Dysphagia 22:37–43 (2007)
DOI: 10.1007/s00455-006-9038-3

Dysphagia

The First Year of Human Life: Coordinating Respiration and Nutritive Swallowing

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Abstract. This study provides the first documented report of the maturation of breathing-swallowing coordination during feeding in ten healthy term human infants through the first year of life. A total of 15,073 swallows were obtained across ten assessments between 48 h and 12 months of age. Midexpiratory swallows represented the dominant pattern of breathing-swallowing coordination within the first 48 h (mean = 45.4%), but the prevalence of this pattern declined rapidly in the first week to 29.1% ($p = 0.012$). Inspiratory-expiratory swallows increased with age ($p < 0.001$), particularly between 9 (37.0%) and 12 months (50.4%). Between 72.6% and 75.0% of swallows were followed by expiration in the latter 6 months, which is an adult-like characteristic. These data suggest that while postswallow expiration is a robust feature of breathing-swallowing coordination from birth, two major shifts in the precise patterns occur: the first after 1 week of postnatal feeding experience and the second between 6 and 12 months, most likely due to neural and anatomical maturation.

Key words: Breathing-swallowing coordination — Feeding — Infant — Deglutition — Deglutition disorders.

Before the 1990s, there was speculation that infants could breathe and swallow simultaneously [1]. However, more recent research has shown that there is always a cessation of respiration (swallowing apnea) during nutritive and nonnutritive swallowing in preterm and term human infants [2–5]. Swallowing apnea (SA) during feeding lasts approximately 0.5 s [6, 7] and can occur in midinspiration (II), between inspiration and expiration (IE), in midexpiration (EE), between expiration and inspiration (EI), or during apneic pauses (P).

Healthy human newborns reportedly present with a highly variable pattern of coordination without an obvious preferred respiratory phase [8]. Other data obtained from healthy term infants have been tainted by the inclusion of data obtained from term *and* preterm infants [6] or the inclusion of infants differing in postnatal age within the first week of life [9]. The need for rigorous control of postnatal age is highlighted by the observation that breathing-swallowing coordination reportedly changes within the first 5 days [3]. There is minimal information on the maturation of breathing-swallowing coordination in the healthy human infant population. Although there are studies that have addressed the maturation in preterm infants [10, 11], none have clearly documented that of healthy term infants beyond 1 month of age [10]. The majority of research on breathing-swallowing coordination of healthy term infants [3, 6, 8, 9, 12] has involved single assessments and, hence, longitudinal data are lacking. Two of the longitudinal studies [3, 12] reported maturational changes when comparing newborns and infants that were a few days older, but these reports were merely descriptions of observations rather than detailed methodical investigations with subsequent statistical analyses.

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Lau et al. [10] appear to be the only researchers to have completed a longitudinal assessment of healthy term infants. They found that the breathing-swallowing coordination of term infants within the first week of life was different than the pattern generated between 2 and 4 weeks of age. This maturation was primarily characterized by a decrease in the number of swallows that occurred during prolonged respiratory pauses. Unfortunately, as noted by the authors, the instrumentation used by Lau et al. inhibited the categorization of swallows into the well-defined five respiratory-phase categories mentioned above. Despite this, the pattern of breathing-swallowing coordination in the term infants changed within the first month of life. However, this pattern did not approximate the predominantly midexpiratory pattern exhibited by adults [13]. This suggested that the maturation pattern was not yet fully mature by 1 month of age and thus warranted further longitudinal investigation.

Normative data obtained from older infants are crucial for the identification of deviant patterns and may play an important role in clinical decision-making given the importance of adequate respiratory-swallow integration in adult [14, 15] and pediatric patient populations [16–18]. Research has identified atypical breathing-swallowing coordination during feeding in children with cerebral palsy [16] and bronchiolitis [17], in whom swallowing and feeding are often compromised [16, 17]. Increases in postswallow inspiration compared with healthy controls have been identified in both groups [16, 17] as well as in adult patients with specific neurologic damage [19]. Thus, postswallow inspiration may be indicative of disordered respiration and/or swallowing [19] and those patients at risk of aspiration [16].

