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Preterm Infant Swallowing of Thin and Nectar-Thick Liquids: Changes in Lingual–Palatal Coordination and Relation to Bolus Transit

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Abstract

Tongue–soft palate coordination and bolus head pharyngeal transit were studied by means of postacquisition kinematic analysis of videofluoroscopic swallowing images of ten preterm infants referred from hospital NICUs due to poor oral feeding and suspicion of aspiration. Sequences of coordinated tongue–soft palate movements and bolus transits during swallows of thin-consistency and nectar-thick-consistency barium were digitized, and time series data were used to calculate continuous relative phase, a measure of coordination. During swallows of nectar-thick compared to thin barium, tongue–soft palate coordination was more likely to be antiphase, bolus head pharyngeal transit time was longer, and coordination was significantly correlated with bolus head pharyngeal transit. Analysis of successive swallows indicated that tongue–soft palate coordination variability decreased with nectar-thick but not with thin-consistency barium. Together, the results suggest that slower-moving bolus transits may promote greater opportunity for available sensory information to be used to modulate timing of tongue–soft palate movements so that they are more effective for pumping liquids.

Keywords

Infant; Swallowing; Coordination; Liquid properties

Typically developing term newborns are usually able to feed successfully from the breast or bottle by rapidly learning to coordinate the many anatomical structures involved in swallowing liquids [1]. However, coordinated swallowing by preterm infants is established much more slowly and may lead to a clinical diagnosis of immature swallowing due to prematurity [2]. Current clinical practice at many hospitals, including our institutions, is to refer some preterm infants for assessment of coordination by means of a videofluoroscopic swallow study. A modified barium study procedure typically involves several options, including changing the nipple, repositioning, and the actual modification of barium. In the latter procedure, an infant is presented with thin-consistency barium, and the clinician determines whether the infant is able to swallow safely. If there is poor coordination during swallowing of the thin-consistency liquid, the clinician presents nectar-thick barium to determine if there is any improvement [3, 4]. The diagnostic logic of this clinical protocol rests on the assumption that some aspect of nectar-thick liquids promotes improved swallowing coordination. However, there are no published studies of infant swallowing that have directly examined this assumption.

The purpose of this study was to begin to identify why nectar-thick liquid may improve coordination of swallowing in preterm infants. We examine tongue and soft palate coordination and bolus transit during swallows of nectar-thick compared to thin-consistency barium. We focus only on the effects of nectar-thick barium used during videofluoroscopic *assessment* of infant dysphagia and not on the efficacy of thickened liquids during *treatment*, since there is some question about the comparability of the liquids used during assessment and those used during Neonatal Intensive Care Unit (NICU) feeding [5]. Our combination of videofluoroscopy and computer-assisted kinematic analysis of preterm infant swallowing, also used widely in clinical practice with adults [6], offers the possibility of quantifying the specific effects of liquid properties on coordination of preterm infant swallowing. There are limited imaging studies of infant swallowing based upon videofluoroscopic [4, 7] or ultrasound methods [8–10]. Moreover, there are no published studies that have actually compared how the coordination patterns involved in preterm infant swallowing may change during feeding with nectar-thick-consistency compared to thin-consistency liquids.

In the adult swallowing literature, several studies indicate that the presentation of liquids with greater viscosity (but not volume) results in increased time to peak lingual pressure [11], increased amplitude in lingual force [12], longer contact duration between tongue and soft palate [13, 14], and increased range of upper hyoid movement [15, 16]. These findings may indicate that nectar-thick liquids are related to an increase in the duration of contact between the tongue and apposing surfaces, including the soft palate, and thus influence their coordination. Although our study did not directly measure force, kinematic analyses of the images recorded during videofluoroscopy make it possible to examine how the timing of contact and release of tongue and soft palate surfaces during swallowing may be influenced by thin consistency compared to nectar-thick consistency liquids [17]. We directly measured the duration of tongue movements and characterized the cycle of contact and release of the tongue and soft palate surfaces as a phase angle ranging between 0 and 360°. Thus, we were able to determine how a liquid-specific increase in durations of surface contacts could have the effect of changing the phase angle within each cycle of swallowing at which particular coordination events occur.

