for the swallow interval includes this initial slowing period. Figure 1 shows swallow intervals and their frequency distribution in two infants during typical feeding runs.

Breathing rate during swallow runs was slower than before feeding. Initial brief apneas were common, and breathing almost always slowed at the onset of feeding. An initial comparison of the breath count over the 30 s preceding a swallow run (prefeed) with the first 30 s of the run showed a significant decline in all infants studied ($p < 0.05$, ranked pairs test; Fig. 2). The mean prefeed breathing rate was 57.6 ± 10.9, compared with 28.3 ± 11.3 during the initial 30 s of feeding.

A more detailed analysis of breath-to-breath intervals during the entire feeding run, excluding intervals > 2 s, showed that breath-breath intervals during feeding ranged between 1.3 and 2.0 s (mean of means 1.70 ± 0.27 s, or 35.3 ± 5.8 breaths/min). The mean coefficient of variation was 0.5, indicating considerably higher variability than for swallowing.

Tidal volume may also be reduced during feeding. Relative changes in breathing amplitude before and during the feeding episode were measured from the chest movement and thermistor bead (airflow) records for the two 30-s periods immediately preceding and immediately following the onset of feeding. Most infants (18 of 23) showed decreases in the amplitude of both recordings, indicating a fall in tidal volume during feeding. Amplitudes of the flow recording before and during the feeding episode were significantly different ($p < 0.05$, ranked-pairs test; Fig. 2). Inasmuch as both the rate and tidal volume fell, the respiratory minute volume must also have decreased. For each infant, a minute ventilation equivalent was calculated as the product of the breathing rate and the mean amplitude of the flow signal over a 30-s period. The value of this product fell by a mean of 61% ($p < 0.001$, ranked-pairs test) in the first 30 s of feeding compared with the 30 s preceding the feed.

Although mild desaturation occurred, heart rate was unchanged. Oxygen saturation declined slightly in most infants during the initial feeding period. The minimum value reached was 85–90%, and full saturation was restored after a few seconds in all infants. Mean heart rate in the same 30-s periods was measured from the recordings. Mean prefeeding heart rate was 155 ± 24, and the mean for the initial 30 s of feeding was 151 ± 25 (NS).

The rhythms of swallowing and breathing were variably related. Both swallowing and breathing rates varied with time. To show graphically the changes in both rates during a feeding episode, swallows and breaths were numbered sequentially from the beginning of the record and their peak times recorded. Plotting the event numbers against time produced a graph in which events (swallows or breaths) occurring at a constant rate lie on a straight line whose slope is a measure of the rate. Changes in rate, and periods when swallowing and breathing occur at the same rate, are readily seen in this type of plot, which can provide an overview of the entire feeding episode. Figure 3*a* and *b* shows chart recordings and the graphic plot by this method of the onset of a swallow run. The initial slowing of breathing and the faster, more regular swallow rhythm are clearly seen in Figure 3*b*. Figure 3*c* shows the entire feeding episode from which Figure 3*b* is taken and shows that a fast swallow rhythm was maintained for about 40 s before being replaced by occasional isolated swallows.

Because swallowing was both faster and more regular than breathing during swallowing episodes, the relationship between swallowing and breathing could not be stable. This is confirmed by Figure 4, which shows rapid changes occurring in the respiratory phase during which pharyngeal swallow occurs. To assess the stability of the relationship between swallowing and breathing, each swallow in a run was classified by its relation to adjacent breaths. Any swallow must be immediately preceded by inspiratory (I) or expiratory (E) airflow or by a pause in which airflow is undetectable (P). (A pause was defined for this analysis as an interruption of respiratory airflow lasting > 0.15 s.) Similarly, a swallow must be followed by one of these three phases. Thus,