A precursor to understanding the potential link between respiratory and swallowing integration during feeding in the paediatric patient population is to establish the nature of typical integration patterns in the healthy human infant population. Given that there are strong links between adequate cardiorespiratory control and efficient feeding in the literature [17, 20–22], further investigation of the integrative processes is crucial. Furthermore, a longitudinal study provides information that is fundamental to the understanding of human growth and development of respiratory-swallowing integration. Therefore, the present study longitudinally investigated the breathing-swallowing coordination patterns during breast and bottle feeding of healthy term infants from birth to 1 year to provide a detailed analysis of the maturation of this integrative process.

Method

Participants

Ten healthy term neonates (8 females, 2 males) were recruited for this study following the approval of the Canterbury Medical Ethics Committee. Written consent was obtained from a parent of each neonate. The neonates were born to mothers with no prenatal maternal complications, were born after 38 weeks gestational age, and had Apgar scores at or above 7 at 5 min after birth. The neonates had no reported medical complications at birth, nor did they have craniofacial, respiratory, or nervous system abnormalities. At each assessment, measures of normal development were documented, i.e., weight, head circumference, and the presence (or absence) of reflexes appropriate for their chronologic age (rooting, walking, grasp, moro, babinski, and tonic neck reflexes). After 1 month of age the Denver Developmental Screening Test II (DDST II) was also completed during each visit. All infants were found to be within normal limits on these measures and considered in good health at the time of each assessment.

Procedure and Equipment

Breathing-swallowing coordination was monitored during unrestricted feeding from either the breast or bottle (as determined by the mothers) in a reclined position. Where infant cooperation was good (in the large majority of assessments), the entire feed was recorded. Assessments were made within the first 48 h, at 1, 2, 3, and 4 weeks, and at 2, 3, 6, 9, and 12 months of age using simultaneous time-locked recordings of submental muscle activity, nasal airflow, and thyroid acoustics. All recordings were captured simultaneously by an integrated hardware-software system (Kay Elemetrics Swallowing Workstation, Lincoln Park, NJ). The collective submental muscle group was located by palpation and the positive and negative surface electromyography (sEMG) electrodes (Thought Technology Triode^{TM}, West Chazy, NY) were positioned over this muscle group with the reference electrode positioned on the forehead. The rectified and averaged submental sEMG signals were sampled at 250 Hz. Submental sEMG has been used previously to identify swallows in infants [2] and adults [23]. Nasal airflow was measured by an infant nasal canula to determine the direction of airflow before and after each swallow [4, 7, 24]. The nasal prongs were situated at the entrance to each nostril and secured firmly around the head. Thyroid acoustics were measured by a laryngeal microphone and were used to rule out submental EMG artifact and confirm swallowing onset [7, 17]. The laryngeal microphone was a modified omnidirectional condenser microphone with a sensitivity of -62 ± 3 dB, an impedance of < 2.0 kω, and a frequency response of 50–12,500 Hz. The microphone was connected to a preamplifier (Rolls mini-mic preamplifier MP13, gain = 6–50 dB). The signal from the preamplifier was sampled at 4000 Hz. The microphone was positioned lateral to the thyroid, which was located by palpation and held or taped in position with standard surgical tape.