We recognize the significant role played by the pharyngeal wall constrictors (e.g., stylopharyngeus) to swallowing, but chose to focus the research on how the tongue may be used to harness the elastic properties of the soft palate during infant swallowing, as in our earlier work. In a previous study, for example, we [18] found that the timing of tongue and soft palate appears to be attracted to certain stable coordination patterns. Three tongue points (anterior, medial, and posterior) were organized around a stable in-phase pattern, with a

phase lag that implied an anterior–posterior direction of motion. Coordination between a tongue point and a point on the soft palate during lowering and elevation was close to antiphase at initiation of the pharyngeal swallow. In this study we extend the methodology of Goldfield et al. [18] by measuring differences in tongue–soft palate coordination and bolus transit during a single videofluoroscopic evaluation. Each infant followed a standard clinical protocol of being reclined in a Tumble-form seat at a 60° angle, presented with a silicone nipple, and swallowing thin-consistency barium presented by bottle for a set number of swallows, or until the clinician was able to visually document swallowing difficulty and/or aspirated liquid in the airway. Those infants who exhibited difficulty swallowing thin-consistency barium were then presented with nectar-thick-consistency barium. We were interested in the degree to which liquid property differences in the two conditions promoted changes in coordination between tongue and soft palate and in bolus transit.

Studies of pharyngeal transit during adult swallowing also indicate that increased liquid viscosity results in increased duration of oropharyngeal transit time [13, 14, 19–21]. This study of preterm infants attempted to determine whether there was similarly an increased duration of pharyngeal bolus transit during swallowing of nectar-thick compared to thin-consistency liquids. We additionally wanted to better understand the mechanism by which the timing of one bolus transit may influence coordination of tongue and soft palate for initiating a subsequent swallow and bolus transit. Therefore, we conducted a swallow-by-swallow analysis of tongue–soft palate coordination during presentation of thin-consistency barium only to determine whether sensory information about liquid properties during pharyngeal bolus transit may be more likely to modulate coordination between tongue and soft palate only after the infant has had the opportunity to produce several swallows. In other words, sensory modulation of coordination may require that the sensory experience of liquid flow occurs over a sequence of swallows. We specifically examined variability in tongue–soft palate coordination over successive swallows in order to better understand whether available sensory information may tend to stabilize the antiphase pattern.

This study presented infants with the opportunity to produce at least ten consecutive swallows of thin-consistency barium, followed by ten consecutive swallows of nectar-thick-consistency barium. Figure 1 is meant to orient the reader to the anatomical relations depicted in the videofluoroscopic images presented below.

We used the same analysis of sequential swallows as in our previous work to address whether sensory information available during swallows of nectar-thick liquids may be used earlier in the sequence of successive swallows to modulate pumping. If so, then we expected the infant to produce fewer swallows before shifting to antiphase tongue–soft palate coordination when swallowing nectar-thick compared to thin-consistency barium. Our previous study also found that near the end of a sequence of swallows of thin-consistency barium, there was a decrease in variability of tongue–soft palate coordination, as measured by standard deviation of continuous relative phase. There is some suggestion in the literature on adult swallowing [22] and in studies of infant apneic breathing [23] that sensory information may serve the function of stabilizing physiological control systems by providing feedback to central neural circuits. Here, we examined whether nectar-thick compared to thin-consistency barium may more rapidly stabilize tongue–soft palate coordination during preterm infant swallowing, as measured by a reduction in magnitude of the standard deviation of continuous relative phase.

To summarize, this study tests the following hypotheses about preterm infant swallowing of thin- and nectar-thick-consistency liquids:

1. There will be a progressively larger phase lag from anterior to posterior points along the tongue surface for swallows of nectar-thick compared to thin-consistency liquids.
2. There will be significantly longer duration and apposition and larger tongue–soft palate continuous relative phase for swallows of nectar-thick compared to thin-consistency liquids.
3. Pharyngeal transit time of each bolus head will be significantly longer for swallows of nectar-thick compared to thin-consistency liquids.
4. During a sequence of swallows, there will be a significantly larger tongue–soft palate continuous relative phase during the final five compared to the initial five swallows of nectar-thick compared to thin-consistency barium.
5. During a sequence of swallowing of nectar-thick liquid, there will be significantly less variability (smaller standard deviation of tongue–soft palate relative phase) during the final five compared to the initial five swallows.

The purpose of this study is to compare how the coordination patterns observed in preterm infant swallowing may change during feeding with nectar-thick-consistency compared to thin-consistency liquids.

