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Age Effects on the Temporal Evolution of Isometric and Swallowing Pressure

Mark A. Nicosia,[1,5] Jacqueline A. Hind,[2,5] Ellen B. Roecker,[3] Molly Carnes,[2,5] John Doyle,[4] Gail A. Dengel,[2,5] and JoAnne Robbins[2,5]

[1]Institute on Aging and the Departments of [2]Medicine, [3]Biostatistics, and [4]Surgery, University of Wisconsin-Madison. [5]Geriatric Research, Education, and Clinical Center, William S. Middleton Memorial Veterans Hospital, Madison, Wisconsin.

Background. The tongue plays a key role in bolus propulsion through the oropharyngeal chamber. In this study, possible age effects on the magnitude and timing of lingual pressure generation were analyzed.

Methods. Oral pressure was measured during isometric and swallowing tasks for 10 elderly (mean age = 81 years) and 10 young (mean age = 51 years) subjects. Three trials each of the isometric task and swallows of three different boluses (3 ml semisolid, 3 ml liquid, and 10 ml liquid) were performed by each subject. The timing and magnitude of isometric and swallowing pressure generation along with the pattern of the swallowing pressure waveform were analyzed.

Results. Whereas maximum lingual isometric pressures decreased with age ($p < .001$), no significant age difference was found for swallowing pressure. Time taken to reach peak pressure also was reduced with age in both the isometric task and swallows of liquid boluses ($p < .05$), while no significant age effect was found for semisolid swallows. Finally, only elderly subjects showed a pattern of liquid swallowing pressure generation in which multiple lingual gestures were required to reach peak pressure (termed “pressure building”), a pattern demonstrated by both young and elderly groups for semisolids.

Conclusions. Decreased lingual strength with age combined with unchanging swallowing pressure leads to a decreased “pressure reserve,” perhaps leaving older individuals more at risk for dysphagia resulting from insults directly or indirectly to the swallowing system. Additionally, swallowing is generally “slowed” with age, apparently due to both central and peripheral factors, and this change may have an impact on bolus flow outcomes.

ABNORMALITIES of swallowing become more prevalent with increasing age (1,2). Although dysphagia often occurs secondary to other conditions such as stroke, head injury, or neurodegenerative disease (3)—many of which increase in frequency with increasing age—the effects of normal aging on the swallowing process are not clear. To aid in the accurate diagnosis of swallowing disorders in older individuals, it is important to differentiate normal age-related alterations in swallowing physiology from disease-related changes.

The profound effect that impaired oral function has on swallowing (4,5) emphasizes its importance during deglutition. Indeed, it is recognized that the tongue plays a major role in bolus propulsion through the oropharyngeal chamber (6,7). Regardless, only a small number of studies have examined alterations in oral function over the normal life span.

These few reports have shown that healthy elderly subjects exhibit generally slowed swallows relative to younger individuals. This includes oral (8) and pharyngeal transit times (8,9), total swallowing duration (9), and duration of hyoid movement (10). Other age effects include increased pharyngeal residue (8) and a higher incidence of multiple hyoid gestures (10) in older subjects. Finally, and of particular clinical significance, is the finding of an increased delay from the time of bolus entry into the pharynx to the beginning of hyoid ascent in older relative to younger subjects (9,11). As laryngeal elevation, in this case reflected by hyoid excursion, is one factor among others (including vocal fold closure and epiglottic descent) in airway protection, this delay corresponds to the time that a bolus may be in proximity to a potentially unprotected airway and is a possible risk factor for aspiration.

The studies mentioned thus far describe oropharyngeal *kinematics*; that is, motion of the bolus or oropharyngeal structures (i.e., hyoid bone) without considering the forces that produce these motions. Contraction of intrinsic and extrinsic lingual musculature as well as pharyngeal musculature provide the driving forces for the oropharyngeal swallow. While manometry is the primary tool to study pharyngeal pressure during swallowing, several different methods have been applied to measure pressure within the oral cavity. Strain-gauge manometry (12,13), force-sensitive resistors (14), and bulb pressure sensors (13,15,16) have been employed to measure tongue-to-palate contact pressure, while cantilever force transducers were used to measure lateral tongue force (17).

