Respiration during feeding on solid food: alterations in breathing during mastication, pharyngeal bolus aggregation, and swallowing

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Matsuo K, Hiemae KM, Gonzalez-Fernandez M, Palmer JB. Respiration during feeding on solid food: alterations in breathing during mastication, pharyngeal bolus aggregation, and swallowing. J Appl Physiol 104: 674–681, 2008. First published December 27, 2007; doi:10.1152/japplphysiol.00527.2007.—During feeding, solid food is chewed and propelled to the oropharynx, where the bolus gradually aggregates while the larynx remains open and breathing continues. The aggregated bolus in the valleculae is exposed to respiratory airflow, yet aspiration is rare in healthy individuals. The mechanism for preventing aspiration during bolus aggregation is unclear. One possibility is that alterations in the pattern of respiration during feeding could help prevent inhalation of food from the pharynx. We hypothesized that respiration was inhibited during bolus aggregation in the valleculae. Videofluorography was performed on 10 healthy volunteers eating solid foods with barium. Respiration was monitored concurrently with plethysmography and nasal air pressure. The timing of events during mastication, food transport, pharyngeal bolus aggregation, and swallowing were measured in relation to respiration. Respiratory cycle duration decreased during chewing (P < 0.001) but increased with swallowing (P < 0.001). During 66 recordings of vallecular bolus aggregation, there was inspiration in 8%, expiration in 41%, a pause in breathing in 17%, and multiple phases (including inspiration) in 35%. Out of 98 swallows, 47% started in the expiratory phase and 50% started during a pause in breathing, irrespective of bolus aggregation in the valleculae. Plethysmography was better than nasal manometry for determining the end of active expiration during feeding and swallowing with solid food. The hypothesis is rejected in that respiration was not inhibited during bolus aggregation. These findings suggest that airflow through the pharynx does not have a role in preventing aspiration during bolus aggregation in the oropharynx.

deglutition/physiology; fluoroscopy; neurophysiology; pharynx

Precise temporal coordination of pharyngeal bolus transit and airway protection is critical for swallowing (14, 15, 21, 29, 33, 35). It is well known that a variety of protective events, including respiratory inhibition, vocal fold closure, and physical separation of the airway from the foodway occur immediately prior to and during the pharyngeal phase of swallowing (21, 33). Thus the bolus is not exposed to the laryngeal airway when it is transported through the pharynx.

During the mastication of solid food, boluses are prepared and transported posteriorly to accumulate first on the oropharyngeal surface of the tongue behind the fauces and then on the valleculae (11, 23), sometimes for up to 10 s prior to swallowing in normal individuals (11). The presence of the accumulated food bolus may place individuals at risk for aspiration if respiration continues and the airway remains open. Indeed, air can be inhaled through the pharyngeal airway while food is but a few millimeters from the laryngeal aditus. It might be predicted, therefore, that respiration would be modified, and perhaps inhibited, during the period of bolus accumulation as a preparatory airway protective function, well in advance of the pharyngeal swallow. Alternately, it might be the case that the necessary protection of the airway occurs immediately prior to and during the critical moments of bolus transport through the pharynx and that protection at other moments is not necessary.

The only data available to address these alternative hypotheses come from a preliminary investigation by Palmer and Hiemae (22). They measured respiratory phasing during swallowing with a small pressure transducer (manometer) attached to a nasal cannula in four subjects and found that bolus aggregation in the valleculae typically occurred during an extended plateau in nasal air pressure. These data suggested that respiration is inhibited during bolus aggregation. However, there is reason to suspect that nasal airflow, as measured in this earlier investigation, does not provide an accurate estimate of respiratory patterning during bolus accumulation and other recording methods are needed such as respiratory plethysmography. The present investigation, therefore, was designed to further explore breathing patterns during the mastication, aggregation, and swallowing of solid food boluses using both nasal manometry and respiratory plethysmography. We hypothesized that respiration was inhibited during bolus aggregation in the valleculae.

