### Tongue pressure modulation during swallowing: Water vs. nectar-thick liquids

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Swallow pressures for water and nectar-thick liquids

Running head: Swallow pressures for water and nectar-thick liquids

Tongue pressure modulation during swallowing: Water vs. nectar-thick liquids

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Tongue pressure modulation during swallowing: Water vs. nectar-thick liquids

Abstract

Purpose

Evidence of tongue-palate pressure modulation during swallowing between thin and nectar-thick liquids stimuli has been equivocal. This mirrors a lack of clear evidence in the literature of tongue and hyoid movement modulation between nectar-thick and thin liquid swallows. In the current investigation, we sought to confirm whether tongue-palate pressures are modulated between discrete swallows of water and nectar-thick juice.

Method

Tongue-palate pressures were measured at three sites (anterior, medial and posterior palate) using an adhered 3-bulb pressure strip in 20 healthy, young adults during discrete swallows of water and nectar-thick apple juice.

Results

Pressure modulation was not noted with respect to pressure amplitudes (in mm Hg), but was identified both in the pressure patterns observed (the sites and number of bulbs activated) and temporal aspects of pressure duration.

Conclusions

Tongue-palate pressure amplitude modulation does not occur for nectar-thick swallows compared to thin liquid swallows. Modulation does, however, occur with respect to the tongue-palate contact surface area and pressure durations. We introduce the concept of pressure slope as a meaningful way to examine tongue-palate pressure application in swallowing.

Key Words

Tongue, Swallowing, Pressure, Manometry, Dysphagia, Viscosity
Tongue pressure modulation during swallowing: Water vs. nectar-thick liquids

Introduction

During the oral phase of swallowing, liquid boluses are held in a chamber along the midline groove of the tongue (Kahrilas, Lin, Logemann, Ergun, & Facchini, 1993). Posterior tongue elevation prevents spillage of material over the tongue base into the pharynx. In order to initiate bolus transfer to the pharynx, the tongue body moves upwards towards the palate, and then moves forward along the palate, thereby creating a squeezing and conveyer-belt type transport mechanism for the bolus (Hiiemae & Palmer, 2003; Martin, 1991; Steele & van Lieshout, 2004a). As the bolus reaches the pharyngeal isthmus, the tongue ceases forward movement and executes a large and rapid downward/backward movement, coinciding with the onset of the pharyngeal phase of swallowing (Steele & van Lieshout, 2004a).

Prior studies have measured the pressures that are generated during tongue-palate contact (Crow & Ship, 1996; Nicosia, et al., 2000) and tongue-pressure generation capacity has become a focus in dysphagia rehabilitation (Lazarus, Logemann, Huang, & Rademaker, 1993; Robbins, et al., 2005; Robbins, et al., 2007; Yeates, Molfenter, & Steele, 2008). It is now commonly accepted that the tongue-palate pressures that are generated during swallowing fall well below the values generated during maximum isometric pressure-generation tasks (Nicosia, et al., 2000; Youmans, Youmans, & Stierwalt, 2009). Furthermore, we know that maximum isometric pressures decline with age (Nicosia, et al., 2000) while swallowing pressure capacity is preserved (Nicosia, et al., 2000; Youmans, et al., 2009).

Bolus flow is an important variable in safe swallowing. Thickened liquids have been widely adopted as a compensatory treatment approach for patients who have difficulty
swallowing thin liquids safely (Garcia, Chambers, & Molander, 2005; Logemann, et al., 2008; Robbins, et al., 2002; Steele, 2005). Several studies have been performed in an effort to capture and describe differences in swallowing motor physiology across liquids of differing viscosity (Chi-Fishman & Sonies, 2002; Ishida, Palmer, & Hiitemae, 2002; Lazarus, et al., 1993; Lof & Robbins, 1990; Miller & Watkin, 1996; Perlman, Schultz, & VanDaele, 1993; Perlman, Vandaele, & Otterbacher, 1995; Poudreux & Kahrilas, 1995; Steele & van Lieshout, 2004b). Although methodological differences exist across these studies, certain patterns can be appreciated from their collective results. Some authors have observed differences in the timing or duration of swallowing events as bolus consistency becomes thicker (Lazarus, et al., 1993; Lof & Robbins, 1990). By contrast, very few studies have demonstrated consistency-related differences in movement amplitudes. Where amplitude differences have been found, these have predominantly taken the form of smaller amplitudes for thin liquids in pairwise comparison to consistencies at the very thick end of the spectrum (i.e., honey-thick liquids, pudding or paste) (Chi-Fishman & Sonies, 2002; Ishida, et al., 2002; Poudreux & Kahrilas, 1995; Steele & van Lieshout, 2004b). Very few studies have investigated differences between thin and nectar-thick liquid swallows and most of these have failed to find significant differences (Chi-Fishman & Sonies, 2002; Steele & van Lieshout, 2004b). Thus it remains unknown whether modulations of swallowing physiology across bolus consistency occur in a graded, linear fashion (as is widely assumed by clinicians) or whether modulation takes a non-linear pattern with non-continuous jumps in behavior as critical thresholds in bolus flow properties are exceeded.