Of these methods, only the Iowa Oral Pressure Instrument, a bulb pressure sensor, has been used to study changes in lingual pressure as a function of healthy aging (15,16). The finding that pressure generated during swallowing was less than maximum isometric pressure for all ages demonstrated that swallowing is a submaximal task (15). Whereas maximum tongue-to-palate contact pressure was shown to decrease with aging, maximum pressure attained during a saliva swallow was preserved, suggesting a decrease in available lingual "pressure reserve" accompanying normal aging. This decline in pressure reserve has important clinical implications in that older individuals may be at risk for dysphagia due to perturbations in the swallowing system for which younger individuals would be able to compensate (15). Increased understanding of aging effects on the biomechanical aspects of swallowing could (i) facilitate prediction of individuals most at risk for dysphagia; (ii) lead to development of interventional dysphagia-prevention programs; and (iii) increase diagnostic sensitivity for the presence of dysphagia, regardless of age.

The current study used specially designed bulb pressure sensors to measure oral pressure as a function of age for healthy adults. Both an isometric task and swallows of three different boluses (3 ml semisolid, 3 ml liquid, and 10 ml liquid) were studied. The specific hypotheses tested were (i) maximum isometric pressure declines with age while maximum swallowing pressure is preserved, (ii) the time taken to reach peak pressure (both isometric and swallowing) increases with age, and (iii) older individuals show a higher incidence of multiple-peaked oral pressure waveforms than younger individuals.

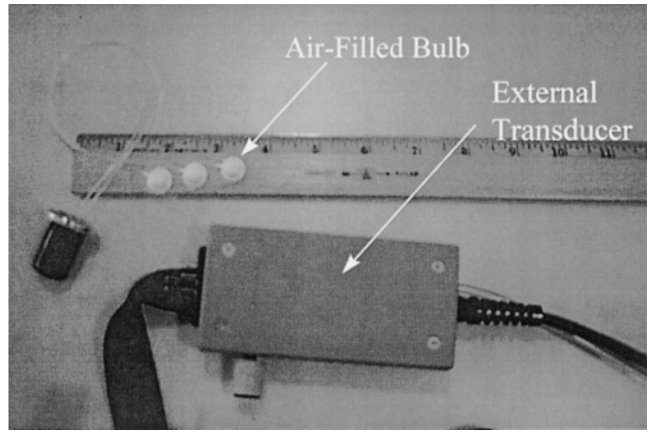

Figure 1. Photograph of bulb sensors and external transducer used to measure oral pressure in this study. The ruler (measuring inches) is shown for reference.

Methods

Subjects

This study was approved by the Institutional Review Board of the University of Wisconsin Health Science Center and the Research and Development Committee of the William S. Middleton Memorial Veterans Hospital. Twenty healthy men and women were separated by age into young (range: 48–55 years, five men and five women) and elderly (range: 69–91 years, five men and five women) groups, on the basis of findings suggesting that age-related swallowing changes begin at approximately 45 years of age (9). Subjects had no prior or existing medical condition or medication use that could potentially influence orofacial motor performance or sensation and no complaints or history of swallowing difficulty. Subjects were scored on the Mini-Mental State (18) to exclude cognitive/intellectual dysfunction.

Pressure Sensor Instrumentation and Placement

Pressure was measured with three air-filled bulbs (13-mm diameter, 8-mm spacing) connected to a transducer (Kay Elemetrics, Lincoln Park, NJ) that was hung from the neck (Figure 1). The bulbs were mounted on a silica strip and attached along the midline of the palate, between the alveolar ridge and the approximate junction of the hard and soft palate. Pressure data and time-linked video images (for swallow studies) were collected with the Kay Elemetrics Swallowing Workstation (Model 7100; Kay Elemetrics, Lincoln Park, NJ).

Isometric Task

Subjects were seated upright and instructed to "press your tongue against the roof of your mouth as hard as possible" (3 trials/bulb). Maximum pressure and the time taken to reach maximum pressure (starting with the first upstroke from baseline) were recorded. As each subject maintained maximal pressure, the waveform often showed a plateau-like form in which small pressure variations could artificially lengthen the rise time. Thus, time taken to reach a threshold pressure, P_{thresh}, was computed, where $P_{thresh} = \gamma P_{max}$, P_{max} is the maximum isometric pressure, and $\gamma = .5$, .75, .9 were examined.

