Does Barium Influence Tongue Behaviors During Swallowing?

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The validity of videofluoroscopic swallowing assessments rests on the understanding that thin, nectar-, honey-, and spoon-thick radio-opaque liquids resemble nonopaque liquids, both in their consistency and in the variations in swallowing that they elicit. Tongue movements during sequential swallows of opaque and nonopaque liquids were studied in 8 healthy participants in 2 age groups (<30 years, >50 years) using electromagnetic midsagittal articulography. Differences included smaller sip size, longer oropharyngeal transit times, and greater variability in tongue movement patterns with opaque liquids compared to nonopaque liquids, but effect sizes for these differences were small. Transit times were significantly longer for older participants than younger participants. We recommend matching radio-opaque bolus size in videofluoroscopy to the patient’s habitually preferred sip mass for comparator nonopaque liquids.

Key Words: swallowing, dysphagia, videofluoroscopy, barium, tongue

Videofluoroscopy is considered the gold-standard instrumental assessment technique for oropharyngeal dysphagia (American Speech-Language-Hearing Association, 2004; Logemann, 1997). In this procedure, radiopaque contrast media are prepared to resemble liquids and foods of different consistencies, and the media are administered to the patient to observe his or her swallowing function. Interpretation of a videofluoroscopic examination is based on the assumption that any functional differences observed between thin and nectar-, honey-, or spoon-thick radiopaque boluses mirror differences that occur outside the testing situation between nonopaque liquids of thin, nectar-, honey-, and spoon-thick consistencies. Previous authors have reported that opaque assessment products differ from nonopaque products both in density and viscosity (Li, Brasseur, Kern, & Dodds, 1992; Mills, 2000; Robbins et al., 2002). This information suggests that speech-language pathologists need to understand the degree to which swallows of contrast media represent swallows of nonopaque stimuli that occur outside the videofluoroscopic testing environment. Given the importance of the tongue in both the oral propulsive and pharyngeal phases of swallowing, it seems reasonable to expect that any differences in swallowing that occur between opaque and nonopaque products should be visible in tongue behaviors. Therefore, the intent of the present investigation was to identify and describe differences in tongue behaviors between swallows of opaque and nonopaque liquids in a small sample of healthy volunteers.

Protocols for videofluoroscopic swallowing assessment typically involve a variety of liquid consistencies, including thin, nectar-thick, and honey-thick liquids, administered in calibrated volumes, beginning with 1 cc and increasing to 3, 5, and 10 cc and larger volumes as tolerated by the patient (Logemann, 1997). Previous comparisons have shown that swallows of radiopaque paste-consistency stimuli elicit increased oral and pharyngeal transit times compared to swallows of opaque thin-liquid stimuli. Similarly, longer durations of tongue base to posterior pharyngeal wall contact, pharyngeal peristaltic waves, and pharyngoesophageal segment opening have been reported with paste-consistency opaque stimuli (Bisch, Logemann, Rademaker, Kahrilas, & Lazarus, 1994; Dantas, Dodds, Massey, & Kern, 1989; Dantas et al., 1990; Lazarus et al., 1993). Other researchers have observed increases in the diameter of pharyngoesophageal segment opening (Dantas et al., 1989, 1990; Lazarus et al., 1993) and in the vertical and horizontal displacements of the
hyoid for paste barium compared to liquid barium swallows (Perlman, Vandaele, & Otterbacher, 1995). In light of these reported effects of bolus consistency, it is important that studies of the influence of bolus opacity on swallowing include liquids of different consistencies.

To evaluate the influence of bolus opacity on tongue control during swallowing, a technique that is sensitive to swallowing behaviors but that does not require the use of contrast media must be used. In our laboratory, we are currently using a nonradiographic technique, electromagnetic midsagittal articulography (EMMA), to study tongue, jaw, and lip movements during swallowing (Steele, 2003; Steele & van Lieshout, 2004). Hyoid movements have been shown to be more variable in discrete (i.e., single swallows) than in repeated sequential swallowing (Chi-Fishman & Sonies, 2000, 2002). Because our interest is in identifying systematic but potentially subtle variations in oral motor behaviors in swallowing as a function of bolus characteristics, it is important to minimize other sources of variability in swallowing behaviors. For this reason, we have chosen to study tongue movements in the context of sequential swallowing, which has been shown to elicit less variable movement patterns than discrete swallowing (Chi-Fishman & Sonies, 2000, 2002; Steele, 2003). Reported here are the results of an EMMA study of differences in tongue behaviors between swallows of opaque and nonopaque liquids of thin, nectar-thick, and honey-thick consistency in healthy participants. Available data on within-subject variability in swallowing behaviors across sessions are sparse due to the risks inherent in repeating radiographic measurements in participants. The EMMA technique allows us to safely observe swallowing on multiple occasions and capture natural variation in performance of the same task across sessions. Therefore, in order to observe and control for normative performance variation in swallowing behaviors across sessions, the data for this study were collected over two sessions per participant, with at least 1 week separating the two sessions. In light of previous observations of greater variability in durational aspects of swallowing among older participants (Lof & Robbins, 1990; Sonies, 1992; Sonies, Baum, & Shawker, 1984), we decided to study both young and older individuals.