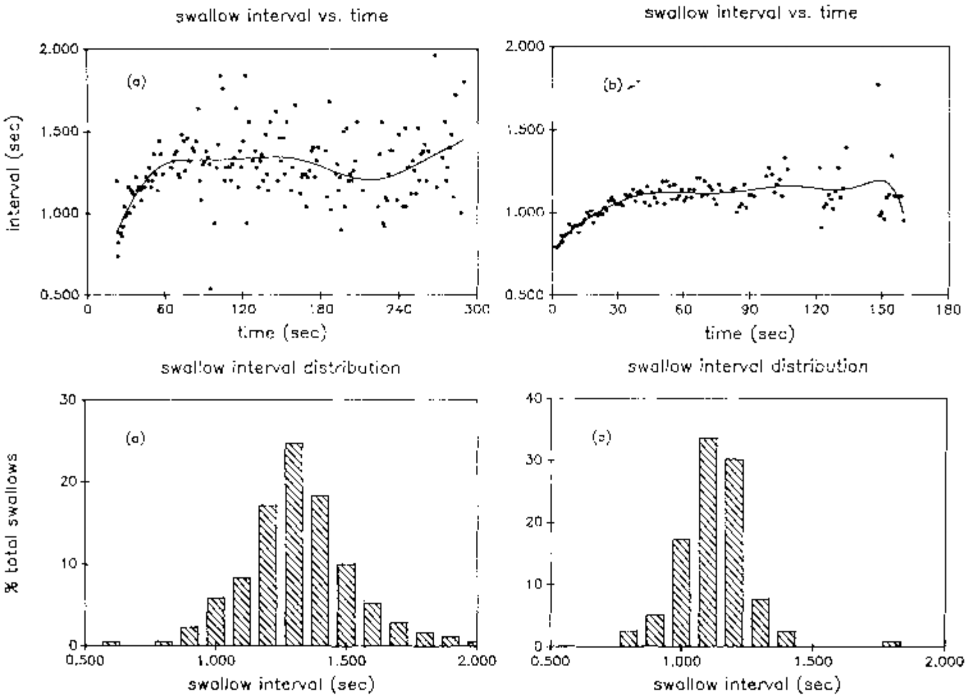

Fig. 1. Typical plots of swallow intervals against time (*upper panels*) and distribution of swallow intervals (*lower panels*) in two full-term neonates during rhythmic suckle feeding. The upper panels both show an initial interval of about 0.75 s, increasing over the first 30–40 s of the feeding run to maintained values. The fitted lines are 8th order polynomials. The distributions shown are for the data in the upper panels: each shows a single peak between 1 and 1.5 s, with almost all intervals between 0.8 and 2 s.

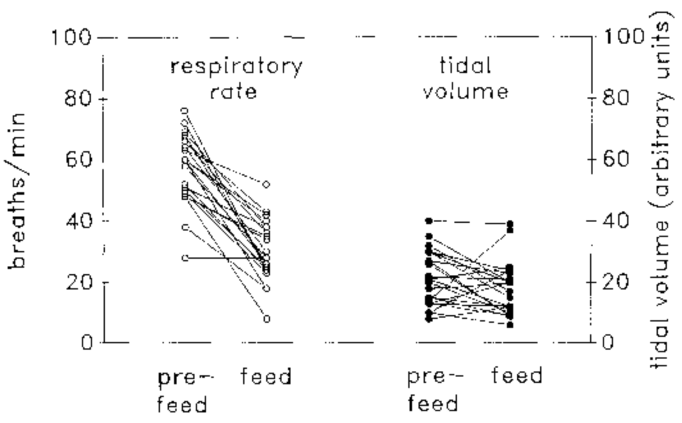

Fig. 2. Changes in average breathing rate and relative tidal volume for full-term neonates between 30 s of control (prefeeding) observations and the first 30 s of feeding. Each pair of points represents one pair of values for a single infant. Breathing rate was obtained by counting the breaths in the two 30-s periods. Relative tidal volume was measured from the amplitude of the chest strain gauge trace, averaged over the same period. Both comparisons show significant differences ($p < 0.05$, ranked-pairs test).

each swallow (sw.) can be placed in one of nine possible classes: *1*) I-sw.-I; *2*) P-sw.-I; *3*) E-sw.-I; *4*) I-sw.-P; *5*) P-sw.-P; *6*) E-sw.-P; *7*) I-sw.-E; *8*) P-sw.-E; and *9*) E-sw.-E.

The frequency of each class was calculated for each infant and averaged for all infants. All classes occurred in almost all infants, and there was great individual variability. However, swallows occurring in midinspiration (class 1) or between expiration and pause (class 6) were rare. Swallows both starting and ending in a pause (class 5) occurred at an average rate of 14.5%; in some individuals these were 35% of the total. Midexpiratory swallows (class 9) occurred at a mean of 14% (individual range, 2–37%). The most frequently occurring class was 7 (I-sw.-E), which accounted for an overall mean of 23.5% (range, 5–50%). In three subjects, this class included 40–50% of all swallows. Figure 5 shows the mean frequencies for each class of swallow, averaged over all the studies.

