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The coordination and interaction between respiration and deglutition in young pigs

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Abstract The anatomical pathways for inspired air and ingested food cross in the pharynx of mammals, implying that breathing and swallowing must be separated either in space or in time. In this study we investigated the time relationship between swallowing and respiration in young pigs, as a model for suckling mammals. Despite the high morphological position of the larynx in young mammals, allowing liquid to pass in food channels lateral to the larynx, respiration and swallowing are not wholly independent events. Although, when suckling on a veterinary teat, the swallows occurred at various points in the respiratory cycle, there was always a period of apnea associated with the swallow. Finally, an increase in the viscosity of the milk altered this coordination, changing respiratory cycle length and also restricting the relative rate at which swallows occurred in some parts of the respiratory cycle. These results suggest that the subsequent changes in respiratory activity at weaning, associated with passage of a solid bolus over the larynx, is preceded by the ability of the animal to alter coordination between respiration and swallowing for a liquid bolus.

Key words Swallowing · Breathing · Respiration · Suckling · Mammal

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Introduction

In all mammals, the two functions of breathing and swallowing must be separated to ensure survival. However, the path taken by ingested food crosses the opening to the lower airway. The anatomically high or intranarial position of the larynx in many mammals, i.e., with the epiglottis positioned above the soft palate, permits the margins of the soft palate to seal the airway from the food passage, producing a physical or spatial separation of the two pathways (Negus 1929; Laitman et al. 1977; Crelin 1987).

In contrast, in adult man the two pathways converge in the pharynx and the functions of this common path are separated temporally. The possibility of aspirating food from the shared oropharynx into the low-positioned larynx is limited by the timing of swallows, relative to the respiratory airflow and by the correlated glottal closure and bodily movement of the larynx. In contrast to this phase-locked activity (Logemann et al. 1992; Maddock and Gilbert 1993; McFarland et al. 1994; Martin et al. 1994; Paydarfar et al. 1995), several studies of infant and juvenile humans suggest variability in the temporal relationship between respiration and swallowing (Peiper 1963; Wilson et al. 1981; Weber et al. 1986; Selley et al. 1989, 1990; Bamford et al. 1992; Laitman and Reidenberg 1993). Despite the methodological differences in these studies, the greatest variability in timing of the swallow with respect to end inspiration was associated with the youngest and the least variability with the oldest subjects, seemingly consistent with a maturational gradient.

The temporal relationship between swallowing and respiration in infant mammals (both human and non-human) is complicated by a number of factors. For example, in the young macaque, the normally intranarial position of the epiglottis depends, during swallowing, upon the viscosity of the liquid being swallowed (Laitman et al. 1977). In adult humans, an increase of bolus viscosity increases bolus transit time through the oro-

pharynx and usually increases the duration of the associated apnea (Dantas et al. 1990; Lazarus et al. 1993; Reimer-Neils et al. 1994; Hamlet et al. 1996). These studies, with a variety of food types, tend to support an increased duration of laryngeal closure with increasing viscosity of food.

Another complicating factor is the increase in respiratory drive that occurs with infant maturation (Farber 1988; Barrington and Finer 1991). Because interruption of an increased rhythmic excitation requires correspondingly greater levels of afferent or descending activity, increased respiratory drive implies greater constraints upon the timing of the swallows. Previous studies on young pigs (German et al. 1996; Crompton et al. 1997) show that both the pathway of the swallow through the oropharynx and the timing of the swallows relative to the respiratory cycles change during ontogeny. These data suggest that breathing and swallowing may not be correlated at the earliest stages of life but that a linkage develops during maturation. This link between respiration and swallowing is surprising because infant pigs use an intranasal larynx to separate the inspiratory and ingestive pathways. Given that food viscosity may change epiglottal position (Laitman et al. 1977), the question then arises of whether swallow/respiration coordination is the same for ingested liquids of all viscosities.

In this study we investigated the relationship between the deglutition of suckling and rhythmic respiration in young mammals. One of our goals was to determine whether the respiratory drive permitted the swallow to occur only at a fixed place in the respiratory cycle or whether, given the high intranasal larynx of young mammals, the activities of swallowing and breathing were wholly independent events. We also tested the alternative hypothesis that, in suckling, it is the swallow that dominates and alters the respiratory rhythm. A third hypothesis concerned changes that might occur in anticipation of feeding on solid foods, which would present a more viscous bolus. We therefore tested whether a change in the viscosity of the milk delivered altered any aspect of the coordination between respiration and swallowing.

Materials and methods

Four 6-day-old littermate female infant pigs (Mini-Hanfords) were obtained from Charles Rivers Laboratory Animals (CRL, Wilmington, Mass., USA). The pigs had been suckling on the sow prior to the study. They were then immediately transferred to bottle feeding and not weaned until after conclusion of the study. During the study the pigs suckled infant pig formula (Soweena/LitterLife – Merrick Foods) from veterinary pig nipples (NASCO, Fort Atkinson, Wis., USA). The suckling behavior of the pigs was recorded by video-radiography, which provided data on both diaphragm movement and swallowing.