Method

Participants

Eight adults, ranging in age from 23–69 years and with no history or complaints of neurological impairment or swallowing difficulty, volunteered for participation in the study. Participants were recruited in two age groups: 4 participants were in a younger age group (range = 23–29 years), and 4 were in an older age group (range = 50–69 years). Gender distribution was balanced within each age group to avoid any potential bias and in line with Canadian ethical guidelines (Medical Research Council of Canada, 1998). All participants provided informed consent to participate and completed a brief medical history questionnaire. The first author, a registered speech-language pathologist, performed an oral-mechanism and motor-speech examination to screen each participant for signs of speech motor or swallowing abnormalities prior to acceptance into the study. Data from these same participants have been reported elsewhere for discrete water swallows (Steele, 2003; Steele & van Lieshout, 2004).

Materials

Three nonopaque liquids were selected for study. These included regular tap water and nectar- and honey-thick apple juice (both Resource Thickened Apple Juice from concentrate, Foodservice, Novartis Nutrition). At the time of data collection, commercially prethickened contrast media were not available in Canada; therefore, standardized recipes were used to prepare opaque thin, nectar-thick, and honey-thick stimuli using E-Z-HD barium sulfate powder (E-Z-EM Therapex). The opaque comparator for water was a barium-sulfate suspension, mixed according to the manufacturer’s instructions for gastrointestinal imaging (340 g powder mixed with 65 cc of water to yield 135 cc of 85% w/w, 250% w/v suspension). Radiopaque comparator liquids for the nectar- and honey-thick juices were prepared by mixing the nonopaque products in a 4:1 ratio with E-Z-HD powder (i.e., 15 cc powder to 60 cc thickened liquid). Rheological profiling to objectively characterize the consistency of the test liquids was completed for all products at 22 °C on a Carri-Med Controlled Stress CSL Rheometer. Detailed descriptions of the rheological testing procedure have been reported previously (Steele, van Lieshout, & Goff, 2003). As shown in Table 1, the opaque liquids differed from their base comparators in characteristics of increased density (i.e., mass per unit volume), increased viscosity (i.e., a measure of the intrinsic ability of a fluid to resist flow under force that is quantified as the ratio of shear stress to shear rate; see Bourne, 1982; Rao, 1992; Tung & Paulson, 1995), and increased yield stress (i.e., the minimum shear stress threshold that must be exceeded before flow occurs; see Tung & Paulson, 1995). It is important to note that the relative rheological differences between the opaque and nonopaque liquids were much greater for the thin-liquid stimuli than for the thickened liquids.

Apparatus and Procedure

The EMMA technique measures movement of midsagittal fleshpoint positions on the tongue, jaw, and lips with high temporal and spatial accuracy, using alternating electromagnetic fields. It provides data that are directly comparable to those obtained using the X-ray microbeam system (Byrd, Browman, Goldstein, & Honorof, 1999; Martin, 1991; Steele & van Lieshout, 2004; Tasko, Kent, & Westbury, 2002). This technique has been extensively used and validated in studies of oral articulatory movements during the production of speech (e.g., Engelke, Schöne, Kring, & Richter, 1989; van Lieshout, Alfonso, Hulstijn, & Peters, 1994; van Lieshout, Rutjens, & Spaunen, 2002) but has only recently been reported for the study of swallowing (Steele, 2003; Steele & van Lieshout,
referred to as the posterior to the anatomical tongue tip; this location will be the most anterior of these three coils was located 10 mm cement (Durelon, Espe Dental AG). As shown in Figure 1, tional Manufacturing) and zinc polycarboxylate dental surgical methacrylate resin (Cyanodent, Ellman Interna-
dorsal surface of the tongue using a combination of study, coil-position data were acquired at 400 Hz. determination of the location of each coil. For the present distance between the transmitter and the transducer is alternating voltage is induced in the transducer. The alternating magnetic field inside the helmet. When a Three transmitters attached to this helmet generate an (62 cm in diameter) that was suspended from the ceiling. With the tongue extended with his or her head positioned inside a large plastic helmet positioned an average of 24.06 ± 7.37 mm posterior to the tongue blade coil. A fourth coil was attached to the mandibular incisors, using a custom thermoplastic dental impression; this allowed for measurement of jaw movement and corrections of the tongue coil data for jaw contributions. Four additional transducer coils were attached in midline to the nose, the vermilion borders of the upper and lower lip, and the gums of the upper central incisors to provide reference data (see Figure 1). Time-locked measurements of the acoustics of swallowing (see the top bar on Figure 2) were acquired at 16 kHz using a nonmetallic Littman Cardiology II stethoscope head, connected to a small microphone and secured around the neck with a Velcro strap. The stethoscope head was positioned on the left neck, just inferior to the thyroid lamina (Cichero & Murdoch, 1998; Hamlet, Nelson, & Patterson, 1990; Perlman, Ettema, & Barkmeier, 2000).