Swallow Studies

Videofluoroscopic swallowing studies were recorded in the lateral view. Each subject performed three swallows each of three boluses: 3 ml semisolid, 3 ml liquid, and 10 ml liquid. Liquids were a 3:1 mixture of water to liquid Polibar Plus (EZ-EM, Inc, Westbury, NY), and semisolids were Esopha-Cat (EZ-EM, Inc., Westbury, NY). Different conditions were presented in a randomized order. Swallow studies were performed both with and without the bulbs (random order) as part of a larger study showing no significant differences in timing measures of the swallow or submental electromyographic activity with bulbs in versus bulbs out (19).

Maximum pressure and time to peak pressure.—Pressure data analysis extended from the first posterior bolus motion until the bolus tail entered the upper esophageal sphincter (9). Maximum pressure and the time taken to reach maximum pressure (from first upstroke from baseline) were recorded. For multiple-peaked waveforms, onset was taken at the first pressure peak unless pressure returned to baseline on all three bulbs between peaks. Here, time to reach peak pressure for each bulb was measured from the onset of the peak, which contained the maximum pressure for that bulb.

Number and pattern of pressure peaks.— Using the definitions shown in Figure 2, a swallow was considered multiple peaked if P_{min}/P_1 and P_{min}/P_2 were both less than some value α (values of $\alpha = .25$, .5, and .75 were examined). Multiple-peaked swallows in which maximum pressure was not reached on the first peak were labeled "pressure building." For a subject to exhibit one of these patterns for a

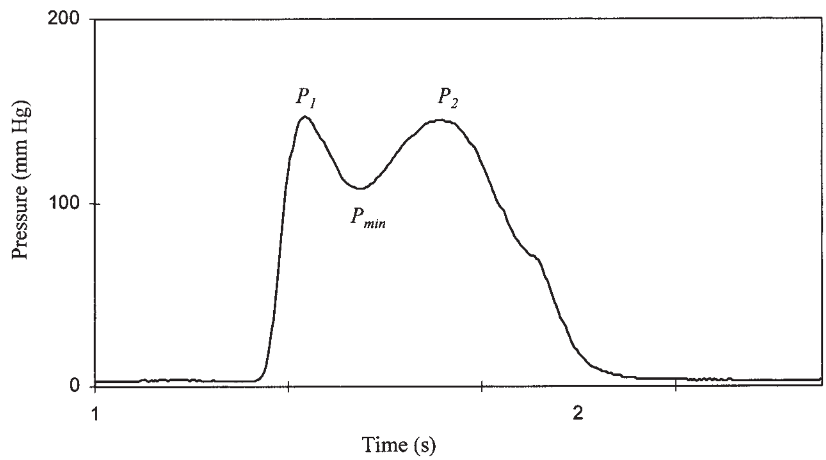

Figure 2. Example waveform of swallowing pressure versus time for a single bulb, illustrating the method used to determine whether a waveform has single or multiple peaks. This swallow was considered to have two peaks if the ratios, P_{min}/P_1 and P_{min}/P_2 were both less than some value α. As the parameter α is arbitrary, values of $\alpha = .25$, .5, and .75 were examined.

given condition, the pattern was required at least once on each of the three bulbs (not necessarily the same swallow).

Data Analysis

The trial corresponding to maximal isometric effort was analyzed for each bulb location and subject. For each subject, maximum swallowing pressure and time to reach peak swallowing pressure were averaged over the three trials for each condition and bulb.

Analysis of variance (ANOVA) for repeated measures models (20) were used to test for differences among consistencies, bulb locations, gender, and age group simultaneously, after initially testing for interactions among these variables. Pearson correlation coefficients were used to explore the relationship between pressures at the various bulbs. Differences in the incidence of multiple-peaked pressure waveforms between age groups were analyzed using Fisher's Exact test. Statistical analyses were performed using Statistical Analysis Software (The SAS Institute, Cary, NC). A p value of $< .05$ was considered statistically significant. Values are reported as mean $\pm$ *SD*.

Results

Isometric and Peak Swallowing Pressure

Age effect.—Maximum lingual isometric pressure was higher in the young group than in the elderly group at all bulbs ($p < .001$), as shown in Figure 3. In contrast, no significant difference in swallowing pressure was found between young and elderly subjects for any bolus condition or bulb location (Figure 3).