METHODS

The study protocol was approved by the applicable institutional review boards. After providing written informed consent, 10 healthy young adult subjects (5 men and 5 women, median age 21.5 yr, range 21–33) were recruited for the study. Subjects had no history of major medical problems and had normal dentition (Class I occlusal relationships). They denied any history of eating or swallowing difficulties and none exhibited signs of abnormal swallowing in a diagnostic 10-ml liquid barium swallow in lateral and posteroanterior projection videofluorography (VFG).

Recording Procedures

Respiration. Respiration was monitored with a respiratory plethysmograph (Respiritrace, Nims, North Bay Village, FL) and nasal pressure transducer (Gaeltec, Skye, Scotland). The plethysmograph bands were placed around the chest and abdomen. The nasal pressure

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transducer was attached to a standard nasal cannula. Respiratory monitoring started at least 3 min before VFG recording of each trial. The respiratory signals from the plethysmograph and nasal pressure transducer were recorded on a laptop computer using digital data-acquisition hardware (Labview, National Instruments, Austin, TX) at 1-kHz acquisition rate. We also recorded the surface electromyogram (EMG) of the submental and masseter muscles on the laptop computer along with the respiratory signals.

Feeding. Radiopaque lead markers (5 mm diameter) were glued to the upper and lower canines and first molars to record jaw movements. Each subject was seated comfortably in upright position and asked to eat 6- or 8-g portions of banana, cookie, and meat with barium paste and 1 g of carrot dusted with barium sulfate while VFG was recorded in lateral projection. They were asked to chew and swallow in their usual manner. VFG recording on S-VHS tape (30 frames/s) began as the food was placed in the mouth and continued until the terminal swallow. Swallowing often occurred several times in one recording. There were two recordings for each food. Radiation exposure time was 5 min or less for each participant. In one subject, recordings with meat were omitted because the subject was a vegetarian.

Synchronization of respiratory signals with VFG recording images. A time code generator was connected to the laptop computer recording respiratory data and the S-VHS recorder storing VFG images. The time code generator sent spike signals to the computer once every second and the associated time in hundredths of a second was recorded on the S-VHS tape. The video and physiological data recordings were synchronized using the output from the time code generator. A sequence of mastication and swallowing was first roughly detected on the physiological records by identifying the surface EMG pattern of submental and masseter muscles associated with feeding. Swallows in the sequences were readily identified by characteristic patterns of EMG and nasal air pressure and matched with patterns of jaw motion and swallowing on the VFG recording. The VFG images and respiratory data were then synchronized precisely by matching the timing of the square wave output from the physiological record with the display of time 00 of the video timer shown on the VFG recording (Fig. 1).

Data Analysis

Feeding. VFG images on S-VHS tape were captured to a desktop computer and stored as digital image files with no image compression using video editing software (Adobe Premiere, Adobe System, San Jose, CA). Out of a total of 122 swallows recorded, 24 were excluded from analysis. Of these, 22 were excluded because of difficulty precisely recording the timing of oropharyngeal bolus aggregation (this was typically in the third or fourth swallow in a sequence, when the amount of food in the pharynx was too small for accurate measurement). Two recordings were excluded saliva swallows occurring during mastication that disrupted the coordination of breathing and swallowing. Thus a total of 98 swallows were included in the analysis.

The following events of bolus aggregation and swallowing were identified using operational definition developed and validated in previous studies (11, 22, 30).

1) Postfaucial aggregation: this is accumulation of triturated food on the pharyngeal surface of the tongue behind the fauces but above the valleculae before the swallow. Postfaucial aggregation before swallow onset was noted in 92 swallows. For these, we measured postfaucial aggregation time (PFAT), defined as beginning when the leading edge of the barium passed under the posterior nasal spine and ending when the leading edge reached the level of the inferior border of the mandible.