### TABLE 1. Rheological and material properties of radiopaque and nonopaque comparator liquids.

<table>
<thead>
<tr>
<th>Consistency class</th>
<th>Item</th>
<th>Density (g/cc)</th>
<th>Yield stress (Pa)</th>
<th>Viscosity (centipoise) for shear rate ranges of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>Water</td>
<td>0.993</td>
<td>0</td>
<td>18 15</td>
</tr>
<tr>
<td>Nectar-thick</td>
<td>Thin barium suspension⁴</td>
<td>2.54</td>
<td>0.338</td>
<td>377 351</td>
</tr>
<tr>
<td></td>
<td>Nectar-thick apple juice⁴</td>
<td>1.067</td>
<td>0.264</td>
<td>667 466</td>
</tr>
<tr>
<td>Honey-thick</td>
<td>Opaque nectar-thick apple juice⁴</td>
<td>1.15</td>
<td>1.055</td>
<td>1,242 863</td>
</tr>
<tr>
<td></td>
<td>Honey-thick apple juice⁴</td>
<td>1.073</td>
<td>1.424</td>
<td>1,774 1,140</td>
</tr>
<tr>
<td></td>
<td>Opaque honey-thick apple juice⁴</td>
<td>1.13</td>
<td>2.109</td>
<td>2,265 1,541</td>
</tr>
</tbody>
</table>

⁴E-Z-HD barium sulfate suspension, 85% w/w, 250% w/v (E-Z-EM Therapex).

Because the focus is on articulatory movement rather than bolus transit, the EMMA procedure does not require the use of radiopaque contrast media; indeed, bolus visualization is not possible. EMMA does not involve gamma radiation exposure and therefore permits collection of substantial amounts of data over extended and repeated sessions in individual participants (Hasegawa-Johnson, 1998; Wright, Boyd, & Workman, 1998). The ability to collect a substantial corpus of swallowing data without requiring the use of contrast media made the EMMA technique ideal for exploring differences in tongue movements between opaque and nonopaque liquids.

The participant was seated comfortably in a dental chair with his or her head positioned inside a large plastic helmet (62 cm in diameter) that was suspended from the ceiling. Three transmitters attached to this helmet generate an alternating magnetic field inside the helmet. When a transducer coil is placed inside this magnetic field, an alternating voltage is induced in the transducer. The distance between the transmitter and the transducer is directly related to the amplitude of the signal induced in the transducer (Schönle et al., 1987), allowing precise determination of the location of each coil. For the present study, coil-position data were acquired at 400 Hz.

Three transducer coils were attached in midline to the dorsal surface of the tongue using a combination of surgical methacrylate resin (Cyanodent, Ellman International Manufacturing) and zinc polycarboxylate dental cement (Durelon, Espe Dental AG). As shown in Figure 1, the most anterior of these three coils was located 10 mm posterior to the anatomical tongue tip; this location will be referred to as the tongue blade. With the tongue extended from the mouth, a ruler was used to mark the target location for the second coil, 30 mm posterior to the tongue blade coil. Subsequent electromagnetic measurements of coil location taken with the tongue held at rest inside the mouth showed this middle coil (tongue body) to be positioned an average of 24.06 ± 4.4 mm posterior to the first coil. The most posterior coil was attached as far back as tolerated by the participant; subsequent electromagnetic measurement of coil location determined the location of this tongue dorsum coil to be an average of 37.14 ± 7.37 mm posterior to the tongue blade coil. A fourth coil was attached to the mandibular incisors, using a custom thermoplastic dental impression; this allowed for measurement of jaw movement and corrections of the tongue coil data for jaw contributions. Four additional transducer coils were attached in midline to the nose, the vermilion borders of the upper and lower lip, and the gums of the upper central incisors to provide reference data (see Figure 1). Time-locked measurements of the acoustics of swallowing (see the top bar on Figure 2) were acquired at 16 kHz using a nonmetallic Littman Cardiology II stethoscope head, connected to a small microphone and secured around the neck with a Velcro strap. The stethoscope head was positioned on the left neck, just inferior to the thyroid lamina (Cichero & Murdoch, 1998; Hamlet, Nelson, & Patterson, 1990; Perlman, Ettema, & Barkmeier, 2000).

### Data Collection Protocol

Prior to the collection of swallowing movement data, 10 speech and nonspeech oral movement tasks were performed for the purposes of collecting baseline static and dynamic position measurements. These included an occlusal plane measurement, which was taken from two transducer coils, mounted with 3 cm separation on a plastic bite plate (Martin, 1991; Westbury, 1994). For each swallowing task, the participant was handed a container of liquid and instructed to perform a series (trial-set) of eight repeated swallows of the liquid in a sequential manner (i.e., without removing the container from the lips between swallows). There was no requirement to complete all eight swallows on a single breath, although this was generally the case. The liquid vessel was weighed on a digital scale immediately prior to and following each trial-set, to permit calculation of average sip size.