Data Processing and Preparation

Swallows were identified by simultaneous bursts of sEMG activity and thyroid acoustics paired with a cessation in nasal airflow. Feeding swallows were analyzed by the primary raters and assigned to one of five categories based on the phase of respiration preceding and following the swallowing apnea (SA): inspiration-

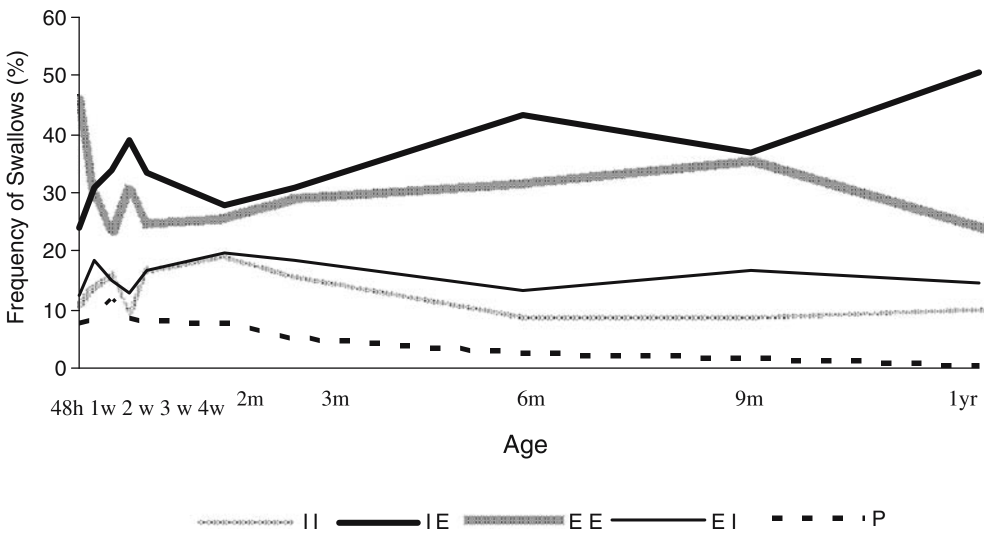

Fig. 1. Percentage frequency of swallows in each respiratory-phase category over time. Note that the data represented are not continuous data but were obtained at discrete ages, displayed in this manner for ease of reference. II = inspiratory-inspiratory, IE = inspiratory-expiratory, EE = expiratory-expiratory, EI = expiratory-inspiratory, P = midpause, h = hours, w = week, m = months, yr = year.

SA-inspiration (II), inspiration-SA-expiration (IE), expiration-SA-expiration (EE), expiration-SA-inspiration (EI), and midpause (P). Midpause swallows were those that occurred during prolonged apneic pauses and included consecutive swallows between which no respiration occurred. The duration of benign apneic pauses in normal healthy infants may be as little as 2 s [25, 26] or as long as 15 s [27]. Thus, swallows that occurred during an apneic pause of 2 s or longer were classified as P. A random 20% of the swallows were reanalyzed by the primary raters and independent raters to determine intraclass correlation coefficients for intra- and interrater reliability, respectively. Repeated-measures analysis of variance (ANOVA) was used to analyze the effects of age and feeding method on the relative frequencies of the different respiratory-phase categories. Respiratory-phase category and age were entered as within-subject effects and method of feeding as a between-subject factor for each age-group analysis. The sphericity assumption for repeated measures was tested using Mauchly's test, and when this assumption was not met, the Greenhouse-Geisser correction was applied to the significance tests. Where significant main or interaction effects were found, they were further explored using Fisher's protected least significant difference (LSD) tests. All statistics were performed using the SPSS statistical software package v13 (SPSS, Inc., Chicago, IL) and $p < 0.05$ was taken to indicate statistical significance.

Results

A total of 15,073 feeding swallows were analyzed (over 1200 swallows at each assessment age). There were over 100 swallows in each respiratory-phase category for all assessment ages with the exception of midpause swallows in which the three older age groups had less than 50 swallows. Intraclass correlation coefficients demonstrated satisfactory inter- and intrarater reliability for respiratory-phase categorization ($r = 0.989$ and $r = 0.964$, respectively).