Methods

Study Participants

Subjects were ten prematurely born infants receiving care in the NICU at Brigham and Women's Hospital or at Beth Israel Deaconess Medical Center, Boston, Massachusetts. Each infant was referred to Children's Hospital Boston for videofluoroscopic swallow study (VFSS) because of feeding difficulties and suspicion of penetration or tracheal aspiration of thin liquid. The research procedure was identical to standard medical care. This meant that it was not possible to manipulate the presentation order of the two liquid consistencies: infants were always presented with thin-consistency liquids before nectar-thick consistency. Other interventions such as positioning and/or using other bottle nipples were attempted for all subjects by their nurse and/or a consulting speech-language pathologist, but failed, prior to referral for videofluoroscopy.

Table 1 presents a summary of the subjects' sex, gestational age at birth, postmenstrual age at videofluoroscopic evaluation, and neurological status. Half of the infants were born at 26 weeks gestation or less. However, the relationship between gestational age and swallowing difficulty was not addressed here and awaits analysis of our larger complete sample. Intraventricular hemorrhage was identified in two of the infants. Infants with any oral anatomical abnormalities such as cleft palate were excluded from the study.

Study Procedure

The attending NICU physician and nurse determined that participating infants were all medically stable. Each infant was transported in a mobile incubator to the videofluoroscopy suite by his or her nurse, with oxygen support continuously available. The radiologic procedure was conducted by a pediatric radiologist (CB), with a speech-language pathologist (JP) and a researcher (EG) present. The adults and infant all wore lead aprons for protection against radiation. The radiology table adjacent to the camera head was placed in a vertical position. A Tumble-form seat was attached to a hospital-designed wedge, which, in turn, was attached to the footplate of the radiology table. Each infant was placed in a sitting position in the seat so that he or she was reclined at a 60° angle.

Each infant was further prepared for the evaluation by placement of two tiny metal markers (Beekley spot number 102, Beekley Corp., Bristol, CT) along the jawline, halfway between the chin and earlobe. A pulse oximeter (Nellcor N-595, Tyco Healthcare, Pleasanton, CA) was used to record percent oxygen saturation during the evaluation (not reported here). Once the baby was seated and strapped in, the radiologist positioned the camera head to obtain a lateral view and narrowed the field of view so that there was minimal radiation exposure.

The speech-language pathologist (JP) prepared the fluids used for the VFSS evaluation: two consistencies of standardized portions of barium sulfate (Liquid E-Z Paque, EZ-Em, Westbury, NY). The undiluted barium was used as the nectar-thick liquid. A consistency that simulated human milk or formula was prepared by diluting the barium sulfate with 5 % glucose in water (Enfamil, Mead Johnson & Company, Evansville, IN) to a 50 % solution. In specially conducted laboratory rheology tests, we determined that barium sulfate diluted with sterile water to a 50 % solution had a viscosity similar to that of human milk or formula. The diluted barium sulfate was modified from the premixed product and fit the recommended American Dietetic Association nomenclature of thin consistency, while the undiluted barium fit the nomenclature of nectar-like consistency [21]. We adopt this nomenclature in the remainder of the article.

A silicone nipple, similar to those used in the NICU, was used to present all liquids to the infants throughout the evaluation. If infants were unable to extract the nectar-thick liquid from the nipple, a cross-cut nipple was substituted. The infants, thus, may have exerted more sucking effort during swallows of nectar-thick liquids. The entire radiation time was a maximum of 3 min, during which the video images were recorded to DVD for later clinical review and, for purposes of the research, for detailed kinematic analyses. During the evaluation, each infant was presented with thin-consistency barium sulfate by bottle and nipple for a period of 60 s or less. The data are based on the first ten swallows in each of the two barium presentation conditions, completed in less than 30 s in each condition. Throughout presentation of the barium by bottle and nipple, the speech-language pathologist clinically evaluated coordination of swallowing and airway protection. All infants in the study produced penetration/aspiration during swallows of thin-consistency liquid; this prompted the clinical decision to proceed to presentations of nectar-thick barium.