The data for this experiment were collected as part of a larger investigation, for which session-to-session variability in swallowing behaviors was also a phenomenon of
FIGURE 1. Electromagnetic midsagittal articulography (EMMA) transducer coil positions. During EMMA studies of swallowing, transducer coils are attached in midline to the fleshpoint positions shown in the diagram. Reference coils are denoted by the letter R.

Data Processing and Event Indexing

The procedures used for EMMA data processing have been described elsewhere (Steele & van Lieshout, 2004). Following filtering and processing, the data were rotated to align them with the horizontal axis of the EMMA measurement field (Westbury, 1994), and tongue coil signals were corrected for jaw contribution using an estimate of jaw rotation, based on the principal component of the mandible transducer coil trajectory for each trial (Westbury, Lindstrom, & McClean, 2002). An automated peak-picking algorithm was used to detect the onset and offset (peaks and valleys) of directional changes in the position signals (Steele & van Lieshout, 2004) using the cyclic spatiotemporal index (cSTI) procedure described below. Figure 2 illustrates the positional minima (valleys, i.e., downward pointing open triangles) and maxima (peaks, i.e., upward pointing open triangles) identified for a single trial-set using this procedure.

Variables

We were interested in identifying any differences in swallowing behaviors that occurred as a function of bolus opacity. Dependent variables of interest included sip size (i.e., both sip mass and sip volume), swallowing transit times, the variability of the spatiotemporal pattern of tongue movement (measured using the cSTI), and kinematic parameters of tongue movement (amplitude, peak velocity, and duration) and their variability. For the kinematic analyses, two segments of the tongue movement pattern (anterior and downward) were extracted for analysis, based on previous literature relating these movements to specific phases within the swallow. Anterior tongue movement has been associated with posterior squeezing of the bolus during the oral propulsive phase (Chi-Fishman & Sonies, 2000, 2002; Martin, 1991; Palmer, Rudin, Lara, & Crompton, 1992). Downward tongue movement has been associated with the pharyngeal phase of the swallow (Martin, 1991; Steele, 2003), we decided to narrow the focus of this investigation to movements of the two posterior tongue transducer coils (tongue body and tongue dorsum).

Sip size. Two measures of sip size were studied: average sip volume and average sip mass. Sip volume (in cubic centimeters) has been the conventional method of reporting sip size in the swallowing literature (Adnerhill, Ekberg, & Groher, 1989; Hamlet et al., 1996). For this investigation, sip mass (i.e., weight in grams) was also considered a variable of interest due to the recognition of large differences in bolus density between opaque and nonopaque liquids (Table 1; see Li et al., 1992). For each measure, a single average value was calculated for each trial-set. Average sip size values were calculated as the total amount (volume or mass) extracted from the cup over the trial-set and dividing this value by the number of sips (eight) in the trial-set.

Swallow transit times. Previous data have shown that the sequence of oral articulatory movement in swallowing is usually led by the mandible or tongue blade and concludes with movement of the tongue dorsum (Steele, 2003). Therefore, for any single trial-set, the total trial-set duration was measured as the difference (in seconds) between the first zero-crossing in the time history of the vertical movement trace for the leading transducer coil (i.e., the beginning of the oral phase) and the last zero-crossing in the time history of the dorsum transducer coil vertical movement trace. This total duration was then divided by the number of swallows in the trial-set (eight) to provide an estimate of average duration (oropharyngeal transit time) for each swallow in the sequential series.

Spatiotemporal movement pattern variability (cSTI). The movement data were divided into movement cycles, with each cycle defined as a single set of approach and return movements within a plane of movement (vertical or horizontal), falling between any two contiguous position minima, as defined above (see Figure 2). The overall variability of the spatiotemporal pattern of cyclic movement within each plane was measured using the cSTI measure (van Lieshout et al., 2002), based on the STI measure developed by Smith and colleagues (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Smith, Johnson, McGillem, & Goffman, 2000). To calculate cSTI, individual movement cycles were extracted, amplitude-normalized, and
then time-normalized, such that coil position at any point in the cycle could be expressed as a percentage function of the total range of amplitude observed in the movement cycle, at a time point relative to the overall duration of the movement cycle. Successive movement cycles can thus be overlapped within a common time and amplitude frame. Each normalized movement cycle was then divided equally into 50 segments in relative time, each representing 2% of the overall cycle duration. At each 2% bin, a standard deviation measure was calculated, to capture positional variability across the corresponding parts of each movement cycle for a given transducer coil in a given plane of movement. The cSTI is defined as the sum of the standard deviations. For example, if all successive cycles, once normalized for amplitude and duration, have exactly the same pattern, they would show perfect overlap and zero variability at each 2% bin. Higher cSTI values reflect greater spatiotemporal pattern variability across successive individual movement cycles within a trial-set. Previous researchers have used this variable to describe articulatory movement variability in speech (van Lieshout et al., 2002). During reiterated production of the bisyllable “api,” normal participants have been reported to have upper lip and lower lip cSTI values of 8.27 ± 1.62 and 11.25 ± 2.33, respectively. Higher cSTI values (upper lip: 22.65 ± 3.35; lower lip: 24.27 ± 2.5) were reported for the same participants during production of the phrase “Bobby brings bananas to Dad” (van Lieshout et al., 2002). Our own preliminary research suggests that spatiotemporal variability for tongue movements in swallowing is similar to that seen during phrase production, with values for discrete water swallows in healthy young participants falling in the range of 29.05 ± 3.35.
6.23 and 22.89 ± 6.4 for the tongue body and tongue dorsum, respectively (Steele, 2003).