At each feeding session, the pigs were individually placed in a Plexiglass box with a non-skid rubber mat in the bottom. This box contained the movements of the pig and directed them towards the nipple, although the animal was able to turn and move freely. The

nipple extended through a hole in the front wall of the box and projected far enough to allow the pig easy access for suckling. Close to the nipple and directed at one of the nostrils was a funnel shaped collector used to detect expiratory airflow; this collector was connected to a differential pressure transducer with a sensitivity of 1V/1 mm water (Micromanometer MDG FC001, Furness Controls, Bexhill, England). Only increases in this signal (Fig. 1a) were valid data; the return of the signal to baseline was a normal function of the AC coupling we used with this instrument. In each animal (under Halothane/oxygen anesthesia) a thermocouple (wire size 0.001 in., response time 0.05 s; Omega) was implanted through the lateral wall of the nose within 5 mm of the external nares. The thermocouple was used to record the temperature of the intranasal airflow as previously described in German et al. (1996). The experiments were carried out at an ambient air temperature of 16–18 °C; the deep body temperature of the pig neonate is normally 39.2 °C.

In preliminary experiments a strain-gauge plethysmograph was used to record the changes in thoracic diameter in respiration. In the conscious animal the plethysmograph was poorly tolerated and was subject to body movement artifacts; it was subsequently used only in validating the functioning of the other recording devices while the animal recovered from anesthesia (Fig. 1).

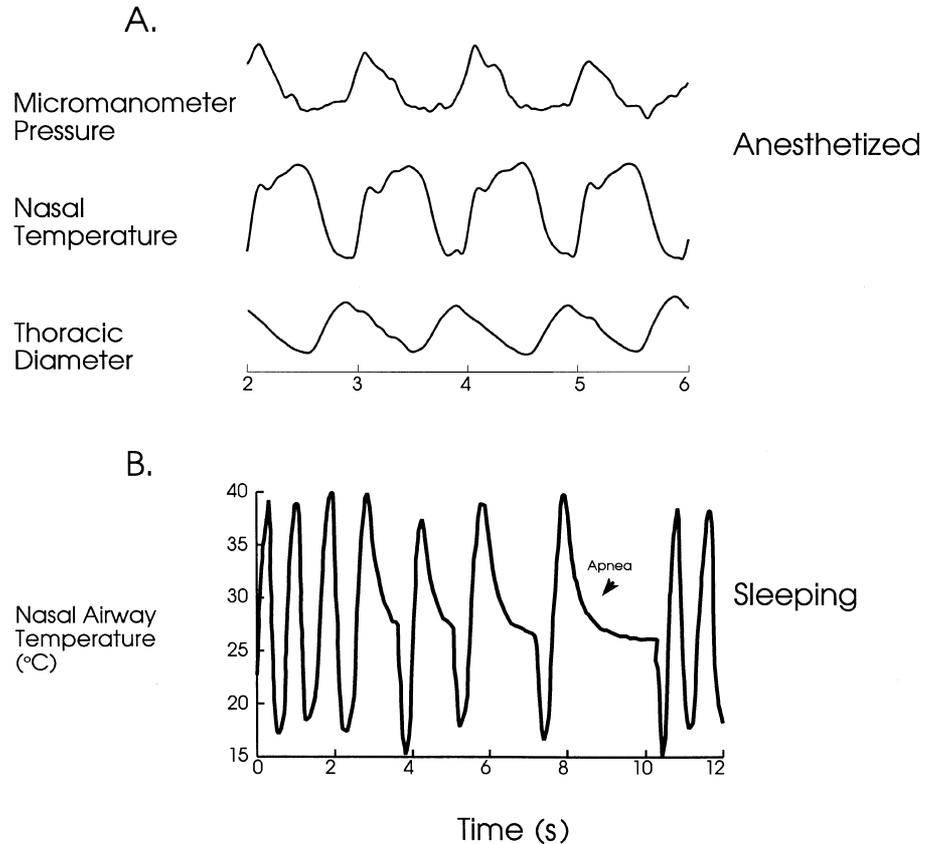
The output signals of the pressure transducer and the thermocouple were recorded on a TEAC XR-5000 16-channel data recorder together with a synchronization signal from the video camera. The signals were played back on a 6-channel Brush Gould Chart recorder both for monitoring during the feeding session and for use later during analysis. The pressure transducer, thermocouple and camera synchronization signals were digitized (10 kHz/channel) and stored as binary data in a Mac IIx computer using LabView software (National Instruments). The high digitization frequency ensured accurate registration of the narrow synchronization pulses from the camera. A manual trigger, which briefly actuated a relay, produced a reduction in the size of the video frame synchronization spikes for about 1/10 s; the movement of the relay armature was also visible on the video record. The video frames of interest could then be synchronized to the digitized pressure transducer and thermocouple signals by matching the onset of movement of the relay armature in the video record with the onset of the reduced spike size in the digitized data.