Although successive swallows generally occurred in different phases of breathing, there were occasional periods during which swallows and breaths occurred in a stable, phase-locked relationship. Under these conditions, swallows were either end-expiratory (E-sw.-I, class 3) or end-inspiratory (I-sw.-E, class 7). Figure 6 shows the beginning of such a period of ordered breathing. The breathing rate increased and became entrained by the swallow rhythm, and the phase relationship between breathing and swallowing became constant. At the same time, the tidal volume increased. It appears that the stable rhythm allows increased ventilation. However, this relationship was maintained for only 14 s, and later swallowing was randomly related to breathing. The swallowing rate was unaffected by the onset of the stable breathing rhythm.

The proportions of swallows that were preceded by E, P, and I in each infant (regardless of the respiratory phase following the swallow) were calculated by combining classes. There was no evidence in our study population for a preferred respiratory phase during which swallowing is initiated. Thirty-six percent of swallows were preceded by I (individual range, 17–61%), and 39% were preceded by E (range, 15–63%). However, an analysis of the respiratory phase after swallows showed that significantly more swallows were followed by E than I (mean, 43% *versus* 26%), although there was considerable individual variability. The range for I was 3–60% and for E, 16–67%.

Some variables change over the first 48 h of life. The age of the infants at the time of study ranged from 14 to 40 h. Because considerable physiologic changes can occur in the infant over this period, we examined our measured and calculated variables for significant correlations with postnatal age. Most of the variables clearly did not change appreciably with age over this range. The overall volume/swallow (*i.e.* feed volume/total number of swallows) appeared to increase with age, although the correlation coefficient ($r = 0.5$, 11 *df*) was not significant. However, the ratio of swallows in runs to total swallows for infants in this age

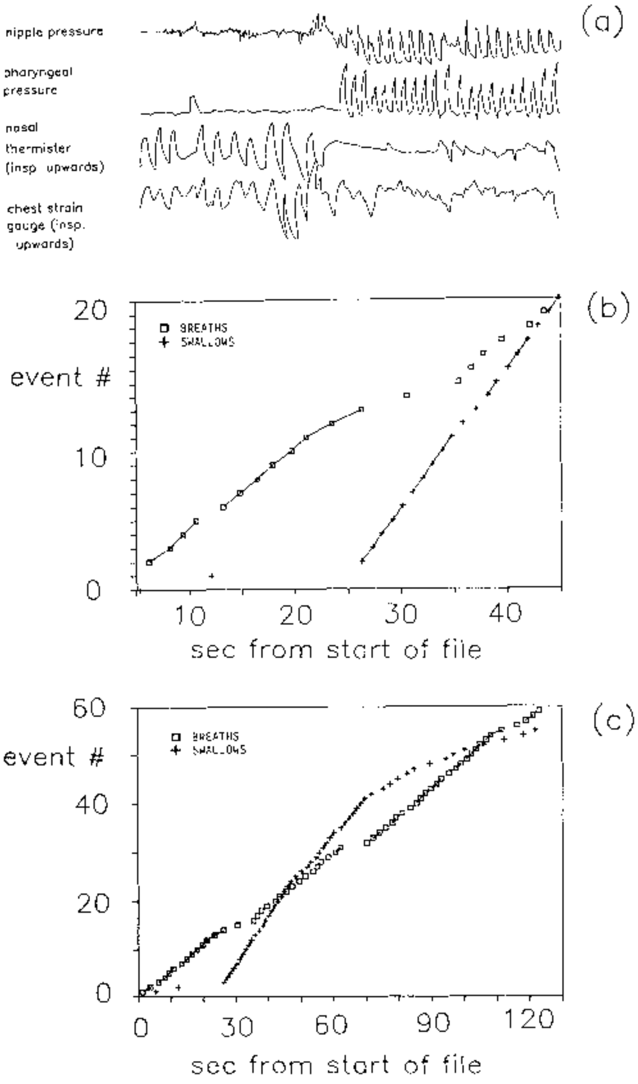

Fig. 3. *a*, Recordings of breathing and swallowing at the onset of a swallowing run. Note the regular oral and pharyngeal pressure waves and the irregular slow breathing as the swallow run starts. The time axis is the same as in *b*. *b*, Graphic analysis of the period of recording shown in *a*. The *x* axis shows time on the same scale as *a*, and the *y* axis shows the swallow or breath number. The steep uniform slope of the swallow event curve contrasts with the more variable and shallow slope of breathing. Note the reduction in breathing rate (slope) as the swallow run starts. See text for details. *c*, Graphic analysis on a compressed time scale of the entire feeding episode from which *a* and *b* are extracted, to show the fast, stable swallow rhythm in contrast to the slower breathing rhythm.