The proportions of swallows followed by expiration at each age are as follows: 48 h (69.4%), 1 week (59.9%), 2 weeks (57.3%), 3 weeks (69.3%), 4 weeks (58.1%), 2 months (53.7%), 3 months (60.3%), 6 months (75.0%), 9 months (72.6%), and 12 months (74.4%). Repeated-measures ANOVA was performed to compare respiratory-phase categorization data across all assessment ages to determine the effects of age on breathing-swallowing coordination. This analysis revealed a respiratory-phase category effect [$F(4, 36) = 35.0$, $p < 0.001$]. Fisher's LSD test revealed differences between the following respiratory-phase categories: IE [mean (M) = 35.0%, SE ± 2.5%] and II (M = 12.9%, SE ± 1.7%), IE and P (M = 6.2%, SE ± 1.1%), and P and EE (M = 30.0, SE ± 1.5%). EI did not differ from any other respiratory-phase category (M = 15.9%, SE ± 2.1%). Approximately 65% of all swallows were followed by expiration (sum of IE and EE).

There was also an interaction between age and respiratory-phase category [$F(5.83, 52.4) = 2.71$, $p = 0.024$]. Further exploration of this interaction using Fisher's LSD indicated that the significant respiratory-phase category effects depicted above were largely consistent across ages but also indicated age-related changes in the differences between IE and EI, II and EE, EI and EE, and EI and P, once between II and P, but never between II and EI. Of particular interest were the significant differences between IE and EE at 48 h and 1 year, with EE being dominant in the former age group and IE being dominant in the latter age group. At 48 h infants swallowed more frequently during midexpiration but by 1 week inspiratory-expiratory swallows had become, and continued to be, the most common category (Fig. 1). To further assess changes over time within each respiratory-phase category, separate repeated-measures ANOVAs were conducted for each respiratory-phase category. Age effects were found

Table 1. Frequency of occurrence of swallows for breast and bottle-fed infants irrespective of age

	Breast		Bottle	
	Frequency (%)		Frequency (%)	
Respiratory-phase category	Mean	SD	Mean	SD
II	13.8	10.7	9.8	7.4
IE	35.7	17.0	37.8	10.7
EE	27.4	12.2	31.4	12.2
EI	16.1	10.6	16.4	7.8
P	6.9	7.0	4.6	7.2

II = inspiratory-inspiratory; IE = inspiratory-expiratory; EE = expiratory-expiratory; EI = expiratory-inspiratory; P = midpause.
SD = standard deviation.

for IE [$F(9, 81) = 3.85$, $p < 0.001$], EE [$F(9, 81) = 2.58$, $p = 0.012$], and P [$F(9, 81) = 3.93$, $p < 0.001$] categories only. The LSD test was applied to data on consecutive ages to explore the nature of these age effects. This revealed an increase in IE swallows between 9 months and 1 year. A decrease was noted for EE swallows between 48 h and 1 week. There were no differences between consecutive ages for P swallows and, hence, the age effect is due to the gradual decrease in P swallows.

To determine the effect of feeding method on breathing-swallowing coordination, repeated-measures ANOVAs were performed for each assessment age where the method of feeding was not homogeneous. Only within the first 48 h of life were all ten infants breast-fed. These analyses revealed no association between the method of feeding and the relative frequency of the respiratory-phase categories over all ages or within each age group. Although the sample size is small for both breast-fed and bottle-fed infant groups, the means and standard deviations of the percentage frequency occurrence of swallows are similar for both groups (Table 1).

Discussion

This is the first longitudinal study to document the maturation of breathing-swallowing coordination during feeding of healthy term infants within the first year of life. Over 15,000 swallows were recorded, substantially more than earlier studies (e.g., 462 swallows in preterm infants [2]). These results add to the growing body of evidence that human infants, like adults, do not breath and swallow simultaneously. Infants in the present study exhibited an adult-like characteristic in that the majority of nutritive swallows (65%) were followed by expiration irrespective of age. By 6 months, 75% of swallows were followed by expiration. Previous research in adults indicate that between approximately 63.5% and 100% thin liquid swallows are followed by expiration [13, 23, 28–31]; thus, this particular feature of infantile breathing-swallowing coordination is similar to that of adults.