Diaphragm movement was recorded in a lateral view using Siemens Tridoros 150G3 videoradiographic apparatus capable of imaging soft tissue. The Siemens x-ray equipment was connected to a Hitachi Denshi KP-M1 Black CCD shuttered video camera (60 fields/s) coupled to a Time Code Generator (TC-3, Bioelectronics) and a JVC BR-S601MU S VHS video cassette recorder. This was used to record video sequences of diaphragm movement as the animals suckled; the timing of swallows were also obtained from the video recordings. The video recordings were analyzed frame by frame using a DataCube Maxvision system (including software modified by David Hertweck) connected to a 486 PC using a Mitsubishi S VHS; data were stored on a REO Pinnacle 650 R/W optical drive.

In each frame of interest, the X/Y coordinates of 30 randomly positioned points along the shadow of the diaphragm were digitized together with a repeatable point of origin on vertebra T3. Distances were first determined between both the point along the diaphragm and the point of origin; then an average of these distances was then used as a measure of diaphragm position.

Barium present in the feed allowed the swallows to be visualized easily; its presence had no noticeable effect on pig suckling behavior. Swallow times during the sequence were defined by the time of entry of a radiopaque bolus into the piriform recess. The event we term a swallow in this paper is equivalent to the pharyngeal swallow of adult humans. It was an instantaneous event given our temporal resolution (60 fields/s). That is, milk was seen in the piriform recesses in one field, and was clear of the piriform recesses by the next. We used appearance of the bolus in the piriform recesses because, prior to that stage, there was an accumulation of the bolus in the vallecular region. Such an accumulation is also observed in drinking in several species of adult mammals; in these

Fig. 1A, B Differing measures of respiration versus time during **A** anesthesia and **B** sleep showing apnea



situations multiple (as many as 17) ingestion cycles may precede the swallow (Hiemae et al. 1978; Thexton and McGarrick 1988; Thexton and Crompton 1989). Accumulation is not therefore part of a single event swallow.

The milk was delivered by an automated feeding system that has been described in detail elsewhere (German et al. 1997). Briefly this consisted of a set of diaphragm pumps (Luft Instrument Company, Lincoln, Mass., USA), that were controlled by purpose-designed circuits to deliver measured volumes of milk at a predetermined rate to the animal via the nipple. A parallel delivery circuit containing higher viscosity feed could be switched into and out of the main delivery circuit so that the milk issuing from the teat was changed to a viscous mix and then changed back again to milk, without interrupting the rate or changing the volume of delivery.

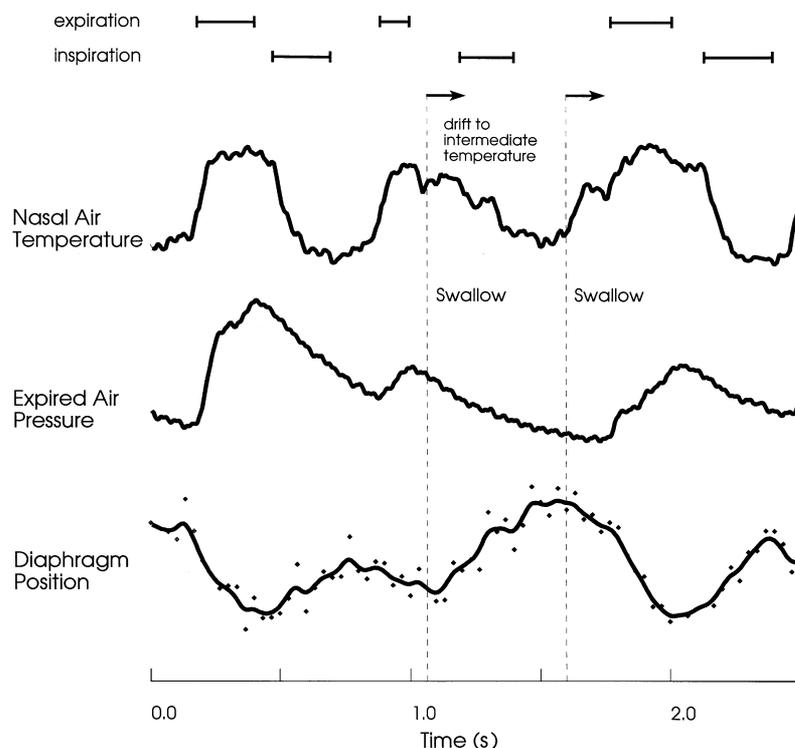
The milk was pumped at a frequency of 3.3 Hz (330-ms intervals), 0.2 ml being delivered at each pump actuation. This was the rate at which animals fed when they determined delivery themselves (German et al. 1997). The standard viscosity of the feed was that of the standard milk formula. The higher viscosity feed was made by adding cornstarch so that the feed was nine times more viscous than the standard formula as determined using a Stormer Viscometer (Fisher Scientific).