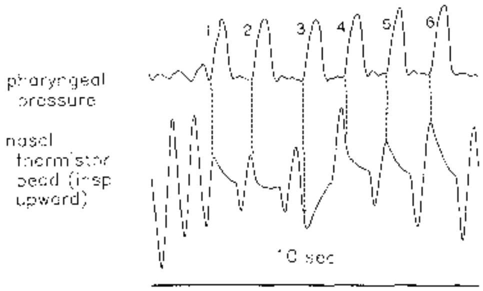

Fig. 4. Recordings of pharyngeal pressure and the nasal thermistor bead signal to show the short-term variability in the timing of swallows with respect to breaths. *Swallows 1, 2, 5*, and *6* terminate inspiration and are followed by expiration, *3* terminates expiration and is followed by inspiration, and *4* is in midexpiration.

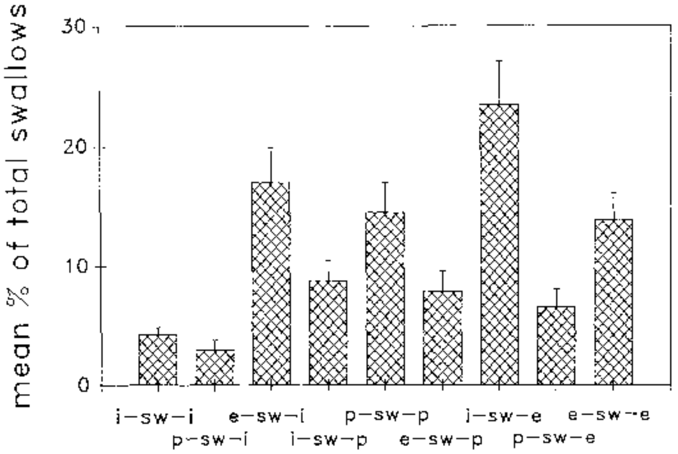

Fig. 5. Frequency (as % of total) of each of the nine possible relationships between swallows and adjacent breaths, averaged over all subjects. See text for details. The highest frequency (23%) is for (I-swallow-E), but (E-swallow-I) is almost as common and all possible relationships occur.

range increased significantly with age ($r = 0.51$, 13 *df*, $p = 0.05$) (Fig. 7). It seems likely that this relationship represents a true developmental change in feeding behavior and that the proportion of swallows organized into runs increases consistently over the first few days of life.

DISCUSSION

The 23 newborn term infants in our study, all apparently competent feeders, did not coordinate their swallowing and breathing rhythms. During feeding, swallowing was the dominant rhythmic activity, and breathing became irregular.

Interference between breathing and swallowing can be minimized if swallow-related closure is initiated at times of zero airflow (*i.e.* at end-inspiration or end-expiration) rather than in midphase. For this to occur, there must be a stable relationship between swallowing and breathing, *i.e.* the rates must be identical and there must be a constant phase relationship between them. Thus, optimal suckle feeding might be expected to show prolonged periods of regularly coordinated swallows and breaths. It is not known whether infants consistently show such patterns. Our data show that newborn infants within 48 h of birth have a stable and uniform swallow rate, but their breathing is not stably coordinated with swallowing, and ventilation is reduced during feeding.

Our study agrees with previous workers who reported reduced ventilation in infant suckle feeding. Fifty percent reductions in minute ventilation have been reported during bottle-feeding in healthy term neonates (11, 12). Feeding apnea and reductions in transcutaneous P_{O_2} have also been described in a group of preterm infants (13). Breast- and bottle-feeding may have different effects: Mathew and Bhatia (3) reported that breathing was reduced in bottle-fed but not in breast-fed infants and suggested that the difference is caused by the bottle producing faster flow, making the infant spend more time swallowing. Inspiratory time was unchanged in breast-feeding but fell during bottle-feeding (12, 14). This could reduce minute ventilation because less time is available for air intake. In both term and preterm infants at 2–7 wk postnatal age, minute ventilation was inversely proportional to the swallow frequency (1).