Data Reduction

The temporal resolution of the lateral view of the infant's lingual pharyngeal anatomy was 30 frames per second, limited by the X-ray image intensifier used for clinical videofluoroscopy at Children's Hospital Boston. Following each VFSS evaluation, the recorded DVD data were converted to a format compatible with the software used for manual frame-by-frame kinematic analysis (MaxTraQ and MaxMATE, Innovision Systems, Columbiaville, MI). During post-VFSS kinematic analysis, a software-generated overlay grid was aligned with the position of one of the skin markers on the infant's jawline, and all points were calibrated with respect to the grid. On each video frame, this grid was used to digitize points along the lingual surface and at a point on the soft palate. Each point digitized with the MaxTraQ software corresponded to *x* and *y* coordinates saved for analysis and display in the companion MaxMATE computer program. These data were then saved as text files for relative phase analysis with custom programs written for MATLAB (MathWorks, Natick, MA).

Bolus Head Pharyngeal Transit Time

Following Kendall et al. [17], bolus head pharyngeal transit time was defined as the time between the onset and completion of bolus pharyngeal transit. Figure 2a, b illustrates a sequence of bolus head positions during pharyngeal transit. Pharyngeal transit onset was

defined as the first movement of the bolus head from a “hold” position that passes the posterior nasal spine and results in some or all of the bolus entering the nasopharynx. Oral transit time was not included in the measurement of pharyngeal transit time. The completion of pharyngeal transit was defined as the moment the bolus had fully entered the upper esophageal sphincter.

Tongue and Soft Palate Coordination

The tongue motion time series was based upon anterior, medial, and posterior tongue marker positions (Fig. 3). The relationship between marker motions of the tongue and soft palate was captured mathematically by measuring their continuous relative phase during each individual bolus head pharyngeal transit. Figure 4 illustrates the procedure used for digitizing a point on the medial tongue and a point on the soft palate in order to calculate continuous relative phase, a measure of tongue–soft palate coordination. Custom-written MATLAB computer programs were used for this purpose.

Determining Relative Phase of Two Time Series

Custom MATLAB programs were written to analyze over successive frames the continuous relative phase of the time series formed by each lingual or soft palate point. Continuous relative phase is a relationship between two time series in which a point on one is related over time to a second point on the other. The resulting phase is presented in angular degrees to reflect the cyclical nature of the relationship between the points over time. Using the MATLAB programs, each time series resulting from a particular digitized point was normalized around zero and low-pass filtered (using a Butterworth filter) with a cut-off frequency of 10 Hz. A peak-picking algorithm determined peaks and valleys of the waveforms and used these to calculate mean and standard deviation of relative phase of any pair of digitized points.

Circular Statistics

A statistical approach, termed circular or directional statistics [24], was used to calculate phase angle from the time series of each point on the tongue and soft palate. These tests assume sampling from a circular analog of the linear-normal distribution. Descriptive circular statistics, the mean angle and circular standard deviation, respectively, are based upon transforming rectangular coordinates X and Y into polar coordinates by means of sine and cosine transformations. Circular statistics may be preferable to other nonparametric methods because the result can be interpreted directionally (i.e., spatially), e.g., for testing whether a phase angle for coordination differs significantly from 0° .

Results

Individual Kinematic Data

Individual subject data are used here to illustrate how we measured bolus head pharyngeal transit time, tongue–soft palate coordination, and the relationship between bolus head pharyngeal transit time and tongue–soft palate coordination in the thin- and nectar-thick-consistency conditions. All swallows were produced as part of a suck/swallow pattern. Because tongue–soft palate coordination was calculated during the period of each individual swallow, it was possible to examine directly the relationship between tongue–soft palate coordination and bolus transit.

Figure 5 illustrates the time course of (a) tongue–palate motion during a period of about 2 s, and (b) the pharyngeal transit time of an individual barium bolus during this same period. During this particular swallow, tongue and soft palate move synchronously in opposite directions at about 1 s, corresponding to the initiation of a bolus transit, and travel through

the pharynx to the upper esophageal sphincter. This correspondence would be expected if the pharyngeal swallow were timed to capitalize on the potential energy stored and released as the soft palate is lowered and elevated.

The group data, considered next, examined tongue–soft palate coordination during swallows of thin- and nectar-thick-consistency barium and how each individual bolus head pharyngeal transit during a sequence of swallows was related to the tongue–soft palate coordination of a subsequent swallow.