The unit of feeding time was a "sequence", i.e., the series of cycles counted from first closure on the nipple to either a voluntary interruption in or to a cessation of that feeding. The data from a total of three feeding sequences were analyzed for each pig for both food viscosities, giving a total of 24 sequences analyzed. The duration of these sequences ranged from 5 s to 35 s and they contained from 6 to 50 respiratory cycles. Respiratory cycles contained from 0 to 2 swallows, for a total of 318 swallows over all sequences. The thermocouple channel provided an index of respiratory airflow. The signal (temperature) rose as air from the pig's lungs was exhaled at deep body temperature and fell as cooler room air was inhaled. In pilot experiments it was found that there was a simple pattern of temperature change in normal respiration (Fig. 1A). If

the airflow was interrupted, as in sleep apnea (Fig. 1B), the thermocouple moved to the intermediate temperature of the stationary air inside the external nares. Depending upon whether apnea occurred after inspiration or after expiration, the temperature would either fall or climb towards the intermediate temperature of the mucosa of the external nares. Nasal mucosa temperature is known to be several degrees below deep body temperature, but above ambient air temperature. When the nasal air temperature was recorded during either anesthetized respiration or during conscious non-feeding respiration, the temperature fluctuated between ambient and deep body temperature (Fig. 1A). In respiration during sleep, it was evident that exactly the same series of changes occurred except during sleep apnea (Fig. 1B). During such periods of apnea the thermocouple recorded a temperature that was between the two extremes of deep body and of ambient air temperature and therefore corresponded to thermocouple temperature without airflow. This temperature would approximate to nasal mucosa temperature because of heat transfer by conduction (via wires), by convection and by radiation.

Additional but less temporally accurate measures (expired air pressure and diaphragm movement) were used to confirm the interpretation of the more complex thermocouple signals obtained during swallowing (Fig. 2). It was evident that the deviations from the smoothly fluctuating thermocouple signal of the non-feeding state (Fig. 1) were associated with swallowing. Where these swallows occurred during the expiratory phase (defined on the basis of the diaphragm movement), there was a period of apnea (defined on the basis of the absence of an expired airflow pressure). At these times the nasal thermocouple approximated to a temperature close to that seen in sleep apnea. Similar interruptions in temperature change were evident during inspiration, again associated with a radiographically defined swallow; during these interruptions the temperature signal again tended towards an intermediate value. Thus, if a period of apnea occurred at or near end inspiration, the thermocouple would rise from the low temperature of inspired air

Fig. 2 The complex changes in nasal airway temperature during suckling illustrated in three respiratory cycles with associated swallows. Respiratory cycles are indicated by three measures of respiration. Nasal airway temperature was used to indicate whether inspired cool air or expired body temperature air was passing over the thermocouple. The expired airflow was also recorded by micro-manometer and the driving force for both inspiratory and expiratory airflow, diaphragm movement, was recorded by cineradiography



to nasal mucosa temperature and if the apnea occurred in expiration, the thermocouple temperature would fall from expired air temperature towards nasal mucosa temperature.

Data analysis

We examined respiratory flow as measured by the thermocouple signal from 150 ms before to 150 ms after each swallow. The thermocouple signal was sampled and plotted for every 10-ms interval. Thus, associated with each swallow, there were 30 measurements of nasal airway temperature (15 values prior to the swallow and 15 after the swallow). The sample size was 319 swallows, classified by individual ($n = 4$) and by viscosity ($n = 2$). In this form it was possible to examine and test variation in nasal airway temperature (and so the phase of respiration) prior to and following the swallow. We measured variation (standard deviation and coefficient of variation) in temperature over all swallows within a sequence (six sequences per individual), at each of the 30 time points. To facilitate the analyses, data were grouped into six 50-ms time intervals, each containing five measurements of variation in temperature. Thus there were six time bins, three before the swallow and three after the swallow. These time bins constituted an additional factor used in further analyses.

The variation or lack of variation in the respiratory signal, both before and after a swallow can be used to test the linkage between respiration and swallowing. If swallows occurred at a fixed point in the respiratory cycle, then variation in the thermocouple signal among cycles would be low both before and after the swallow (Fig. 3A). If swallows occurred in a random or more variable place in the respiratory cycle, then variation in the thermocouple signal would be high prior to and after the swallow; sometimes the signal would be rising due to the exhaled body temperature air and at other times falling due to inhaling cool ambient air (Fig. 3B). If the swallow had an impact on respiration, then variation in the respiratory signal after the swallow would be low relative to variation before the swallow (Fig. 3C). If a period of swallowing apnea occurred, the thermocouple signals should tend towards a single value intermediate between ambient air and deep body temperature.

We used a mixed-model, multifactor ANOVA to test relationships between airflow and swallowing based on variation in the thermocouple signal. The factors in the model were:

1. Individual (random factor), to account for individual variation (see Schaffer and Lauder 1985).
2. Viscosity (fixed factor), to test the impact of the viscosity of the bolus on the relationship between swallowing and respiration.
3. Time (fixed factor), which had six levels corresponding to the six 50-ms bins.