Despite the clinical importance of feeding coordination, it has received little attention and the results are inconsistent. In adults, most isolated swallows occur in midexpiration (15, 16). A recent study on eight term and five preterm infants (2–7 wk postnatal) found that sucking during bottle feeds could occur in inspiration or expiration (1). In continuous sucking, there was a fairly

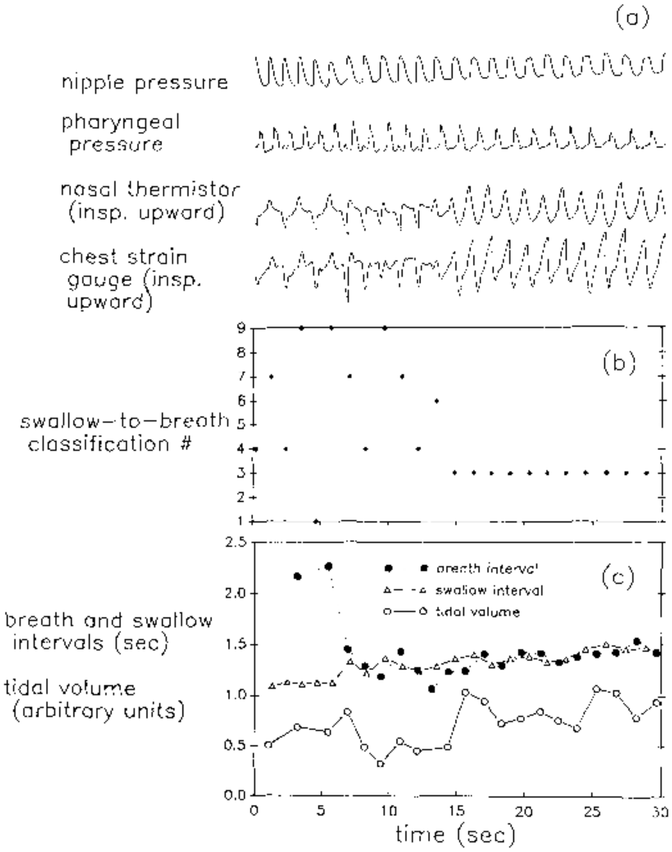

Fig. 6. *a*, Recordings of swallowing and breathing to show the onset of a period of regular breathing during a suckle feeding episode in a term neonate. Note the increase in amplitude of the respiratory signals as regular breathing is achieved. The time scale in *c* applies to all three panels. *b*, Graph to show the classification of each swallow in *a* according to its relationship with the preceding and following breaths (see text). During the first 15 s, swallows occur at end-inspiration (*7*), mid-expiration (*9*), and end-inspiration followed by a pause (*4*). The onset of regular breathing (*a*) corresponds to the start of a period of stable coordination between swallows and breaths. The classification (*3*) of coordination in this stable period corresponds to (E-swallow-I). *c*, Plots to show breath and swallow intervals and relative tidal volume from the chest strain gauge for the period of recording shown in *a*. The onset of stable coordination between breaths and swallows is associated with an increase in tidal volume and convergence of breath and swallow intervals.

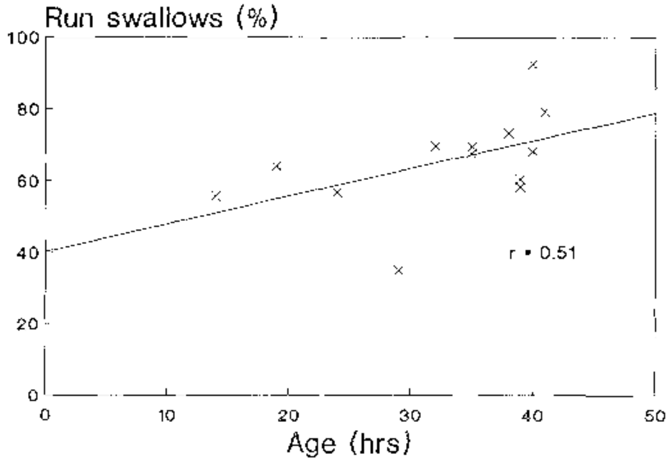

Fig. 7. The proportion of swallows occurring in runs (*i.e.* >3 at intervals < 2 s), as a percentage of the total number of swallows recorded, plotted against age in h. The correlation coefficient is statistically significant ($p < 0.05$). There appears to be an increase in the organization of swallowing in the first 48 h postnatal.