In the present study, we collected tongue-palate pressure data at three locations (anterior, mid and posterior palate) in healthy young adults during different tongue-pressure and swallowing tasks. The current manuscript specifically examines tongue-palate pressure behaviors
in discrete water swallows compared to those seen in discrete swallows of a commercially available nectar-thick apple juice (Resource, by Novartis Nutrition, now Nestlé Nutrition, Highland Park, MI). We describe the patterns of tongue-palate pressure generation observed in our participants and the nature of pressure modulation seen between water and nectar-thick swallows.

Background Literature

Pouderoux & Kahrilas (1995) were among the first to explore tongue-palate contact in swallowing using air-filled pressure bulbs. A major goal of their study was to validate air-bulb manometry for recording tongue forces during the pulsive phase of swallowing (corresponding to oral bolus propulsion) and to compare the response characteristics of an air-bulb manometry system to the more familiar strain-gauge system used to measure deglutitive clearance pressures in the oropharynx (Shaker, Cook, Dodds, & Hogan, 1988). Pouderoux and Kahrilas chose to represent their tongue measurements in units of force (Newtons), based on careful study of the response characteristics of three different sizes of air-filled bulb attached to the Iowa Oral Performance Instrument (IOPI) device (IOPI Northwest, Carnation, WA). A medium-sized bulb (2.7 ml volume) was used for recording tongue forces at mid-palate and posterior-palate locations during the swallowing of 3 ml volumes of water, chocolate pudding and mashed potato in 8 healthy young adults. Forces at these two locations were, respectively, 5.3 +/- 0.4 N and 5.5 +/- 0.5 N with the water stimulus. A statistically significant increase, to 7.7 +/- 0.5 N and 7.8 +/- 0.5 N was recorded with the pudding stimulus. A further statistically significant increase, to 9.5 +/- 0.6 N and 9.4 +/- 0.6 N was observed with the mashed potato stimulus. By referencing these force values to the response characteristics table provided for the 2.7 ml bulb, one can convert these force values to equivalent pressure values of approximately 150, 200 and 250 mm Hg for the
three stimuli, respectively. Of interest, Pouderoux and Kahrilas also demonstrated that the larger (5 ml) volume air-bulb registered lower pressures than the 2.7 ml bulb, and that pressure events recorded with the larger bulb had an advanced onset temporally compared to those recorded using the 2.7 ml bulb.

A second seminal study in the area of tongue pressure measurement was that conducted by Nicosia and colleagues (2000). These authors utilized a Kay Elemetrics tongue bulb manometry system (a precursor of the manometry module currently available with the KayPentax Digital Swallowing Signals Lab, KayPentax, Lincoln Park, NJ) to record pressures using 3 air-filled bulbs (each 13 mm in diameter) attached to the hard palate at anterior, mid and posterior palate locations with a fixed inter-bulb distance of 8 mm. In contrast to the IOPI bulbs used by Pouderoux and Kahrilas (1995), the smaller bulbs used by Nicosia were glued in place using an adhesive strip. Nicosia and colleagues (2000) recorded tongue pressures concurrently with videofluoroscopy during the swallowing of 3 ml and 10 ml volumes of thin liquid barium (diluted Polibar Plus, EZ-EM Inc., Westbury, NJ) and a 3 ml semi-solid stimulus (Esopha-CAT, EZ-EM Inc., Westbury, NJ). The Nicosia study contributed four major findings to the literature. First, they demonstrated the now well-accepted finding that swallowing pressures are submaximal, falling below 50% of the pressure values registered during maximal isometric tongue-palate pressure generation tasks. Secondly, they demonstrated that maximal isometric tongue-palate pressures decline with age, but that healthy older adults can still generate swallowing pressures of the same magnitude as younger adults. Thirdly, they reported that pressures progressed in magnitude from the front to the back of the oral cavity, with lower values at the anterior bulb and the highest registered pressures at the posterior bulb. Finally, Nicosia and
colleagues reported that the semi-solid stimulus elicited significantly higher pressures than the thin liquid stimulus.