Tukey post hoc tests, with Bonferroni corrections of the time factor, were used to test two of the hypotheses stated in the Introduction: (1) whether swallows occurred in a fixed pace in the respiratory cycle, and (2) whether the swallow alters the respiratory rhythm. The statistical interpretation of the first hypothesis is that variation in the respiratory signal is equal pre- and post-swallow. The second hypothesis was tested by comparing the variation in the respiratory signal over the three time bins prior to the swallow with the variation over the three time bins following the swallow. These tests would distinguish among the three possible situations diagrammed above in Fig. 3A–C.

To test the impact of viscosity on the timing of the swallow relative to respiration, we examined the change in the distribution of nasal airway temperature over the six time bins for the two consistencies. If a swallow-associated apnea existed, as determined by the ANOVA outlined above, then the distribution of nasal airway temperatures in, e.g., bin 6 (100–150 ms post-swallow), would be a normal distribution centered on the intermediate temperature of the external nares that existed in the absence airflow. Comparisons of the pre-swallow distributions of nasal airway temperature to this post-swallow distribution would then provide a measure of respiratory phase prior to the swallow. If the temperatures in bins one through three (150–0 ms pre-swallow) were predominantly higher temperatures, then the swallow would have been preceded by an expiratory phase. If bins one to three contained predominantly lower temperatures, then the swallow would have been preceded by an inspiratory phase. The limits for dividing the data in bin one were based on two standard deviations from the mean value of bin six (i.e., greater or lesser than 95% of the values

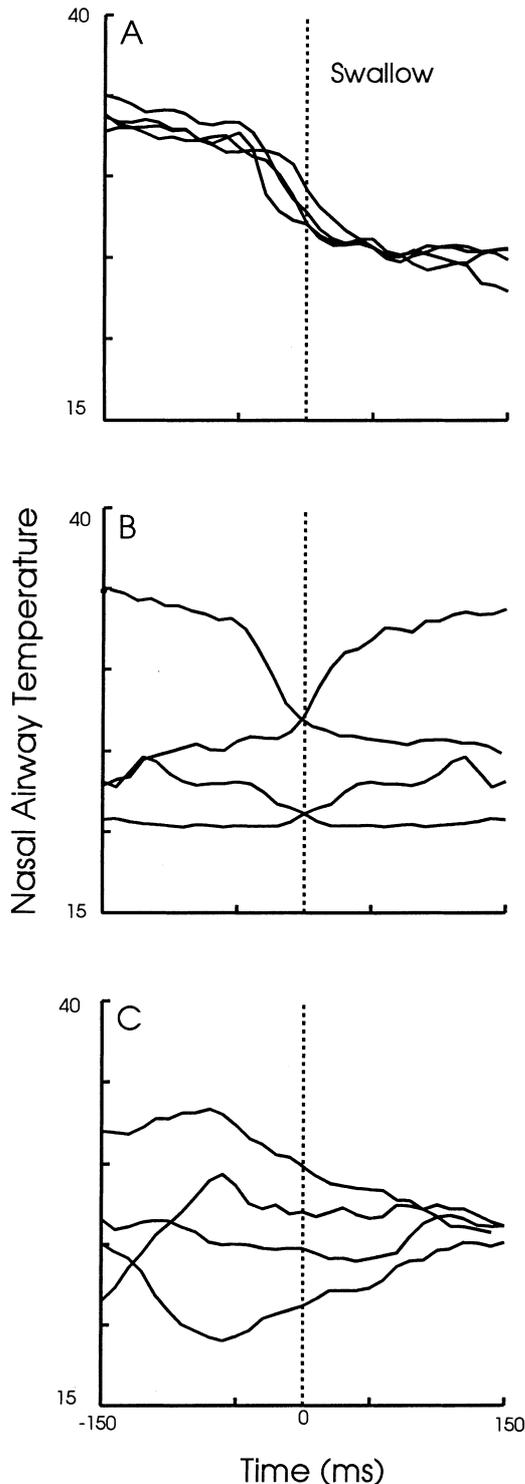


Fig. 3A–C Three hypothetical patterns of variation in the respiratory signal near the swallow, with nasal airway temperature as a function of time. Each pattern contains four respiratory cycles lined up at the swallow. **A** If swallows occurred at a fixed point in the cycle, then little variation would exist in nasal temperature among the cycles. **B** If the swallow occurred randomly with respect to the respiratory cycle, then there would be high levels of variation among the cycles. **C** If the swallow occurred at a random point in the respiratory cycle, but impacted on respiration (e.g., a period of apnea following the swallow), the variation in thermocouple signal would be high prior to the swallow, and low after the swallow

in bin six). We used these levels to divide the distribution in bin one into three parts: swallows occurring during expiration, during apnea, and during inspiration. We compared the number of swallows in each of these categories between the two viscosities using a two-way chi-squared test.

Results

The question of whether or not swallows occurred at a fixed point in the respiratory cycle was tested by plotting the time of entry of a bolus into the piriform recesses relative to records of respiration. Figure 2 shows three respiratory cycles from a typical suckling sequence in which the standard milk formula was delivered. When similar sample data from all animals were examined, swallows were found to occur not only during the periods of no measurable airflow, that is at the end of inspiration and at the end of expiration, but also during inspiration and expiration as well.