![Schematic figure depicting the synchronization of videographic data with respiratory data from the recorder. The videofluorography (VFG) image and respiratory data were reconciled by matching the timing of the spike of the time code generator (1 Hz) on a laptop computer and the time 00 in each second of the time code generator (displaying time in 0.01-s increments) shown on the monitor of the VFG image at the time of swallows. Swallowing VFG was clearly identified on both data screens.](image-url)
2) Vallecular aggregation: this is accumulation of triturated food in the valleculae after it has passed through the postfaucial area. Pre-swallow vallecular aggregation of food was identified for 66 swallows. In these cases, we measured vallecular aggregation time (VAT), defined as starting at the end of PFAT and ending when the leading edge of the barium passed the edge of the epiglottis, entering the hypopharynx.

3) Pharyngeal swallow: we defined the time of pharyngeal swallow onset as the start of rapid anterior and superior excursion of the hyoid bone associated with a swallow, and swallow offset as the end of that hyoid bone excursion.

4) Hypopharyngeal transit time (HTT) was the period during which the bolus passed through the hypopharynx during a swallow. It was defined as beginning at the end of VAT and ending when the trailing edge of the barium reached the upper esophageal sphincter. We did not measure pharyngeal transit time, because there was typically a bolus of triturated food in the pharynx for several seconds before onset of the pharyngeal swallow.

Respiration. The sum of chest and abdominal respiratory signals was processed with digital signal analysis software (DADiSP 2002, DSP Development, Boston, MA). The time of the start and end of inspiration was extracted from the plethysmograph data using a peak detection function. Respiratory cycle duration (TRC) was defined as the time from the start of one inspiration to the start of the next inspiration. These cycles were each divided into inspiratory and expiratory phases. Inspiratory phase duration (TI) was defined as the time from the onset of inspiration to the end of inspiration and expiratory phase duration (TE) was defined as the time from the end of inspiration to the onset of the next inspiration (Fig. 2). Each respiratory cycle had clear inspiratory and expiratory phases, usually with a pause after active expiration. The timing of the pause within cycles was somewhat variable. The transition from expiration to pause was gradual, so the plethysmograph output showed an asymptotic return to the baseline. This made it impossible to identify a precise time of transition, so we did not measure duration of the pause, but simply included it in the duration of the expiratory phase. (This is usual practice for studies of respiration and swallowing.) “Swallow apnea” is commonly measured in studies with liquid swallows (2, 14, 15, 26), but we did not attempt to measure swallow apnea duration because the pauses in breathing often began substantially before the swallow, and the swallow occurred during these extended pauses, with no way to delineate the start of respiratory pause for swallowing.

We classified respiratory cycles (RCs) into the following groups: 1) prefeeding RCs occurring before the onset of feeding; 2) feeding RCs occurring during VFG recordings from the start of ingestion until the terminal swallow; and 3) postfeeding RCs occurring after the completion of the VFG recordings of feeding. Feeding RCs were further divided into: 2a) feeding RCs without swallow and 2b) swallow RCs.

To examine the temporal relationships between breathing and bolus aggregation and swallowing, the time of end-inspiration (onset of the expiratory phase) for each swallow RC served as a reference “time zero for that sequence.” We calculated the intervals from end-inspiration to the onset of PFAT, VAT, HTT, and of the swallow. When a subject performed multiple swallows during a single recorded sequence, and the swallows occurred in different RCs, these intervals were calculated for each swallow RC. If multiple swallows occurred in one RC (total of 8 RCs with 2 swallows and 2 RCs with 3 swallows), only the first swallow was analyzed. We noted which phase or phases of respiration occurred during each episode of postfaucial or vallecular aggregation. We also noted the phase of respiration during which each of the following events occurred: onset of swallow, onset of HTT, end of HTT, and end of swallow.

Statistical Analysis

Sixty feeding sequences including 98 swallows were analyzed. To examine the effect of feeding and swallowing on respiratory rhythm, we compared the average duration of RCs among the RC types using mixed-model ANOVA: the dependent variables were the RC and phase durations (TRC, TI, and TE), and the independent variables were RC group (fixed factor), food (fixed factor), and subject (random factor). The Tukey test was used for post hoc paired contrasts.