**Direction-specific kinematic parameters.** The waveform data for each movement cycle were further subdivided into approach (i.e., minimum position to subsequent maximum position) and return (i.e., maximum position to subsequent minimum position) phases of movement, resulting in direction-specific segments of movement data (up, down, anterior and posterior). From these data, the anterior and downward segments of tongue body and tongue dorsum movement were extracted for further analysis, based on their reported relationships to the oral propulsive and pharyngeal phases of swallowing (Palmer et al., 1992). For these segments, three kinematic measurements were derived, as illustrated in Figure 2: amplitude (in millimeters), peak velocity (in millimeters per second), and duration (in milliseconds). For each trial-set, mean values were calculated for each kinematic parameter across the direction-specific movement segments in the trial-set. Additionally, for each kinematic variable, the direction-specific standard deviation for each trial-set was calculated as a measure of within-trial-set variation.

**Statistical Analyses**

The statistical analyses were performed in Number Cruncher Statistical System (NCSS) 2001 software (Hintze, 2001). Mixed-model repeated measures analyses of variance (ANOVAs) were used with a between-subject factor of cohort (2) and within-subject factors of opacity (2), consistency (3), and session (2), with subject used as the blocking variable. The alpha level for statistical significance was set at $\alpha = .05$. When multiple comparisons were performed across the different transducer coils and movement directions, Bonferroni corrections were applied to the alpha criterion (Stevens, 2002). A correction of $\alpha = .05/4$ (i.e., two coil positions × two planes of movement) = .013 was applied for the orientation-specific analysis of the cSTI data. For the kinematic analyses, additional corrections were warranted in recognition of expected correlations between the amplitude and peak velocity variables (Munhall, Ostry, & Parush, 1985). Therefore, a correction of $\alpha = .05/8$ (i.e., two coil positions × two movement directions × two groups of independent variables) = .006 for the direction-specific analyses of movement amplitude, peak velocity, and duration. Box’s $M$ and Mauchly tests were conducted for all ANOVA results, to identify any violations of the assumptions of homogeneity of variance, covariance matrix circularity, and compound symmetry. Wherever violations of these assumptions were detected, the Huynh-Feldt epsilon corrected alpha levels are reported below and denoted using the convention $p^{\text{HF}}$. Effect sizes are reported for statistically significant findings using Cohen’s $d$ standardized effect size, which is calculated as the difference in group means divided by the pooled standard deviation (Dunlap, Cortina, Vaslow, & Burke, 1996). Effect size can be interpreted as strong for $d$ values of 0.8 or higher, moderate for $d = 0.5–0.79$, and weak for $d = 0.2–0.5$ (Kotrlik & Williams, 2003; Levine & Hullett, 2002).

**Results**

**Sip Size**

Means and standard deviations for sip volume and sip mass are shown by cohort, consistency, and opacity in the upper and lower panels of Figure 3, respectively. Notably, the upper 95% confidence interval boundary for thin-liquid sip volume was between 8 and 10 cc, with smaller volumes observed for all other items (range = 4–7.5). Minimum sip volumes by cohort were 1 cc for thin-liquid barium swallows in the older cohort and 2 cc for nonopaque nectar-thick liquids in the younger cohort. A repeated measures ANOVA with a between-subjects factor of cohort (2) and within-subjects factors of opacity (2), consistency (3), and session (2) was first performed on the variable of sip volume. A significant Consistency × Opacity interaction was observed for sip volume, $F(2, 12) = 6.73, p^{\text{HF}} = .01, d = 0.92$, with larger sip volumes seen for nonopaque in comparison to opaque liquids, and this difference being greater for the thin liquid than for the nectar- and honey-thick consistencies. Although Figure 3 shows that the older participants generally took sips of smaller volume, no statistically significant differences in sip volume were found between the two cohorts of participants, and there were no significant session effects.

Sip size modulation was further investigated using a repeated measures ANOVA of sip mass with a between-subjects factor of cohort (2) and within-subjects factors of opacity (2), consistency (3), and session (2). A significant Opacity × Consistency interaction with moderate effect size was observed, $F(2, 12) = 5.28, p^{\text{HF}} = .03, d = 0.78$, with post hoc Tukey-Kramer tests showing greater sip mass with thin compared to thickened liquids, and this difference being more marked for the opaque liquids. Interestingly, a significant main effect of opacity was not found for sip mass, in contrast to the pattern observed for sip volume. As with sip volume, no statistically significant cohort or session effects were observed, despite the observation of consistently smaller sip mass values for older participants across different bolus types.