In order to establish, quantitatively and in a larger sample, whether swallows occurred preferentially at any respiratory phase and whether all swallows had a constant effect on nasal airflow, thermocouple temperature was plotted against time relative to the swallow, i.e., for the 150 ms preceding and the 150 ms following a swallow. Data from swallows in three different sequences, each containing multiple swallows, all from one individual drinking milk, are shown in Fig. 4.

In all three sets of swallows, the nasal airway returned towards a temperature, intermediate between ambient air temperature and deep body temperature, after the swallow. In Fig. 4A the swallow clearly occurred at one of two set places in the respiratory cycle, i.e., it was preceded by a high airway temperature indicative of expiration or it was preceded by a low airway temperature indicative of inspiration. Only 2 of the 24 sequences recorded from the four pigs showed this pattern. In all other sequences (22/24, or 92%), the pattern was of the type shown in Fig. 4B,C where swallows were preceded by a variety of airway temperatures consistent with the swallows occurring at different phases of the respiratory cycle. The average duration of a respiratory cycle was, however, the same (1052 ms) irrespective of the viscosity of the feed.

When, in the course of a normal feeding session on milk, the milk-delivery circuit was switched so that the animals were supplied with the higher-viscosity feed, all animals showed a drop in the rate at which swallows occurred, despite constant delivery rate. When feeding on milk, the average interval between swallows was 545 ms ($n = 206$) but this changed to 835 ms ($n = 113$) when feeding on the more viscous mix.

The data for nasal airway temperature during swallowing (all animals) was then plotted, for both milk and for the viscous mix, as a series of histograms for the three 50-ms time bins preceding and the three 50-ms bins succeeding each swallow. First, the variation in airway temperature prior to a swallow was always greater than

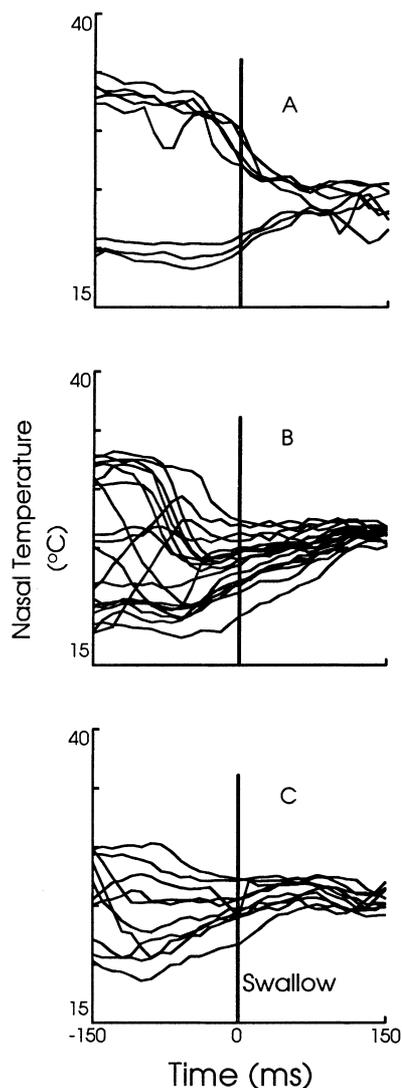


Fig. 4A–C Variation in the nasal airway temperature 150 ms before swallowing and 150 ms after swallowing. In each graph, the *x*-axis is time in ms, 0 ms being the time of entry of food into the piriform recess. The thermocouple signals (*y*-axis) have been lined up so that the actual times of entry of food into the piriform recess superimpose at 0 ms (vertical line). The variation in nasal airway temperature before swallowing was greater than that after swallowing, when the temperature moved towards a level that was characteristic of zero airflow. **A**, **B** and **C** are data obtained from three different feeding sequences each of which contained multiple swallows. All three data sets shown were obtained from the same individual suckling normal viscosity milk

that following a swallow, irrespective of the feed viscosity (Fig. 5). Second, many swallows were preceded by airway temperatures intermediate between those of inspired and of expired air, i.e., approximately at the temperature (30 °C) that corresponded to a lack of nasal airflow (Fig. 5A,B). When milk was swallowed, the airway temperature data prior to swallowing was suggestive of a bimodality with peaks at about 29 °C and 24 °C; the lower airway temperatures correspond to inspiration.