Group Data Comparisons During Swallows of Nectar-thick- and Thin-Consistency Liquids

The data in the following subsections examine tongue motion and tongue–soft palate coordination during swallows of thin compared with nectar-thick barium, whether later swallows in a sequence of nectar-thick-barium swallows are more likely than thin-barium swallows to exhibit close to antiphase coordination, whether bolus head pharyngeal transit times differ in these two barium consistency conditions, and whether there is any relationship between bolus head pharyngeal transit time and tongue–soft palate continuous relative phase.

Tongue Motion—To test the hypothesis that nectar-thick liquids may promote a larger anterior–posterior tongue motion, we compared the time series for digitized points at anterior, medial, and posterior tongue points. We were interested in whether there was a progressively larger phase lag between tongue points in an anterior-to-posterior direction, indicating a direction of motion that would move liquid to the back of the tongue. Of particular interest was whether the phase angle between the most anterior and posterior tongue points was larger when infants swallowed nectar-thick compared to thin-consistency liquid. Table 2 presents the mean phase angle vector and circular standard deviation for each of the three tongue positions for the nectar-thick and thin-consistency liquid conditions. There was a significant phase angle main effect of position [$F(2,54) = 7.91, p = 0.0001$] and condition [$F(1,54) = 3.97, p = 0.05$], but no significant interaction between position and condition. This implies that over a sequence of swallowing, the overall direction of motion of tongue movements was anterior to posterior. Post hoc tests revealed that relative phase between anterior and posterior points was significantly greater in the nectar-thick barium than in the thin-consistency barium condition ($p < 0.01$). Thus, nectar-thick barium had the effect of increasing phase lag in such a way that the most posterior point was always further in its cycle of moving away from the soft palate than either of the other points at the same moment in time.

Coordination Between Tongue Motion and Soft Palate Elevation—To test the hypothesis that tongue–soft palate coordination was significantly closer to antiphase (180°) during swallows of nectar-thick compared to thin-consistency liquids, we first collapsed swallow means for each subject across all ten swallows and compared the means and variability measures in the two conditions (Fig. 6). The mean continuous relative phase of the tongue and soft palate in the thin-consistency condition was 128.35 ($SD = 38.25$), and in the nectar-thick-consistency condition it was 162.01 ($SD = 27.15$). We were interested in whether swallows of nectar-thick barium promoted tongue–soft palate coordination close to antiphase. A one-way analysis of variance was used to compare the mean continuous relative phase of the tongue and soft palate in the two conditions. The tongue–soft palate phase angle was significantly larger for swallows of nectar-thick compared to thin-consistency liquids [$F(1,18) = 14.54, p = 0.0012$]. Thus, there was a significant difference in tongue–soft palate coordination in the two conditions. Nectar-thick barium was more likely to promote near antiphase tongue–soft palate coordination than thin-consistency barium.

Duration of Tongue–Soft Palate Gap Closure and Apposition—To examine the effect of nectar-thick and thin-consistency barium on tongue–soft palate timing, we directly measured tongue–soft palate gap closure and apposition during each of ten swallows in the two conditions. The means and standard deviations of tongue–soft palate movement and apposition duration are presented in Table 3. A Wilcoxon matched-pairs test revealed that durations were significantly longer during swallows of nectar-thick barium than during swallows of thin-consistency barium ($Z = 3.92$, $p = 0.0001$). We also examined whether the duration measure might be related to the shift in tongue–palate coordination toward antiphase by means of a correlational analysis. There was a significant correlation between tongue–soft coordination and tongue–soft palate gap closure and apposition ($r = 0.741$, $p = 0.01$). Thus, nectar-thick barium appears to result in longer periods during which the tongue and soft palate approach and make contact with each other, and these longer durations are related to the increased phase lag that moves tongue–soft palate coordination toward antiphase.