To test the effect of bolus location on respiratory rhythm, we examined the interval from end-inspiration in the swallow RC until the onset of events of interest (onsets PFAT, VAT, HTT, and of the swallow) using mixed-model ANOVA: the dependent variables were these intervals, and the independent variables were food (fixed factor), occurrence (vs. nonoccurrence) of vallecular aggregation before swallowing (fixed factor for HTT and swallow only), and subject (random factor). We also tested whether the average onset time of each event was before or after onset of expiration (in the swallow RC) using t-tests. The critical value for rejecting the null hypothesis was α < 0.05. Statistical analyses were performed with SPSS 12.0 (SPSS, Chicago, IL).

RESULTS

One subject had an unusual respiratory pattern: breathing was disrupted as soon as eating began. The mean TE in this subject was more than 5 s during food processing before the swallow compared with 2.5 s in the prefeeding RCs (resting tidal respiratory rate). Furthermore, duration of expiration was 8.5 s on average during swallow RCs. In one record, the whole sequence of eating banana from ingestion to terminal swallow was completed in 18 s between breaths (Fig. 3). This prolonged expiratory phase reflected an extended period of respiratory pause prior to the next inspiration. Given the atypical pattern of breathing and feeding, this subject was not included in the analysis.
Respiratory Cycles Before, During, and After Feeding

Respiratory cycle durations pre- and postfeeding did not differ significantly \((P = 0.98)\). The respiratory rhythm was significantly altered during feeding, however (Fig. 4). Respiratory cycles and both their inspiratory and expiratory phases were generally shorter once feeding started. Median RC duration \((T_{RC})\) at rest was 3.76 s prefeeding, but dropped to 3.12 s for feeding RCs without swallow \((P < 0.001)\). This represents an increase in average respiratory rate from 16.0/min prefeeding to 19.2/min during feeding. Indeed, \(T_{RC}\) was shortest in feeding RCs without swallow \((P < 0.001)\) and longest in swallow RCs \((P < 0.001)\) compared with all other RC types (Fig. 4). The respiratory rhythm returned to baseline after feeding, although the respiratory rhythm was occasionally perturbed when subjects cleaned up residual food in their mouths (mouth clearance).

Average TE duration mirrored \(T_{RC}\) duration in that it did not vary significantly between pre- and postfeeding RCs, was shortest during feeding RCs without swallow \((P < 0.001)\), and was longest in swallow RCs \((P < 0.001, \text{Fig. 4)}\). Average TI duration was similar: it was shortest during feeding RCs and did not vary significantly between pre- and postfeeding RCs. There was a major difference, however. Average TI duration was also short during swallow RCs. Food type had no significant effect on RC duration, and there was no significant interaction between food and respiratory cycle types. The changes in respiratory pattern associated with feeding, including both inspiratory, expiratory, and total RC durations, varied significantly among subjects \((P < 0.001)\), but not among foods \((P \geq 0.07)\), and there was no significant interaction between food and RC type (feeding, nonfeeding, pre- or postfeeding, \(P \geq 0.12)\).

Most subjects showed low amplitude oscillations in nasal air pressure during feeding that were linked temporally to motion of the jaw and hyoid bone. These oscillations were not found in the plethysmograph recordings (Figs. 3 and 5).

Airflow During Bolus Aggregation and Swallowing

Most respiratory cycles included inspiration, expiration, and a pause in active respiration. For sequences with bolus aggregation in the pharynx before swallowing, we noted the direction of airflow during the full period oropharyngeal bolus aggregation (PFAT plus VAT) and during VAT alone (Table 1). There were multiple respiratory phases (including at least one inspiration) during 75% of recorded episodes of oropharyngeal bolus aggregation, and in 22%, airflow was expiratory only (or expiratory plus a pause). Breathing was paused throughout the oropharyngeal aggregation only 2% of the time. There were 26 episodes of oropharyngeal aggregation with no vallecular aggregation (postfaucial aggregation only). In those cases, 50%
Table 1. Respiratory phase(s) during episodes of oropharyngeal bolus aggregation before swallowing