**Swallow Transit Times**

Means and standard deviations for swallow transit times are shown by cohort, consistency, and opacity in Figure 4. It is noteworthy that maximum values for swallow transit times in the younger participants fell close to 2 s, because a 2-s value has been proposed by Logemann (1997) to be the upper limit of normal transit time duration for the combined oral and pharyngeal phases of swallowing. A repeated measures ANOVA with a between-subjects factor of cohort (2) and within-subjects factors of opacity (2), consistency (3), and session (2) identified no statistically significant session effects. A very strong main effect of cohort was observed, $F(1, 6) = 11.14, p = .016, d = 1.35$, with longer transit durations seen in the older participants. Significant but weaker main effects were also observed for opacity, $F(1, 6) = 17.99, p = .005, d = 0.45$, and consistency, $F(2, 12) = 9.94, p = .003, d = 0.31$. These differences took the form of longer transit durations for the
opaque liquids compared to nonopaque liquids, and for the honey-thick consistency compared to the nectar-thick and thin liquids, as shown in post hoc Tukey–Kramer analyses. No significant interactions were observed.

**Spatiotemporal Variability**

Repeated measures ANOVAs for the cSTI variable were performed separately by transducer coil and movement orientation with a between-subjects factor of cohort (2) and within-subjects factors of opacity (2), consistency (3), and session (2). As shown in Table 2 and Figure 5, statistically significant but weak effects were observed only in the vertical direction of movement for both transducer coils. These included greater spatiotemporal variability in vertical tongue dorsum movements for the older participants, significantly higher cSTI values with the opaque liquids for vertical movement of both the tongue and tongue dorsum, and higher cSTI values for vertical tongue dorsum movements with honey-thick compared to nectar-thick liquids. No significant session effects or interactions were observed.

**Kinematics**

Univariate repeated measures ANOVAs with a between-subjects factor of cohort (2) and within-subjects
factors of opacity (2), consistency (3), and session (2) were performed on trial-set mean and within-trial-set variation kinematic data (amplitude, peak velocity, and movement duration) for both anterior and downward movements of the tongue body and tongue dorsum. Statistically significant findings are tabulated in Table 2. Significant main effects of opacity were not observed for mean trial-set values but were seen in the form of greater within-trial-set variation with opaque liquids for the peak velocity of downward tongue body movement and the duration of downward tongue dorsum movement. Modest significant main effects of consistency were seen in the trial-set means for the amplitude of downward tongue body movement with post hoc Tukey–Kramer analyses identifying larger movement amplitudes for the thin consistency than for either the nectar- or honey-thick consistency. A significant but weaker Consistency × Opacity interaction was found for the duration of anterior tongue dorsum movement, but post hoc Tukey–Kramer analyses failed to identify any significant pairwise contrasts. Similarly, a weak but significant effect of consistency was observed for within-trial-set variation in the durations of downward tongue dorsum movement, but post hoc tests again failed to identify significant differences for paired comparisons of

TABLE 2. Analysis of variance results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Transducer coil</th>
<th>Movement direction</th>
<th>Effect</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>Effect size (d)</th>
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<td>cSTI</td>
<td>Tongue body</td>
<td>Vertical</td>
<td>Opacity</td>
<td>1, 6</td>
<td>16.11</td>
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<tr>
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<td>Tongue dorsum</td>
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<td>Trial-set mean</td>
<td>Tongue body</td>
<td>Downward</td>
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<td>Trial-set mean</td>
<td>Tongue dorsum</td>
<td>Anterior</td>
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<td>12.8</td>
<td>.012</td>
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<td>Within-trial-set</td>
<td>Tongue body</td>
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<td>Duration</td>
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<td>.004</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tongue body</td>
<td>Consistency × Opacity</td>
<td>1, 6</td>
<td>17.22</td>
<td>.006</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tongue dorsum</td>
<td>Session</td>
<td>2, 12</td>
<td>6.92</td>
<td>.01</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Note. cSTI = cyclic spatiotemporal index.
*Huynh-Feldt epsilon corrected value.
the three different consistency levels. Significantly greater within-trial variation was observed in the duration of anterior tongue body movements in the first of the two data collection sessions, while a weak but statistically significant Session × Cohort interaction was found in the mean peak velocities of anterior tongue dorsum movement, reflecting a greater increase in peak velocity values from the first to the second session in the younger participant group. Significant main effects of cohort were not observed in any of the analyses performed.

Discussion

The current study explored differences in tongue movements during swallowing between opaque liquids and the nonopaque liquids they are assumed to resemble. Overall, the results of this investigation are encouraging for clinicians, given that minimal differences were observed in the actual kinematics of anterior and downward tongue movements across liquids with and without contrast media. However, a number of interesting differences were identified between opaque and nonopaque swallows, and these require consideration for the conduct and interpretation of future videofluoroscopic swallowing examinations. These differences will now be discussed under the headings of sip size, spatiotemporal variability and aging.