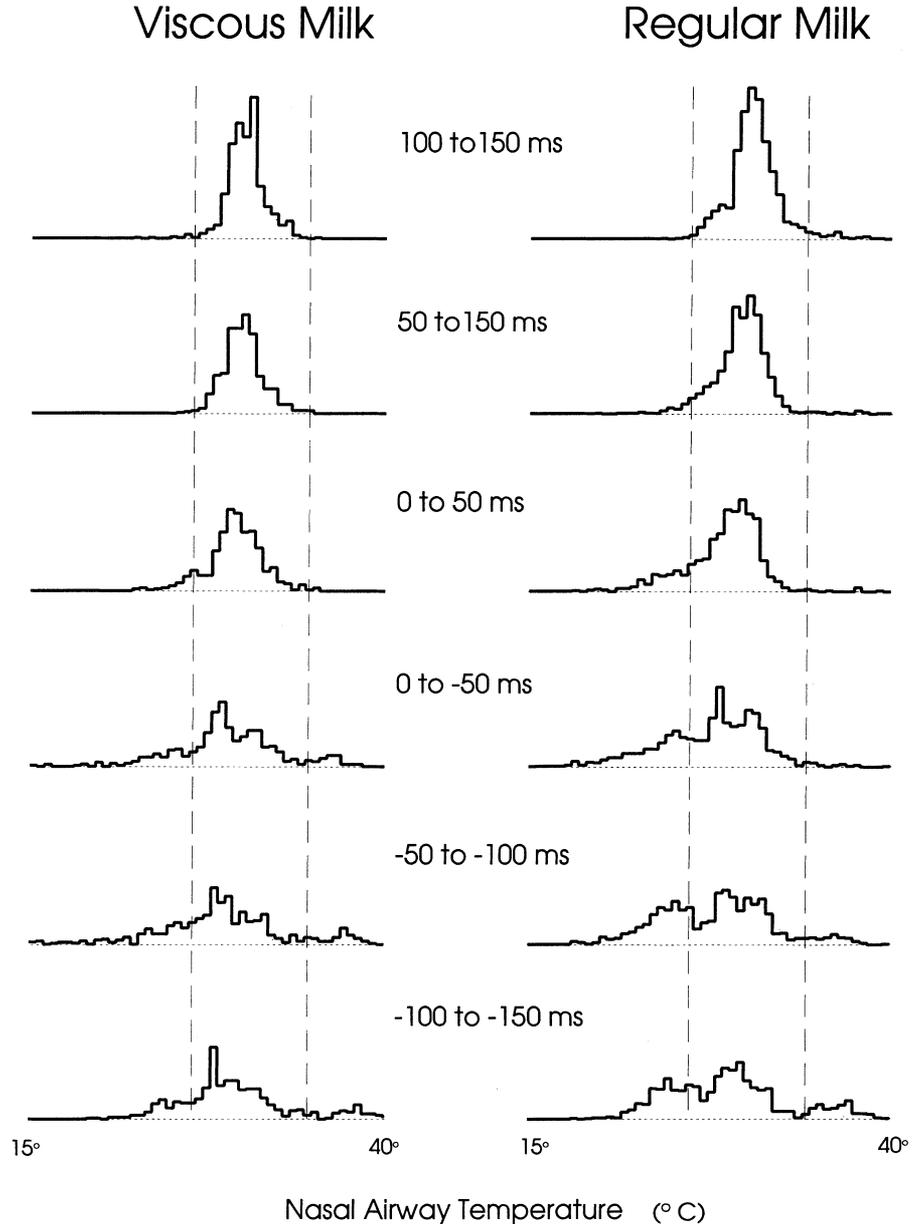
In the ANOVA analyses of the variation across time bins, there were significant differences in variation in nasal temperature among individuals, between the two viscosities and over time (all $P < 0.0001$). When the variation in nasal temperature before the swallow was compared to the variation after the swallow, the difference was highly significant ($P < 0.00001$). Tests of variation among the three time bins prior to the swallow (Fig. 5) showed no significant differences. However, after the swallow there were significant changes in the variation in nasal airway temperature (Fig. 5). The variations in bin five (50–100 ms post-swallow) and in bin six (100–150 ms post-swallow) were less ($P < 0.016$ and $P < 0.005$, respectively) than that in bin four (0–50 ms post-swallow); bins five and six were not significantly different from each other. The variation in nasal airway temperature in bin four was, however, significantly different from each time bin prior to the swallow ($P < 0.0001$). Thus, variation in temperature was uniformly high prior to the swallow, significantly reduced within 50 ms of food reaching the piriform recesses and reduced again over the next 100 ms. This is evident in Figs. 4 and 5.

The thermocouple data obtained in the period 100–150 ms prior to a swallow (Fig. 5) was divided into three groups depending upon whether it indicated no airflow (the temperatures corresponded to the mean ± 2 SDs of the values 100–150 ms after a swallow), expiratory airflow (the temperatures exceeded the mean $+2$ SDs of the values 100–150 ms after a swallow) or inspiratory airflow (the temperatures were less than the mean -2 SDs of the values 100–150 ms after a swallow). When feeding on milk, 60 out of 205 swallows (29.3%) were preceded by nasal airflow temperatures characteristic of inspiratory airflow, 119 out of 205 (58.0%) by no significant airflow and 26 out of 205 (12.7%) by expiratory airflow. When feeding on the viscous mix, only 22 out of 113 swallows (19.5%) were preceded by inspiratory airflow, 79 out of 113 (69.9%) were preceded by no significant airflow and 12 out of 113 (10.6%) by expiratory airflow. These differences in distribution were significantly different for the two foods (chi-squared, $P < 0.001$).