<table>
<thead>
<tr>
<th></th>
<th>In (%)</th>
<th>Ex (%)</th>
<th>Pause (%)</th>
</tr>
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<tbody>
<tr>
<td>OPAT—no VA</td>
<td>1 (1)</td>
<td>20 (22)</td>
<td>2 (2)</td>
</tr>
<tr>
<td>OPAT (92 swallows)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPAT</td>
<td>13 (50)</td>
<td></td>
<td>13 (50)</td>
</tr>
<tr>
<td>VAT (66 swallows)</td>
<td>5 (8)</td>
<td>27 (41)</td>
<td>11 (17)</td>
</tr>
</tbody>
</table>

Expiration (Ex) may include a pause after active expiration; Multiple phases include at least 1 inspiratory (In) phase. OPAT, oropharyngeal aggregation time; VAT, vallecular aggregation (VA) time; n, number of swallows.

Table 2. Respiratory phase at time of four events of pharyngeal swallow, for swallows with (n = 66) and without (n = 32) vallecular bolus aggregation before swallowing

<table>
<thead>
<tr>
<th></th>
<th>In (%)</th>
<th>Ex (%)</th>
<th>Pause (%)</th>
</tr>
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<tbody>
<tr>
<td>HTT onset</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With VA</td>
<td>1 (2)</td>
<td>65 (98)</td>
<td></td>
</tr>
<tr>
<td>No VA</td>
<td>32 (100)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTT end</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With VA</td>
<td>66 (100)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No VA</td>
<td>32 (100)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swallow onset</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With VA</td>
<td>2 (3)</td>
<td>31 (47)</td>
<td>33 (50)</td>
</tr>
<tr>
<td>No VA</td>
<td>1 (3)</td>
<td>15 (47)</td>
<td>16 (50)</td>
</tr>
<tr>
<td>Swallow end</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With VA</td>
<td>2 (3)</td>
<td>35 (53)</td>
<td>29 (44)</td>
</tr>
<tr>
<td>No VA</td>
<td>2 (3)</td>
<td>17 (53)</td>
<td>15 (47)</td>
</tr>
</tbody>
</table>

HTT, hypopharyngeal transit time; n, number of swallows. Differences between swallows with VA and with no VA were not statistically significant.
timing of active expiration and the subsequent respiratory pause.

Nasal manometry captures changes in air pressure associated with breathing, but also those associated with air movement between the oral and nasal cavities during feeding. During eating, the fauces are open and air moves between the two cavities in association with masticatory jaw movement (1, 12, 22). This oscillating movement of air alters nasal pressure and makes it difficult to detect respiratory events, especially the transition from active expiration to the subsequent respiratory pause. This transition involves a gradual change in nasal pressure that is readily obscured by the oscillating pressures associated with jaw movement. Other disadvantages of nasal manometry are that it does not detect oral breathing and that it is altered by closure of the nasopharyngeal isthmus. Impedance plethysmography, on the other hand, reflects changes in volume of the chest and abdomen, and is not sensitive to jaw movement during mastication, a clear benefit over nasal manometry. Nasal manometry may provide valid measures for the respiratory pause during liquid swallows, but clearly not respiration during feeding and swallowing with solid food.

Fig. 5. Complete sequence including 3 swallows with banana, recorded in the same subject shown in Fig. 2. Typical bolus transport and aggregation periods in the pharynx were shown with feeding kinematics (jaw and hyoid movements) and breathing pattern (nasal pressure and plethysmography). Low amplitude oscillation associated with jaw motion was seen in nasal air pressure but not in the plethysmograph during feeding. Bolus transport and aggregation periods were defined as PFAT, postfaucial aggregation time; VAT, vallecular aggregation time; and HTT, hypopharyngeal transit time. Ti and Tp phases are shown in gray and white, respectively. Expiration was prolonged in swallow RCs. For the first and second swallows (SW1 and SW2), VAT and HTT started during the expiratory phase, but PFAT started about 2 s before end inspiration. Both PFAT and VAT for the third swallow (SW3) occurred in late expiration.