Subsequent studies with an adhered tongue bulb array have concentrated on non-effortful and effortful saliva swallows (e.g. Huckabee & Steele, 2006; Steele & Huckabee, 2007) or on pressures registered during the swallowing of liquids with different taste profiles (Pelletier & Dhanaraj, 2006). Surprisingly, to our knowledge, there are no prior studies using an adhered tongue bulb array to measure comparative pressures during the swallowing of thin liquid and nectar-thick liquid stimuli. Investigations of tongue pressure variations across liquid stimuli of differing consistency have been restricted to studies using the hand-held IOPI bulb system. While this approach allows registration of pressure amplitudes in single locations, it does not permit concurrent registration of pressures at multiple sites throughout the oral cavity and does not easily allow one to appreciate the temporal characteristics of pressure events.

Youmans and Stierwalt have published a series of studies (Stierwalt & Youmans, 2007; Youmans & Stierwalt, 2006; Youmans, Youmans & Stierwalt, 2009) reporting tongue-palate pressure measurements taken with the IOPI and a bulb 3.5 cm in length and approximately 4.5 cm in diameter. Based on images provided in the Pouderoux and Kahrilas article (1995), one can deduce that the bulb used by Youmans & Stierwalt (2006) corresponds to the medium-sized 2.7 ml volume bulb used in the Pouderoux & Kahrilas study. In their most recent publication, Youmans and colleagues (2009) placed the IOPI bulb in an anterior position and then added stimuli varying from 5-15 ml in volume to the mouth for swallowing. Among the stimuli were 5 and 10 ml samples of two commercially available pre-thickened liquids, “Resource” nectar-thick and honey-thick apple-juice (Novartis Nutrition, now Nestlé Nutrition, Highland Park, MI). The results of this study were reported both using raw pressure measurement values (in kPa) and also
Swallow pressures for water and nectar-thick liquids

with those same values expressed as a percentage of maximum isometric pressures. Regardless of the format in which the data were reported, the results showed that women generated significantly higher swallowing pressures than men. With respect to variations in tongue pressure across different stimuli, Youmans et al. (2009) found that both nectar-thick and honey-thick apple juice stimuli elicited significantly higher pressures than water (at both 5 ml and 10 ml volumes), but there were no significant differences between the nectar-thick and honey-thick stimuli in pairwise comparisons. Based on the charts provided, it can be ascertained that the magnitudes of pressures recorded from healthy young adults in their study were in the range of 32-36 kPa (240-270 mm Hg) for 5 and 10 ml volumes of water, 40-42 kPa (300-315 mm Hg) for 5 and 10 ml volumes of nectar-thick apple juice, and 45-47 kPa (337-353 mm Hg) for 5 and 10 ml volumes of honey-thick apple juice. Additional charts in the manuscript suggest that these values corresponded to percent maximum isometric pressure values of 48-50% for water, 54-56% for nectar-thick apple juice and 58-60% for honey-thick apple juice. Maximum isometric pressures for the young participants in the Youmans et al. study (2009) were reported to be 75 kPa (563 mm Hg), on average, with significantly higher values obtained in the female participants (77.63 kPa vs. 73.25 kPa).

A question of possible importance arises from comparison of the pressure values obtained using the hand-held IOPI by Youmans, Youmans & Stierwalt (2009) to those obtained using the stable adhered 3-bulb manometry system by Nicosia and colleagues (2000). Although neither study reported specific descriptive statistics, charts in the Nicosia study suggest that maximum isometric pressures at the anterior bulb location for healthy young participants were in the range of 590 mm Hg, with swallowing pressures for 10 ml boluses of approximately 120 mm Hg and 150 mm Hg, respectively, for the liquid barium and semi-solid stimuli. Thus, although the
maximum isometric pressures recorded by Youmans, Youmans & Stierwalt are similar to those recorded by Nicosia and colleagues, the values they obtained using the IOPI bulb for swallowing pressures were substantially higher (more than double) than the values obtained by Nicosia and colleagues using the stable 3-bulb array. It is unclear how methodological differences in these studies might have contributed to these differences, but crucial that they be reconciled, and the possibility that the measurement devices and methods might themselves have contributed to the differing results must be resolved.