Swallow-by-Swallow Analysis of Tongue Motion and Soft Palate Elevation—

We used the swallow-by-swallow analysis to address several questions. To test the hypothesis that nectar-thick liquids might reduce variability of tongue–soft palate coordination over a sequence of swallows, we analyzed the means and standard deviations of tongue–soft palate coordination at each of 12 swallow positions in sequence. We first determined whether there was a particular point in the sequence when tongue–soft palate coordination revealed an increased tendency toward antiphase (as measured by increased mean relative phase) and a reduction in variability (as measured by decreased SD of relative phase). Figure 7 plots the SD of the tongue–soft palate relative phase over the ten successive swallows of nectar-thick and ten successive swallows of thin-consistency liquids (always administered in that order). Most notable in the figure are the changes apparent at around swallow number 6: a reduction in variability (SD). Therefore, we conducted an additional analysis of the mean and SD of tongue–soft palate relative phase for swallows 1 through 5 compared with swallows 6 through 10. There was no overall statistical difference between the means of tongue–soft palate continuous relative phase during swallows of thin consistency compared to nectar-thick liquid. However, for swallows 6 through 10, a Wilcoxon matched-pairs test indicated that the standard deviation of tongue–soft palate continuous relative phase was significantly smaller than it was for swallows 1 through 5 ($Z = 2.023$, $df = 4$, $p = 0.043$). Thus, after infants were given the opportunity to experience the sensory information available during five initial successive swallows of nectar-thick liquid, their tongue–soft palate coordination during the next five swallows stabilized close to antiphase.

Bolus Head Pharyngeal Transit—To examine the influence of barium consistency on bolus head pharyngeal transit time, we calculated for each infant the mean transit durations for swallows in each of the two barium consistency conditions. For thin-consistency barium, the mean bolus head pharyngeal transit time was 1.55 s ($SD = 0.534$), and for nectar-thick-consistency barium, the mean was 2.278 s ($SD = 0.569$). A nonparametric Wilcoxon matched-pairs test comparing the means indicated that mean bolus head pharyngeal transit time was significantly longer for swallows of nectar-thick barium than for thin-consistency barium ($Z = 2.701$, $df = 10$, $p = 0.0007$). Thus, nectar-thick barium moved significantly more slowly through the pharynx than thin-consistency barium.

Discussion

The findings generally support the study hypotheses. As in our previous report [18], tongue and soft palate coordination during preterm infant swallowing was organized around stable in-phase and antiphase patterns. There may be a functional basis for the organization of the

oral anatomy into patterns of in-phase and antiphase. In-phase and antiphase patterns may provide a coordinated timing of opening and closing of the pharynx that functionally segregates the shared pathway for air and liquid as it comes to apposition with the tongue. It is in this sense that the oral anatomy may function as a pump during swallowing. A positive displacement, or fluid-static, pump accumulates liquid in a confined space, reduces the volume of that space to apply forces that have the potential of displacing the liquid, and then opens an outlet that allows the liquid to be propelled along a specific pathway [19]. In the case of infant swallowing, the movement of the tongue dorsum and soft palate in opposite directions at a particular moment in time (i.e., antiphase coordination) creates a lingual–palatal space for containing liquid transferred to the back of the mouth, then compresses and releases it at the initiation of the pharyngeal swallow. Coordinating anterior–posterior tongue motions that move liquid into a space created by tongue–soft palate movements may transform the oral–pharyngeal anatomy into a biological positive displacement pump.

The question of the role of nectar-thick liquids for improving swallowing of preterm infants takes on functional significance when placed in the context of how the coordinated activities of tongue and soft palate may be used for pumping. There are at least two ways that it may be possible to improve preterm infant pump function: (1) by taking greatest advantage of the elastic properties of the tissues comprising the component organs of the pump for forcefully propelling the liquid during initiation of pharyngeal transit, and (2) by taking greatest advantage of available sensory information about movement of the liquid across the surfaces of the pumping organs as feedback for timing successive swallows. The results of this research suggest that nectar-thick liquid may improve the pumping function during preterm infant swallowing in both of these ways. Consider, first, how nectar-thick liquid may promote coordination that better harnesses the potential energy stored in the elastic tissues of the soft palate. The palate–pharyngeal arch is, upon dissection, surprisingly large, and has structural properties amenable for storing elastic potential energy as it holds together the laryngeal cartilages [21]. By initiating muscular contraction so that the timing of soft palate lowering and elevating is in antiphase with respect to the back of the tongue, these organs may be used together to more forcefully propel the bolus through the pharynx. Nectar-thick liquids had the effect of increasing the phase lag of the most posterior part of the tongue so that it was closer to antiphase with the soft palate than was the case during swallows of thin-consistency barium. It is possible that volume played some role in the difference of phase lag between nectar-thick and thin-consistency liquids. Future work in which we use a computer-controlled delivery of liquid bolus will allow us to address this possibility.