The average expiratory phase duration was 1.86 s longer in swallow RCs than in feeding RCs without swallowing. (Inspiratory phase duration was not affected by swallowing, however.) This prolongation of the expiratory phase duration reflects, in part, the time required for bolus aggregation and a swallow, but the prolongation is actually longer than the duration of the swallow itself. Preiksaitis and Mills (27) reported that breathing cycles that included swallows were 17% longer for solid food (cookie) than liquid (5 ml) swallows. The mean duration of swallow RCs for cookie in that study was 5.1 s, comparable to the median of 5.0 s in the present study. The time required for food transport and bolus aggregation in the oropharynx may explain the longer RCs during eating than drinking.

We found consistent temporal relationships between phase of respiration and swallowing. The onset of hyoid excursion occurred during expiration in 47% and during a pause in expiration in 50% of swallows. Hypopharyngeal transit of the bolus was initiated during a pause in breathing for every swallow and nearly always ended with expiration or a pause in breathing after bolus passage to the esophagus. Resumption of respiration in exhalation may help prevent inhalation of residual food in the piriform sinuses or hypopharynx after swallowing (19, 34). These findings are consistent with those of previous studies (14, 17, 20, 27, 31, 34, 36).

Respiration and Mastication

Mastication significantly altered the respiratory rate. We found that the duration of the respiratory cycles including both
the inspiratory and expiratory phases were shortened during mastication, indicating a 20% increase in respiratory frequency, consistent with previous studies (7, 17). The metabolic demands incurred by contracting the muscles of mastication could account for the increased respiratory frequency. Fontana et al. (7) reported that respiratory frequency increased during gum chewing at normal speed and increased further with gum chewing at the maximum chewing rate. Alteration in tidal volume has also been reported; it tends to decrease during mastication in association with the increased respiratory frequency, thus offsetting some of the increase in minute ventilation (7, 17, 20, 36).

One subject presented an extended period of respiratory pause during feeding, a pattern that was consistent among all trials for that individual. The pause persisted for as long as 18 s, covering an entire feeding sequence from ingestion to terminal swallow. Prolonged periods of pause associated with mastication have been previously reported in a normal subject (17) and several laryngectomized subjects (4) and may represent an exaggerated physiological response to the presence of food in the oral cavity and pharynx.

Mechanical Constraints on Coordination of Respiration and Swallowing

Mechanical factors may place constraints on the coordination of respiration and swallowing, as noted by Charbonneau et al. (4). At the onset of swallowing, elevation of the larynx contributes to airway protection. In addition, there is shortening of the pharynx by ~2 cm, which reduces the volume of pharynx and is a component of pressure generation during the swallow (24, 25). The larynx is tethered by its attachment to the trachea, which is in turn attached to the lungs and indirectly connected to the diaphragm. When the diaphragm contracts in inspiration, it pulls downward on the trachea and, thereby, on the larynx (18). This downward pull on the larynx can impede laryngeal elevation. In the present study, swallow onset, defined as the start of elevation of the hyoid, occurred during inspiration in only 3% of swallows. Swallowing during expiration (while the diaphragm is rising) or during a pause in inspiration (when the diaphragm is relaxed) may facilitate elevation of the larynx and shortening of the pharynx (4).

Clinical Implications

The presence of the food in the valleculae before swallowing may increase the risk of aspirating food. Swallows during the inspiratory phase of breathing are more frequent in individuals with Parkinson’s disease, cerebrovascular disease, or the other neurological diseases (3, 8, 9, 13, 32), and may be related to the increased incidence of aspiration pneumonia in these diseases (6, 16). Mechanisms for preventing aspiration during bolus aggregation remain unclear. As shown in the present study, respiration is not affected by bolus aggregation in the valleculae, so some other mechanism(s) must be responsible. There are at least two alternatives: mechanisms: Dua et al. (5) reported partial vocal fold closure when food reaches the valleculae; this could prevent aspiration by limiting access to the larynx from above. Prinz and Lucas (28) proposed another mechanism based on the characteristics of the food. They suggest that bolus consistency is modified during mastication so as to optimize cohesion, preventing the bolus from falling apart during aggregation and transport in the pharynx. Further studies are necessary to evaluate the role of these factors in individuals with abnormal swallowing.

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