Another issue to note is the manner in which individual raw data have been transformed (or not) prior to analysis in prior studies. It is considered good practice for other swallowing-related signals (most notably submental surface electromyography) to correct for possible variations in signal strength, quality and sensor-location across participants by transforming amplitude values for each participant relative to a common reference value, namely the maximum raw value obtained on a reference task (Ding, Larson, Logemann, & Rademaker, 2002; Perlman, 1993). This approach has been adopted by some (Huckabee & Steele, 2006) with respect to tongue pressure signals but not by others (Stierwalt & Youmans, 2007; Youmans & Stierwalt, 2006). Youmans, Youmans & Stierwalt (2009) devoted considerable attention in their recent paper to analyzing swallowing pressure amplitudes both in raw form and as a percent of maximum isometric pressure values. While this latter approach has the same effect as transforming data relative to a common maximum amplitude reference, it is customary to convert the resulting percentages back into measurements in the familiar unit (e.g., mm Hg or kPa) prior to analysis.
Swallow pressures for water and nectar-thick liquids

The Current Investigation

The goals of the current investigation were two-fold. First, we sought to describe tongue-palate pressure patterns in detail during the swallowing of water and nectar-thick stimuli by healthy people. We wanted to consider concurrently-registered pressures at three locations in the mouth (anterior, medial and posterior palate), to describe the patterns of pressure generation across those three locations in terms of the number and locations of bulbs registering pressure activation for specific tasks, and to describe both amplitude and durational characteristics of the resulting pressure waveforms in detail. With respect to pressure pattern, we were also curious to determine how often the pressures registered at a single bulb were single-peaked or multi-peaked. With respect to amplitude, we wanted to position the swallowing pressure data in the larger context of each participant’s pressure-capacity range, by transforming data relative to a maximum isometric pressure task. Second, we wanted to determine whether, and to what degree, healthy adults modulate either the pattern, amplitude and/or durational characteristics of swallowing pressures between water and nectar-thick stimuli. With respect to this second goal, we wanted to test the null hypothesis that swallowing pressure modulation would be absent in a comparison between water and nectar-thick stimuli.

Methods

Participants

Twenty healthy adults (10 male) between the ages of 20 and 40 volunteered for participation in the study. Due to a technical problem, data for one male participant were not available for analysis. All participants completed a health questionnaire and reported no history of swallowing difficulty, neurological conditions or gastrointestinal disorders. All participants passed a brief oral mechanism examination and swallow screening conducted by a registered
speech-language pathologist prior to acceptance into the study. The study was approved by the local institutional research ethics board.

*Stimulus Characterization*

The nectar-thick liquid chosen for use in this study was a commercially available thickened apple-juice (Resource by Novartis Nutrition, now Nestlé Nutrition, Highland Park, MI). Prior to data collection, samples of this stimulus underwent rheological analysis using an AR 2000 rheometer (TA Instruments, New Castle, DA). Samples were placed on the temperature-controlled testing plate and allowed to equilibrate for 2 minutes prior to analysis. A steady rate sweep test from shear rates of 1–100 s⁻¹ was conducted at body temperature (37°C) using cone-and-plate geometry (cone diameter: 20 mm; angle: 4 degrees; gap: 95 µm). Each sample was tested in triplicate. The results of this testing are displayed in Figure 1. This particular nectar-thick liquid was found to have a density of 1.067 g/cc, and apparent viscosities of 661 mPa.s, 497 mPa.s and 448 mPa.s at shear rates of 25, 50 and 80 reciprocal seconds, respectively. To date, there is no consensus regarding the value of shear rates that operate in the mouth during swallowing; however, it has been common practice in previous literature to use 50 reciprocal seconds as the reference point for comparing the flow of different liquids (Cichero, Hay, Murdoch, & Halley, 1997; Shama & Sherman, 1973; Steele & Cichero, 2008; Steele, van Lieshout, & Goff, 2003).

<< INSERT FIGURE 1 ABOUT HERE >>

*Instrumentation*

Tongue pressure data were collected using a 3-bulb spineless tongue bulb array and the orolingual manometry module of the KayPentax Digital Swallowing Workstation (DSW). The bulb array was attached to the participant’s palate, in midline, using a small amount of dental
Swallow pressures for water and nectar-thick liquids

adhesive (Iso-Dent [Isobutyl Cyanoacrylate], Ellman International Inc., Oceanside, NY). The anterior bulb was attached on the alveolar ridge, directly behind the front teeth; inter-bulb spacing was fixed at 8 mm. Pressure data were acquired at a sampling rate of 250 Hz, using an upper amplitude recording limit of 750 mm Hg.