Discussion

The main index of airflow used in this paper was the nasal airway temperature, supported by measures of the pressure of the expired airflow and of diaphragm movement. In the absence of other evidence for expired airflow, the recorded nasal airway temperature was intermediate between that of expired air at deep-body temperature and that of inspired air at room temperature. Upon cessation of either inspiration or expiration the airway temperature measured by the thermocouple moved towards this intermediate temperature (Fig. 1B). However, it should be noted that there was a delay (see

Fig. 5 Histograms of airway temperatures in six time bins for regular and viscous milk. There are a total of 319 swallows (206 for normal milk, and 113 for viscous milk) from six sequences for each of four individuals. The *vertical dotted lines* indicated two standard deviations from the central value for bin six, when nasal airway temperature has returned to an intermediate point. Variation in temperature is much higher prior to the swallow than after the swallow, and is bimodal in the histograms for regular milk



Materials and methods and Fig. 1) between the onset of a period of apnea and its full registration by the thermocouple.

The first hypothesis tested was that, in the 6-day-old pig, the intranarial position of the larynx enables swallowing and respiration to be independent functions with no interaction and no impact on each other, as suggested by Negus (1929), Laitman et al. (1977) and Crelin (1987). If true, then, in a sufficiently large population of swallows, the variation in respiratory phase as measured by nasal airway temperature should be the same before and after a swallow. However, the results of this study indicated that variation in airway temperature was high prior to the swallow and low afterwards (Figs. 4, 5). In particular the airway temperature converged on an intermediate temperature within 150 ms after the entry of food into the piriform recess. After allowing for the

overall delay in detecting cessation of airflow, the data are consistent with a period of apnea that starts up to 50 ms prior to entry of the bolus into the piriform recesses and extends beyond that time.

The second hypothesis was that swallowing is constrained to a particular part of the respiratory cycle. If true, there would have been a consistent pattern of airway temperature prior to the swallow, which was not the case. Although there was a large variation in nasal airway temperature prior to the swallow, suggesting that swallows could occur in any portion of the respiratory cycle, most swallows (58% milk; 70% viscous feed) tended to occur at a nasal temperature indicative of zero or near zero airflow. A smaller number were preceded by falling airway temperatures, indicative of inspiratory airflow (milk 29%; viscous mix 19%), and fewest were preceded by a rising airway temperature, indicative of

expiratory airflow (milk 13%; viscous mix 11%). The distribution of swallows across the respiratory cycle was consequently neither random nor uniform.

A third hypothesis tested was that a change in the viscosity of the bolus would have some impact on the temporal relationship between swallowing and respiration. If this was true, then variation in nasal airway temperature, indicating variation in the respiratory phase preceding the swallow, would change significantly with change in the viscosity of the feed. The evidence was consistent with this hypothesis. When feeding on the standard milk formula, swallows were distributed across the respiratory cycle with a mode at a temperature consistent with near zero airflow. When the viscosity of the feed was increased ninefold, swallows occurred less frequently during inspiration or expiration and the percentage of swallows associated with zero airflow increasing from 58% to 70%.

One unexpected consequence of changing the feed from milk to the more viscous formula, was that the interval between swallows increased from 545 ms to 835 ms, i.e., by approximately 53%. Because the volume of each delivery and the rate of pumped delivery remained the same, the volume of the bolus in each swallow of the viscous mix must have been greater than in each swallow of milk. The average respiratory intervals when feeding on the two formulae were, however, the same (1052 ms). Consequently the more frequent milk swallows could, on average, occur nearly twice within each respiratory cycle. The bimodality evident in the airway temperature prior to swallowing milk (Fig. 5: -100 to -150 ms) would seem to reflect the consequent requirement to swallow at two different phases of the respiratory cycle. The majority of swallows nevertheless occurred at a temperature consistent with zero airflow. This unfortunately does not indicate whether the swallows occurred during post-inspiratory or post-expiratory pauses. In the case of the higher viscosity feed, the average swallowing interval corresponded to approximately 80% of the average respiratory cycle duration. Apart from the fact that a proportion of inter-swallow intervals might then coincide with individual respiratory intervals, it is difficult to see why this should result in a more unimodal distribution of airway temperature prior to a swallow.

These results differ from those previously reported for pre-term pigs feeding on milk (German et al. 1997). Those data indicate a fixed relationship between respiration and swallowing, the entry of food into the piriform recess occurring before termination of inspiration. It is uncertain whether the difference in outcome between the two studies is due to biological or methodological differences. A biological interpretation of the difference, accepting that a more fixed swallow/respiratory relationship exists in a pre-term animal than in an older animal, is against the general trend evident in the literature (see Introduction). There are, however, methodological differences in the two studies. In the present study, the sample size was larger ($n = 218$ against

$n = 55$) and was coupled with a quantitative determination and statistical analysis of respiratory phase. We therefore tend to the view that the previously published results (German et al. 1997) underestimated the variability of the swallow/respiratory link. This emphasizes the need for quantitative analyses of these data. Qualitative assessments of data are clearly insufficient for exact and accurate conclusions.

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