Sip Size

Sip size was not experimentally controlled in the present study but was measured after each trial-set by dividing the volume of liquid extracted from the vessel by...
The number of swallows performed. Using this procedure, we observed minimal differences in tongue movements between opaque and nonopaque stimuli. However, it remains unknown whether greater differences in tongue behaviors for swallowing, including differences at the level of kinematics for direction-specific movement segments, would emerge if the present investigation were repeated using identical, calibrated sip volumes across items. Traditionally, sip volume has been calibrated and controlled during videofluoroscopic swallowing assessments. Bolus volume is then incrementally increased (in the range of 1–30 cc), contingent on the patient demonstrating functional swallowing for smaller volumes (American Speech-Language-Hearing Association, 2004; Logemann, 1997). Once a range of increasing, controlled bolus volumes has been assessed, clinicians will often hand the patient a cup and evaluate the swallow under free-drinking conditions. In the present study, the lower limits on natural sip volume were in the range of 1–3 cc for the older participants, but higher (2–6 cc) for the younger participants. This suggests that the small volumes (1–3 cc) that are traditionally administered at the beginning of a videofluoroscopic examination may elicit representative behaviors in older individuals but may require modification with younger patients.

The sip-sizing procedures used in this study differ distinctly from the syringe-delivered calibrated volume procedure employed in previous swallowing research (Chi-Fishman, Stone, & McCall, 1998; Martin, 1991; Stone & Shawker, 1986; Tasko et al., 2002) and from recommended clinical procedures for videofluoroscopy (Logemann, 1997). However, similar procedures have been used by others, with comparable results (Daniels & Foundas, 2001). Clearly the method used to measure average sip size does not permit precise determination of sip size for each swallow within the series. Nevertheless, the participants in this study have been shown to be remarkably consistent in average sip size for specific liquids, both across trials within a session, and across data collection sessions on different days (Steele, 2003). Additionally, as reported elsewhere, no significant differences in average sip size were seen for these same participants in a comparison of sequential and discrete series of swallowing (Steele, 2003). This suggests that it is possible to generalize the conclusions of the present investigation to discrete swallowing tasks, such as those used commonly in videofluoroscopy.

Our decision to allow natural sip sizing in the present investigation led to the unexpected finding that participants systematically downscaled the volume of liquid taken in each sip when drinking radiopaque products. Given that our analysis did not reveal a significant opacity effect for the sip mass variable (which takes differences in the density of opaque and nonopaque liquids into account), this suggests the possibility that participants may have been striving for a preferred range of sip mass in their sip-sizing behaviors. Based on this observation, we propose that procedural planning of videofluoroscopy should take patients’ preferred sip mass into consideration. Specifically, we suggest that radiopaque boluses should be calibrated in size to match the mass (in grams), rather than the volume, of the nonopaque boluses they are intended to represent. If the clinician wishes to evaluate swallowing function for a 5-cc thin-liquid bolus, we propose that the appropriate volume of thin-liquid barium suspension to evaluate this task would be one that weighs the same as a 5-cc volume of water. Using the density values obtained for stimuli administered in the present investigation (Table 1), this would translate to a targeted stimulus mass of 5 g and thin-liquid barium bolus of 2 cc. In the present study, mean sip mass for a nonopaque nectar-thick liquid bolus in the younger participant cohort was 4.2 g. If a clinician wished to match a radiopaque nectar-thick stimulus to this targeted sip mass using an opaque nectar-thick stimulus similar to the one used in the present study (4:1 ratio of nectar-thick juice to barium powder), this would translate to a targeted opaque sip volume of 3.65 cc.

If, as suggested by this study, sip volume modulation is itself a component of normal swallowing behavior, we further propose that sip size should ideally be tailored to the individual sip-sizing preferences of a patient. Our data suggest that under natural conditions, sip volume for thin liquids does not exceed 12 cc in healthy individuals. This estimate is consistent with previous scintigraphic investigations (Hamlet et al., 1996), and is considerably lower than the 20- and 30-cc volumes proposed for use in videofluoroscopy by previous authors (Logemann, 1997). Larger volumes may be suitable for investigation in patients who are dependent for feeding and denied the opportunity to control sip size at the mealtime. However, for those who do feed independently, we propose that measurement of habitual sip mass (using a digital balance) could easily be incorporated into the noninstrumental clinical examination that typically precedes a videofluoroscopic assessment. Patient safety concerns could be accommodated by imposing an upper limit on sip size (i.e., filling individual medicine cups with a maximum of 12 cc of water), and measuring the volume extracted from each cup on single sips by the patient. Similar methods could be used with thickened liquids, to determine appropriate target sip mass for videofluoroscopy.