After an initial period of acclimatization, data collection began with the measurement of static tongue postures and speech tasks (to be described elsewhere). Swallowing task sequences were then included amongst other tongue-palate pressure tasks, in a randomly ordered data collection protocol. Each task sequence involved the reiterated performance of 5 task repetitions. A maximum isometric tongue pressure task with anterior emphasis ("press the front of your tongue up to the front of your palate as hard as you can; repeat this 5 times, with a brief rest between each press") was included as the reference task to allow for subsequent pressure amplitude data transformation. In the case of the swallowing tasks that are reported in this manuscript, the participants were instructed to take 5 comfortably-sized sips of liquid in a row from a cup containing approximately 150 ml of the stimulus liquid. They were instructed to swallow at a comfortable rate, removing the cup from their lips between sips. Prior research from our lab suggests that healthy adults typically take sips of 5-10 ml in volume under these experimental conditions (Bennett, van Lieshout, Pelletier, & Steele, 2009).

Data Processing

Following data collection, the pressure waveforms for each pressure bulb were displayed on a computer monitor. Two trained research assistants indexed the onsets, peaks and offsets in each pressure waveform and extracted amplitude measures for each indexed event. Ten percent of the data were re-analyzed for the purposes of calculating inter-rater agreement, which was high (Cronbach’s alpha = 0.999). At this stage of the analysis, the pressure pattern was coded to
identify the specific bulbs at which pressures were registered, and the sequence of pressure activation across bulbs. The number of peaks recorded at each pressure bulb was also documented. When a pressure waveform event showed several amplitude peaks, these were classified and indexed as multi-peaked events only if the signal dropped back to the zero baseline between apparent peaks (see Figure 2).

Prior to subsequent analysis, each participant’s data for the maximum anterior emphasis isometric swallowing pressure task were examined to identify their maximum isometric swallowing pressure value (in mm Hg) for subsequent amplitude data transformation. The maximum peak pressure value registered at the anterior pressure bulb was used for this purpose, and was assigned a standard value of 600 mm Hg, representing the previously reported norms for maximum isometric pressure in young adults (Nicosia, et al., 2000; Youmans, Youmans & Stierwalt, 2009). All other pressure amplitude data were then transformed relative to this value.

Data processing continued with the calculation of four pressure variables: a) pressure amplitude range for the pressure rise phase (peak minus baseline, in mm Hg); b) pressure amplitude range for the pressure release phase (peak minus offset, in mm Hg); c) pressure rise duration (peak minus onset, in ms); and d) pressure release duration (offset minus peak, in ms). In some cases, more than one pressure peak was identified within a swallowing event, i.e. between the first pressure onset and eventual return to baseline pressure. For these situations, the earliest pressure onset (departure from baseline), latest pressure peak (maximum amplitude) and latest pressure offset (return to baseline) were used for the calculation of pressure measures. In some cases, complete data were only available for 4 of the 5 task repetitions on a particular task. Therefore, mean values for each pressure measure were calculated across the first 4 available
task repetitions performed by each participant for each task. The resulting dataset comprised 38 pressure measure sets for the anterior bulb location, and 37 pressure measure sets each for the medial and posterior bulb locations. These data were then organized by gender and task and the distributions were inspected for outliers, defined as values falling beyond the 95% confidence interval limits for each measure. Missing values and outliers were replaced by the task-specific and gender-specific mean values for that variable.

Analysis

For the description of pressure bulb activation patterns, chi-square analyses were performed with a factor of stimulus (water vs. nectar-thick apple juice). In this analysis there were two levels of inquiry. First, we examined the pressure bulb activation patterns to identify the number of times that the anterior, medial or posterior pressure bulbs registered pressures either in isolation or combination. Second, we examined the frequency with which the pressures registered at each bulb involved absent, single or multiple pressure peaks. For the analysis of pressure variable differences between water and nectar-thick apple juice swallows, repeated measures ANOVAs were performed separately by bulb with factors of gender, stimulus (water, nectar-thick apple juice), and pressure phase (rise, release). Statistical analyses were performed in SAS for Windows, version 9.1 (SAS Institute, Cary, NC). An alpha criterion of $p < 0.05$ was used for all statistical comparisons. Effect size was calculated for all of the ANOVA significant main effects using Cohen’s $d$ (Dunlap, Cortina, Vaslow, & Burke, 1996); effect sizes indexed by this measure can be interpreted as weak ($d = 0.2-0.49$), moderate ($d = 0.5-0.79$) or strong ($d \geq 0.8$), respectively (Kotrlik & Williams, 2003; Levine & Hullett, 2002).
Results