constant interval between suck and swallow, so presumably swallows could also occur in any phase of breathing. Weber *et al.* (17) report that most swallows occur at end-expiration at 4–5 d but can be during either inspiration or expiration at 2 d. This study included only six breast-fed and six bottle-fed infants, each studied once. Numbers in each group were therefore small, and no statistical treatment was attempted. This study was criticized by Selley *et al.* (18) on the grounds that the breathing monitor used is unreliable during feeding; these authors reported that mature infants swallow at end-inspiration or during expiration, but never at end-expiration. More recently, the same group confirmed their earlier finding. In 15 of 19 infants, the predominant pattern was inspiration-swallow-expiration, and an average of 83% of swallows were followed by expiration (2). However, isolated nonfeeding swallows in infants were found to interrupt ventilatory airflow in any phase (7). Bu'Lock *et al.* (6) studied swallowing using ultrasound in 14 infants from 33 to 38 wk gestational age. Their report is largely a description of movements of the pharynx and larynx, but they also commented on coordination between breathing and swallowing rhythms. They report that all subjects achieved "some periods" of sucking, swallowing, and breathing at 1:1:1 and that the proportion of the feed in which this occurred increased "fairly uniformly" with maturity. Their paper contains no numerical data. The study of Selley *et al.* (2) includes a 5-s section of recording from a 4-d infant showing stable 1:1 swallowing and breathing, and these authors comment on "the regularity of accurately coordinated patterns" shown by most infants (age 8 h–6 d; no mean given) in their study.

On balance, the literature suggests that in early neonatal life there is considerable variability in the phase relationship between swallows and breaths, but that a regular pattern develops at some later date.

Our study is the first to address specifically the question of coordination between swallowing and breathing in the normal newborn infant at less than 48 h. The results show clearly that although short periods of stable coordination occur the most commonly observed condition is one in which breathing slows and becomes irregular while a regular swallow rhythm is expressed. Swallows can occur at any time during the breathing cycle and are equally likely to be preceded by inspiration or expiration. It appears that at less than 48 h postnatal age there is essentially no coordination between the swallow and breathing rhythms.

However, there must be some coordination between individual swallows and breaths. The mechanisms by which breathing is interrupted during swallowing are well established: the motor pattern of swallowing includes vocal fold adduction and laryngeal compression, thus arresting airflow, and stimulation of pharyngeal receptors inhibits breathing centrally. Breathing therefore stops on the initiation of a swallow, and food does not penetrate the airway. The newborn defends the airway effectively, but at the cost of disrupting the breathing rhythm and reducing ventilation. It appears from the mild and transient desaturations noted in this study that the newborn tolerates such hypoventilation well, but the same may not be true for older infants with an increasing metabolic demand, a decreasing tolerance for hypoxia, and an increasing respiratory drive. Infants with chronic lung disease may also tolerate periods of reduced ventilation less well than normal infants.

The role of respiratory control in the development of efficient suckle feeding has not been adequately studied, but several workers have described a possible link between feeding efficiency and the control of breathing. Groups of optimal and nonoptimal feeders, defined largely on the basis of formula intake, with equal birth weights had different feeding patterns. The "optimal" feeders had more suckles and longer pause times (thus more breathing) and tended to feed for longer (19). A study on preterm infants (7) proposes a linkage between immature cardiorespiratory control (defined as a high frequency of apnea, bradycardia, and periodic breathing) and poorly coordinated feeding characterized by apneic bursts of swallowing with desaturation. An earlier paper from the same group (4) concluded that at up to 6 mo infants with immature cardiorespiratory control (defined as above) were also poor feeders with low milk intake both per second and per suck. Thus, there is some evidence for a connection between unstable breathing patterns and inefficient feeding. It is possible that developmental changes in feeding patterns could provide a useful index of maturation of respiratory control, which is notoriously difficult to study directly.

Efficient feeding is essential for normal growth and development, but it seems that the coordination required to maintain rhythmic breathing during feeding may be beyond the abilities of newborns within the first day or two of postnatal existence. Our data appear to show that newborn infants, faced with the difficulty of maintaining both ventilation and swallowing, reduce their breathing drive and concentrate on feeding. Maturing infants probably develop a pattern of coordination that allows a maintained breathing rhythm, but it is not known how or when this occurs. Knowledge of the normal course of development could allow early detection of abnormality, with an improved chance of successful therapy before a severely impaired feeding pattern is established.

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