**Spatiotemporal Variability**

The participants in this study displayed greater spatiotemporal variability in their patterns of tongue movement with opaque compared to nonopaque liquids. Such differences were observable at the level of the overall movement cycle and in within-trial variation rather than trial-set mean values of the kinematic measurements of anterior and downward tongue movements, which are presumed to represent tongue behaviors in the oral propulsive and pharyngeal phases of swallowing. In terms of session-to-session performance variability, the implications of the single observed Session × Cohort interaction in the mean peak velocities of anterior tongue dorsum movement remain unclear; given the isolated nature and weak effect size of this observation, it is likely spurious. Overall, we interpret the data on variability in this study to suggest that opaque liquids can indeed be used to elicit swallowing behaviors that are similar to those seen with nonopaque
liquids. However, our data do suggest that at a higher level of motor control, swallowing behaviors observed under videofluoroscopy may be more variable than those that occur outside the assessment context. This possibility requires further investigation using the sip mass matching procedures proposed above. A further possible interpretation of these data is that the increased variability in spatiotemporal patterning observed with the opaque liquids could be a direct consequence of longer swallowing transit times. This interpretation would be consistent with previous evidence of negative correlations between movement rate and movement variability in the speech science literature (Treffner & Peter, 2003; van Lieshout, 2004). Future studies employing sip mass matching will be able to determine whether transit time differences are attributable to differences in bolus density between opaque and nonopaque liquids, and whether differences in spatiotemporal pattern variability depend on the presence of transit time differences.

Aging

Swallowing transit times differed significantly between participants in the younger and older age groups in this investigation, with longer transit times observed in the older participants. This observation is consistent with previous observations of significant increases in pharyngeal response time (Logemann et al., 2000) and longer transit times for 10-cc liquid swallows (Sonies, Parent, Morrish, & Baum, 1988) in older participants. Since videofluoroscopic assessments were not part of the present investigation, it is not possible to speculate whether clinically meaningful differences would be observable in these same participants using that procedure. However, it should also be remembered that participants in the present investigation had no history of swallowing difficulties, and were judged to have normal swallowing based on clinical examination. Given the absence of statistically significant Age × Opacity or Age × Consistency interactions in the present data, it is also considered unlikely that age-related changes in sensory discrimination abilities related to bolus density or viscosity would be responsible for the observed differences. Although the observation of age group differences does not directly speak to our primary research question (i.e., the influence of contrast media on swallowing), it does clearly point to the need to gather additional data regarding normal age-related changes in swallowing. The sample size in this study (4 participants in each age group) is clearly too small to permit conclusions to be based on our findings of age-related differences in swallowing; however, it must be noted that despite this reservation the effect sizes for age group differences in swallow transit time were strong. These data serve as preliminary evidence that such differences are detectable using fleshpoint tracking techniques, and they justify further research into the prevalence, age of onset, magnitude, and clinical significance of age-related changes in swallowing.

Limitations

EMMA provides a two-dimensional midsagittal representation of tongue movements and does not permit visualization of the bolus. Previous authors have concluded that tongue movements for bolus accommodation and propulsion occur primarily along the midsagittal groove of the tongue (Hamlet, 1989; Hamlet, Stone, & Shawker, 1988; Kahrilas, Lin, Logemann, Ergun, & Facchini, 1993; Pouderoux & Kahrilas, 1995). Recent data suggest that the EMMA system is able to capture the main degrees of freedom for oral tongue movements during swallowing (Steele & van Lieshout, 2004). However, we cannot exclude the possibility that interesting events occur along the lateral margins of the tongue, in response to the experimental manipulations explored in this study.

For the present analysis, it must be recognized that industry-wide standard recipes do not exist for the preparation of opaque liquids; thus, the recipes used in this study likely differ from those used in some clinical settings. In particular, the opaque thin liquid in this study was mixed according to the manufacturer’s instructions for gastrointestinal imaging. It is quite common for clinicians to dilute thin-liquid barium suspensions beyond this concentration for use in oropharyngeal videofluoroscopic examinations (Li et al., 1992; Mills, 2000). Since watered-down suspensions would differ both in density and viscosity from the liquids used in this analysis, caution must be exercised in generalizing the present findings to all videofluoroscopic assessment situations. Further research should determine the minimum ratio of contrast medium to liquid required for bolus visualization in videofluoroscopy, in order to limit the inevitable differences in rheological properties between opaque and nonopaque stimuli (see Table 1). This minimum contrast product can then be matched for sip mass to data for nonopaque thin-liquid stimuli as suggested above.

A further limitation of the present study is the fact that the liquid stimuli differed not only in opacity and consistency but also in taste. The impact of taste on swallowing has received limited attention in the literature to date (Logemann et al., 1995; Pelletier & Lawless, 2003), but it seems probable that swallowing behaviors including sip size and oral movement may well vary according to taste properties and stimulus palatability. Such influences require investigation in future studies.

Conclusion

In summary, these preliminary data from a small group of healthy participants suggest that radiopaque liquids can be used as proxies for nonopaque liquids during swallowing assessment. We recommend that the use of opaque liquids should be carefully planned to simulate the kinds of bolus-consistency and sip-sizing variations experienced during normal eating. In particular, it is proposed that clinicians should consider measuring their patients’ habitual sip size (mass) for different bolus consistencies prior to radiographic assessment, to develop consistency-specific target sip mass values for use in the videofluoroscopy suite. Clinicians should also be aware that swallowing behaviors outside the radiology suite might be less variable than those observed using radiopaque boluses.
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