Pressure Bulb Activation Patterns

Inspection of the data revealed 6 different patterns of pressure generation: isolated activation of any one of the three pressure bulbs (anterior, medial or posterior) alone; activation of two bulbs (either anterior-posterior, or medial-posterior); or activation of all three pressure bulbs. Where multiple bulbs were activated, the temporal sequence of activation across bulbs progressed from the front to the back of the mouth in 100% of cases. Activation of all three pressure bulbs occurred in the majority (61%) of the recorded swallowing trials overall, and was significantly more likely to occur on the nectar-thick stimulus (73% of the time) than the water stimulus (49% of the time), $\chi^2 = 9.45$, $df = 1$, $p = 0.002$. Isolated activation of the anterior bulb was rare (4% overall) and was isolated to swallows of the water stimulus (7.5%) ($\chi^2 = 6.24$, $df = 1$, $p = 0.01$). Activations of: a) the anterior and posterior bulbs without activation of the medial bulb (12% overall); b) the medial and posterior bulbs without activation of the anterior bulb (3% overall); c) the medial bulb alone (0.6% overall); and d) the posterior bulb alone (13% overall) did not differ significantly in their rates of occurrence between the two stimuli.

With respect to the number of times that each task elicited no pressure peak, a single pressure peak or multiple pressure peaks at each bulb site (anterior, medial, posterior), chi-square analyses revealed that water swallows were significantly more likely than nectar-thick juice swallows to result in a pressure pattern without any pressure detected at the medial bulb ($\chi^2 = 12.22$, $df = 1$, $p = 0.0005$) or posterior bulb ($\chi^2 = 4.01$, $df = 1$, $p = 0.05$). Chi-square analyses further showed that double-peaked pressure patterns were significantly more likely to occur during nectar-thick juice swallows at the anterior bulb ($\chi^2 = 8.90$, $df = 1$, $p = 0.003$) and medial bulb ($\chi^2 = 7.32$, $df = 1$, $p = 0.007$). Similarly, chi-square analyses showed that triple-peaked
pressure patterns were significantly more likely to occur with nectar-thick juice swallows at the anterior bulb ($\chi^2 = 6.83, df = 1, p = 0.009$) and medial bulb ($\chi^2 = 4.74, df = 1, p = 0.03$).

**Pressure Amplitude Range**

Descriptive statistics for the amplitude range of maximum anterior isometric pressure (transformed vs. a standard within-participant maximum value of 600 mmHg), measured at the anterior pressure bulb are shown in the first two rows of Table 1. Pressure ranges for the swallowing tasks follow, tabulated by bulb and pressure phase (rise, release). Although the pressure values at the individual bulbs were not statistically compared, examination of Table 1 shows that the trend of rising pressure values from the front to the back of the mouth previously reported by Nicosia and colleagues (2000) was only observed for the nectar-thick stimulus.

Statistically significant differences were found in pressure range between the two pressure phases (rise vs. release) at all three bulb locations. In all cases, a greater range of pressure change was measured during pressure rise than during pressure release. However, despite these statistically significant differences, all three findings demonstrated very weak effect size: anterior: $F(1, 34) = 43.06, p < 0.0001, d = 0.04$; medial: $F(1, 32) = 35.07, p < 0.0001, d = 0.12$; posterior: $F(1, 33) = 7.28, p = 0.0109, d = 0.07$. As shown in Figure 3, pressures registered at the medial bulb location were significantly higher in female participants, concurring with the previous findings reported by Youmans, Youmans & Stierwalt (2009), although the effect size was only weak: $F (1, 32) = 8.37, p = 0.0068, d = 0.24$. There were no statistically significant effects of stimulus on pressure range at any bulb location.
Swallow pressures for water and nectar-thick liquids

**Pressure Duration**

Descriptive statistics for pressure phase duration are tabulated by task, phase and gender in Table 2. The durations of pressure events differed significantly at all three bulb locations between the rise phase and the release phase. In all three cases, the pressure rise phase was longer than the pressure release phase (see Figure 4). All three findings had strong effect size:

- **Anterior:** $F(1, 34) = 69.15, p < 0.0001, d = 1.09$;
- **Medial:** $F(1, 32) = 23.23, p < 0.0001, d = 0.95$;
- **Posterior:** $F(1, 33) = 44.11, p < 0.0001, d = 1.22$.