Substantial maturation patterns were seen in the midpause and end-expiratory phase categories. Within the first two days of life, there was a higher proportion of swallows in midexpiration (EE) than during any other respiratory-phase category. By 1 week, however, the proportion of EE swallows decreased to a level similar to IE swallows. Very little change in the pattern of breathing-swallowing coordination was observed between 1 week and 3 months of age. However, from 6 months the large majority of swallows were followed by expiration (> 72%), and between 9 and 12 months there was a notable increase in the IE swallow proportion such that they dominated EE swallows. Throughout the year there was a gradual decrease in the proportion of P swallows. The association of prolonged respiratory pauses with nonnutritive swallowing in infants could be either peripherally or centrally governed [32]. Peripheral stimulation of pharyngeal and laryngeal sensory receptors may induce apnea and swallowing [32]. Alternatively, central respiratory-swallowing neural interaction in the brain stem during apnea may trigger swallowing [32]. Both hypotheses could apply to nutritive swallowing; however, the declining P swallows in the present study may merely be a reflection of the decline in the frequency of respiratory pauses in the maturing respiratory system [27, 33, 34]. Nonetheless, the overall pattern of maturation was largely governed by two shifts: the first occurring within the first week of life followed by a plateau, and the second between 6 and 12 months during which further modifications were seen. The early maturation process may have been the result of postnatal sensory-motor experience and the latter the impact of relatively protracted neural and anatomical maturation.

The effect of early postnatal feeding experience in the present study is similar to that of prior research that indicates infants between 5 and 8 days of age exhibit more "mature" coordination of breathing and swallowing patterns, most often in IE, than their 2-day-old counterparts who swallowed less frequently in the IE category [12]. However, our results are not in agreement with those of Bamford et al. [8] who found that within the first 48 h of life, IE swallows occurred more often than EE swallows (23.5% vs. 14%, respectively) in contrast to our findings of 24.0% vs. 45.4%, respectively. A possible explanation for this discrepancy is the way in which swallows were categorized. Bamford et al. [8] created five more categories from those swallows that occur during apneic pauses (inspiration-pause, expiration-pause, pause-pause, pause-inspiration, pause-expiration) and defined a pause as a cessation in respiration of greater than 150 ms. Although this categorization has been used again more recently [11, 35], the justification for this classification system is unclear and may have led to the inclusion of more swallows in the P categories and fewer in the remaining four expiratory and inspiratory categories.

The change observed within the first week of life highlights the potential impact of early postnatal experience on the central pattern generators that coordinate breathing and swallowing. Stevenson and Allaire [5] summarize this process as follows: ‘‘Oral feeding for the newborn is entirely reflexive’’ and does ‘‘not appear to require suprabulbar activity. Immediately after birth, however, the learning process begins with its dependence on experiential opportunities, sensory inputs, and suprabulbar neurologic maturation’’ so that ‘‘feeding and swallowing gradually changes from a reflexive to a volitional process’’ (p. 1449). In the present study, the increase of IE swallows with age may be the result of peripheral and central nervous system maturation associated with postnatal sensory-motor experience. The peripheral nervous system matures dramatically in the first two years of human life [36]. Postnatal maturation of the brain stem and peripheral nerves appears responsible for the maturation of feeding-related reflexes in animals [37]. Thus, it is possible that this maturation partially accounted for the changes observed in the first year of life of the infants in the present study.

Suprabulbar input is also a likely contributor to the maturation of breathing-swallowing coordination given evidence that it contributes to similar functions such as feeding behavior and oral reflexes. First, documentation exists of a ‘‘critical period’’ in which the lateral hypothalamus becomes important in the feeding behavior of infant rats [38]. Second, it has been suggested that descending cortical input may augment brain stem reflexes such as sucking and swallowing and suppress stereotypical reflexes [39]. This is supported by clinical observations that feeding and swallowing disorders can result from cortical damage in human neonates [39]. Furthermore, oral movements similar to those observed in the rooting and sucking reflexes of newborns have been observed in adult patients with diffuse cortical atrophy thereby indicating the importance of descending regulatory input from the cortex [40]. Postnatal myelination, which is important for neural transmission [41], may result in increased descending input from suprabulbar neural structures. Myelination of the neural connections between the cortex and the brain stem (the corticobulbar tract) occurs primarily during the first two years of human life [39] during which descending suprabulbar input is likely to increase.