Next, consider the effect of nectar-thick liquid on making available sensory information that could provide feedback for timing of successive swallows. We found that bolus transits through the pharynx were significantly longer for swallows of nectar-thick barium compared with thin-consistency barium. Bolus transits of nectar-thick liquids persisted longer in the pharynx than thin-consistency liquids and so were more likely to co-occur with successive swallows. It was, perhaps, the co-occurrence of mechano-receptor sensory feedback with these swallows that may have stabilized (i.e., reduced the variability of) the successive bolus transits [12].

What can we conclude about why infants exhibit dysphagia, and why swallowing of some preterm infants improves with nectar-thick compared with thin-consistency barium? Due to the immaturity of the central nervous system of preterm infants, suckling and swallowing may be governed primarily by intrinsic pattern generation that is just beginning to be adaptable to sensory input [25, 26]. With increasing maturity, the challenge for an increasingly adaptive neuromechanical system [27] may be to identify particular moments within intrinsic oral–pharyngeal activity during which sensory information may be useful for modulating behavior of tongue, soft palate, and other organs so that they adapt to constantly

changing conditions within the oral environment. Our data suggest that this may be accomplished through modification of the phase lags of activities comprising the oral and pharyngeal swallow stages. As indicated during videofluoroscopic evaluation of these preterm infants, there was slower pharyngeal transit of nectar-thick compared to thin-consistency barium. The slower pharyngeal transit of the nectar-thick bolus may have increased the availability of sensory information for modulating the phase between tongue and soft palate movements. With each successive swallow, the tongue–soft palate coordination pattern phase lag may have increased so that initiation of the pharyngeal swallow gradually occurred when the tongue and soft palate were moving in opposite directions at the same time (i.e., close to antiphase). We are currently examining whether nectar-thick liquids may also have a similar phase-shifting influence on the organs responsible for protecting the airway during preterm infant swallowing.

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Fig. 1.
A sagittal videofluoroscopic image (*left side*) and line drawing identifying the major structures (e.g., tongue, soft palate) and a bolus transit. Drawing courtesy Professors A.W. Crompton, Harvard University, and Rebecca German, Johns Hopkins University

Fig. 2.

A sequence of bolus head positions during pharyngeal transits. **a** The tongue is compressing the nipple and the bolus head advances. **b** Bolus head has passed the vallecula and is entering the upper esophageal sphincter

Fig. 3.

A sequence of tongue positions during infant swallowing. *Point 1* is the tongue tip, *point 2* is a medial tongue point, and *point 3* is a posterior tongue point. *Left* the tongue at rest during suckling. *Right* maximum nipple compression by the tongue

Fig. 4. Changing marker positions indicating the functional component of a pump that moves tongue and soft palate in opposite directions at the same time to create a chamber that receives liquid and compresses it prior to initiation of the pharyngeal swallow. **a** The soft palate is at rest. **b** The soft palate begins elevation

Fig. 5.
a At approximately 1 s, tongue and soft palate are close to antiphase (see text). **b** Initiation of bolus head pharyngeal transit

Fig. 6. Group differences for all ten infants in mean continuous relative phase of tongue–soft palate coordination during swallows of thin and nectar-thick consistency barium, respectively

Fig. 7. Swallow-by-swallow analysis collapsed over infants at each successive swallow position of standard deviation of continuous relative phase

Table 1

Demographic characteristics of subjects

Number	Sex	Gestational age (weeks)	Postmenstrual age at VFSS (weeks)	Presence of perinatal intraventricular hemorrhage
1	M	25	39	Yes
2	F	26	38	No
3	F	28	39	No
4	F	24	39	Yes
5	M	26	40	No
6	F	35	43	No
7	M	28	47	No
8	F	26	36	No
9	F	30	38	No
10	M	32	41	No
Mean		28.00	40.00	
SD		3.43	3.09	

Table 2

Phase of marker points as a function of tongue location and barium consistency (°)

Condition	Anterior	Medial	Posterior
Thin consistency	5.11 (5.48)	11.08 (8.47)	12.05 (11.11)
Nectar-thick consistency	7.08 (1.78)	13.86 (7.81)	19.19 (8.25)
Overall	6.09 (4.09)	12.47 (8.06)	15.62 (10.21)

Values are mean (SD)

Table 3

Duration of tongue–soft palate gap closure and apposition as a function of barium consistency

Condition	Duration (s)
Thin consistency	0.765 (0.072)
Nectar-thick consistency	0.958 (0.149)