Posteriors pressure bulb event durations were unaffected by participant gender or stimulus. However, a significant difference in the durations of pressure events was detected between genders at the anterior bulb location, with male participants showing longer event durations for both rise and release phases (see Figure 5). Gender (anterior bulb): $F(1, 34) = 18.29, p = 0.0001, d = 0.53$; Stimulus X Gender: $F(1, 34) = 8.08, p = 0.0075$. Significant stimulus differences (and stimulus by direction interactions) were detected for both the anterior and medial bulb locations, with longer rise phases seen for the nectar-thick stimulus: Stimulus (anterior bulb): $F(1, 34) = 24.34, p < 0.0001, d = 0.61$; Stimulus X Direction: $F(1, 34) = 23.01, p < 0.0001$; Direction X Stimulus X Gender: $F(1, 34) = 16.95, p = 0.0002$; Stimulus (medial bulb): $F(1, 32) = 5.29, p = 0.0281, d = 0.45$; Stimulus X Direction: $F(1, 32) = 6.91, p = 0.0130$.

**Discussion**

This study sheds new light on the complexity of tongue pressure modulation across different swallowing tasks. Although the amplitudes of pressures measured using an adhered 3-
Swallow pressures for water and nectar-thick liquids

bulb palatal array did not differ significantly in this study between water swallows and nectar-thick apple juice swallows, we did find statistically significant evidence of other forms of pressure modulation between these two tasks. Most notably, our data suggest that nectar-thick juice swallows engage a larger anatomical area of tongue-palate contact than water swallows, reflected by the significantly higher probability that pressures would be registered at all three palatal bulbs (anterior, medial and posterior) in this study. Furthermore, we observed two probably-related findings indicating that the necessary tongue-palate pressures for bolus propulsion are not achieved as easily for nectar-thick juice swallows as they are for water swallows. Specifically, our participants were more likely to demonstrate pressure rise patterns with multiple peaks at the anterior and medial bulb locations for nectar-thick juice swallows, and the duration of the pressure rise phase at these locations was significantly prolonged for nectar-thick juice swallows compared to that observed for water. Multi-peaked pressure patterns have previously been noted to increase in occurrence in the elderly (Nicosia, et al., 2000), and have been interpreted to reflect greater effort and to be necessary to overcome underlying age-related declines in functional muscle reserve. The degree to which the occurrence of multi-peaked pressure patterns in the elderly interacts with the occurrence of multi-peaked pressure patterns across stimuli of increasing consistency will be an important question for future study.

To our knowledge, this is the first study in which both the rise and release phases of tongue-palate pressures in swallowing have been examined. Our data suggest the intriguing possibility that stimulus-related modulations in pressure might occur in both phases. We examined amplitude and temporal characteristics of the pressure waveforms separately in this study, but the results of our analysis have prompted us to consider a new variable, which we call pressure slope, namely the degree of pressure amplitude change divided by the time required for
that change to occur. Recognizing the possible importance of this variable, we performed a post-hoc examination of pressure slope using the data acquired for the current study, with some very interesting results. Specifically, this analysis revealed a main effect of pressure phase (rise versus release) at all three bulbs, with more rapid changes in pressure seen during the release phase [anterior: $F(1, 34) = 36.43, p < 0.0001, d = 0.91$; medial: $F(1, 32) = 6.48, p = 0.012, d = 0.57$; posterior: $F(1, 33) = 9.97, p < 0.003, d = 0.65$. Additionally, a statistically significant 3-way interaction (Direction X Gender X Stimulus) was found for pressures registered at the anterior bulb, $F(1, 34) = 4.48, p < 0.0417$, with male participants showing a more gentle rise phase for nectar-thick liquids than for water, but a steeper (more rapid) drop in pressure for nectar-thick liquids than water during the release phase (see Figure 6). Interestingly, the female participants in this study did not modulate pressure slope between the two stimuli tested. It is tempting to speculate that a slow release of pressure, with a gentle slope, might afford greater control of bolus flow for thin liquids. Further exploration of this phenomenon will be necessary to determine whether pressure slope is graded in a linear fashion according to bolus flow properties, and whether there are slope-related limits or thresholds at which the physiology of oral bolus transport switches to the patterns more commonly seen for solid boluses, whereby processed portions of the bolus accumulate in the valleculae prior to the pharyngeal swallow (Hiiemae & Palmer, 1999).