Another likely contributor to the maturation of breathing-swallowing coordination in the first year of life is anatomical change, specifically the descent of the hyoid bone and larynx. One of the two major vertical and horizontal shifts of the supralaryngeal structures involved in breathing and swallowing occurs before 1 year of age [42]. During this process the epiglottis ‘‘descends’’ such that the epiglottic-to-soft-palate approximation is lost between 4 and 6 months of age [43]. This approximation allows a continuous passage between the nose and trachea [44]. The loss of this approximation coincides with the transition from primarily nasal to oral respiration in human infants [43]. Interestingly, this age also coincides with the time at which the large majority of swallows are followed by expiration and, more specifically, the inclination for IE swallow proportions to increase in the present study, suggesting a possible link. By 6 months, nine of the ten infants were tolerating solid food. Infants typically tolerate a variety of food textures by 6 months of age as a result of the maturation of the digestive system and tongue action [45]. This coincides with the disappearance of certain feeding-related reflexes by 6 months (e.g., the rooting reflex) as a result of descending cortical inhibition [46]. In the healthy infant, both neural and anatomical maturation influence respiration and swallowing; thus, the impact on the coordination of breathing and swallowing is inevitable. With this in mind, the present study provides important developmental data that will allow for future comparison with infants with anatomical anomalies of the head and neck (e.g., cleft palate), neurologic impairment, and respiratory and swallowing disorders.

The present study indicates that early postnatal feeding experience, paired with the relative protracted neural and anatomical maturation, and not environmental factors (i.e., method of feeding, the type of ingested fluid), account for the observed changes in the pattern of breathing-swallowing coordination in the first year of life. Previous research suggests that environmental factors influence infantile feeding biomechanics. Tongue biomechanics of breast-fed infants differs from that of bottle-fed infants [3] and, according to Qureshi et al. [47], ‘‘suck or swallow rate, pressure generated, or volume intake may differ in breast- and bottle-fed infants, the underlying rhythmicity and patterning of suck and swallow rhythms are less likely to be influenced by feeding modality" (p. 39). The comparison of breast-fed and bottle-fed infants in the present study revealed no differences in the coordination of breathing and swallowing between these two groups. This is supported by the similarity in the means and standard deviations between the two groups. Thus, the absence of an effect of method of feeding on the relative frequency of the respiratory-phase categories in the ANOVA reflects a true finding rather than a manifestation of the small sample size.

For the first time, the maturational patterns of the integration of breathing and swallowing during feeding in healthy term infants beyond 1 month of life are described. Irrespective of age, the large majority of feeding swallows are followed by expiration, even soon after birth, a pattern reported in the literature for nutritive swallows in adults. Although this pattern is adult-like from birth, further breakdown of these postswallow expiratory swallows into IE and EE categories reveals maturation patterns evident within the first week of life (EE dominant), and again in the latter 6 months of age and particularly at 1 year (IE dominant). The early maturation of breathing-swallowing coordination may be the result of postnatal sensory-motor experience. The later maturation of this coordination may be the result of the relatively protracted impact of neural, anatomical, and respiratory system maturation. These data provide a detailed longitudinal description of normative processes. Future comparisons with infants with breathing and swallowing disorders may thus identify pathologic patterns that interfere with feeding safety and efficiency.

Acknowledgments. The authors thank the participants and their caregivers and the interraters Elizabeth Haughey, Li Pyn Leow, and Lauren Ragg. The authors also thank the Foundation for Research Science and Technology for financial support and the staff in the Medical Physics and Bioengineering Department and the Burwood Birthing Unit of the Canterbury District Health Board for their technical support and assistance in subject recruitment, respectively.

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