One possible limitation to this observation arises from the fact that pressure release in this study was shown to be significantly smaller in range (mm Hg) than pressure rise. The offset of pressure was indexed as the place in the waveform where pressure returned to a steady baseline value. It is, therefore, somewhat surprising to discover that the pressure range measured during
the rise phase was significantly larger than that measured during release, although the observed
effect size was weak. Whether this phase difference in pressure ranges reflects some sort of delay
in pressure bulb re-inflation following the release of peak pressure needs to be clarified.

In summary, then, we have demonstrated that tongue pressure modulation does occur
between swallows of water and a nectar-thick stimulus with a viscosity in the range of 500 mPa.s
(@ 50 s$^{-1}$). This modulation is not evident in pressure amplitudes, but rather in the pattern and
time course of pressure generation. Previous studies have failed to demonstrate modulations in
other aspects of swallowing physiology between these two same stimuli (Steele & van Lieshout,
2004b) or between similar stimuli (Chi-Fishman & Sonies, 2002). The current data lend further
support to the idea that swallowing physiology may be modulated to match fairly small
differences in bolus consistency, and suggest that modulations of the interaction between
movement amplitudes and the time-scale in which movements are performed may be of
particular importance.
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Swallow pressures for water and nectar-thick liquids 22

References


Swallow pressures for water and nectar-thick liquids


Doctoral dissertation, University of Wisconsin-Madison, Madison, WI.


Figures and Tables

Figure Captions

Figure 1. Rheogram for the nectar-thick liquid stimulus used in this study, plotting viscosity as a function of shear rate.

Figure 2. Three examples of tongue pressure waveforms. The top signal, acquired from the anterior pressure bulb, is an example of a single-peaked pressure event. The bottom signal, acquired from the posterior pressure bulb, is an example of a multi-peaked pressure event in which the waveform dipped down to the zero amplitude level in between two successive pressure peaks for a single swallow. The middle signal, acquired from the medial pressure bulb, is an example of a pressure event in which there were two apparent peaks, but the waveform did not dip down to the zero amplitude level between peaks. In this case, the entire event was captured as a single-peaked pressure event, with the highest amplitude peak representing the transition between pressure rise and release phases.

Figure 3. Mean values for pressure range (maximum amplitude minus minimum amplitude, in mm Hg) during discrete swallows of water and nectar-thick liquid, shown by pressure bulb location (anterior, medial and posterior), pressure phase (rise, release) and gender. The error bars represent standard deviations. Female participants had larger pressure ranges than male participants on all bulbs, with this difference reaching statistical significance ($p < 0.05$) at the medial pressure bulb location.
Figure 4. Mean values (with standard deviations shown by the error bars) for the duration (in seconds) of tongue-palate pressure events during discrete water and nectar-thick liquid swallows, shown by pressure bulb location (anterior, medial, posterior) and pressure phase (rise, release). Pressure rise phases were significantly longer ($p < 0.05$) than release phases.

Figure 5. Means and standard deviations (shown by the error bars) for the duration (in seconds) of anterior and medial tongue-palate pressure events during discrete swallows, shown by pressure phase (rise, release), gender and stimulus (water, nectar-thick juice). Male participants had significantly longer pressure event durations than female participants ($p < 0.05$). Rise phase durations were significantly longer with the nectar-thick juice stimulus ($p < 0.05$).

Figure 6. Means and standard deviations (shown by the error bars) for pressure slope (change in pressure amplitude, divided by pressure phase duration, in mm Hg/s) are shown for pressures registered at the anterior bulb during discrete swallows of water and nectar-thick juice. Slopes were significantly steeper (i.e., more rapid change) for the release phase compared to the rise phase ($p < 0.05$). Male participants showed a more gradual pressure rise and a more rapid pressure release for the nectar-thick juice stimulus ($p < 0.05$).
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Table 1.

*Descriptive Statistics for Pressure Amplitude Range (in mm Hg) by Task, Bulb, Phase (Rise vs. Release) and Gender*

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Table 2.

*Descriptive Statistics for Pressure Phase Duration (in milliseconds) by Task, Bulb, Phase (Rise vs. Release) and Gender*

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