Bulb location and consistency effect.—For both age groups, the highest isometric pressure was generated at the posterior bulb, followed by the anterior bulb and finally the middle bulb ($p < .001$). Swallowing pressure differed significantly among the different bolus types ($p < .001$) and bulb locations ($p < .001$). Semisolid boluses tended to evoke higher pressure than liquid boluses at all bulb locations (Figure 3), consistent with previously published reports (12,13). Pressure was greatest at the posterior bulb for each bolus condition, and pressure at the middle bulb was greater than at the anterior bulb for the 3-ml liquid and semisolid boluses.

The relationships among maximum swallowing pressure at the various bulb locations for each bolus type and age group were examined using Pearson correlation coefficients, as illustrated in Figure 4. For liquid swallows, pressures among all three bulbs tended to be correlated in the elderly group, while only pressures between the anterior and middle bulbs tended to be correlated in the young group. For semisolid boluses, pressures among all three bulbs were correlated in both groups.

Gender effect.—There were no significant gender differences in isometric or swallowing pressure.

Time to Reach Peak Pressure

Age effect.—Mean values for time to reach peak pressure for both the isometric and swallowing tasks are shown in Figure 5. Time taken to reach maximal isometric pressure was longer in the elderly group than in the young group (data shown for $\gamma = .75$; see Methods; other values of γ were similar). Recall that the young group attained significantly higher isometric pressure than the elderly group.

For swallowing pressures, the difference between elderly and young subjects in time to reach peak pressure varied significantly by bolus type ($p = .03$). For liquid boluses, the elderly group took longer to reach peak swallowing pressure than the young group, as shown in Figure 5. In contrast, for the semisolid bolus, there was not a significant difference in time to reach peak pressure between the young and elderly age groups.

Bulb location and consistency effects.—Time to reach peak isometric pressure did not vary by bulb location. Time

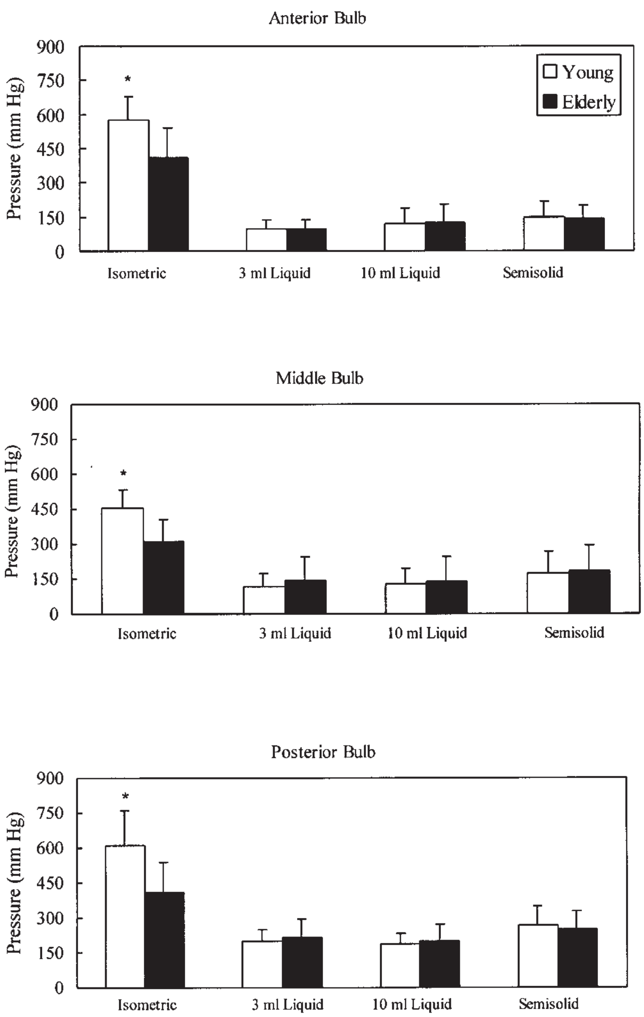

Figure 3. Comparison of maximum pressures between age groups for each task. Isometric pressures were significantly reduced with age while swallowing pressures were unchanged. *Indicates a significant difference ($p < .001$) between young and elderly by ANOVA across bulb.

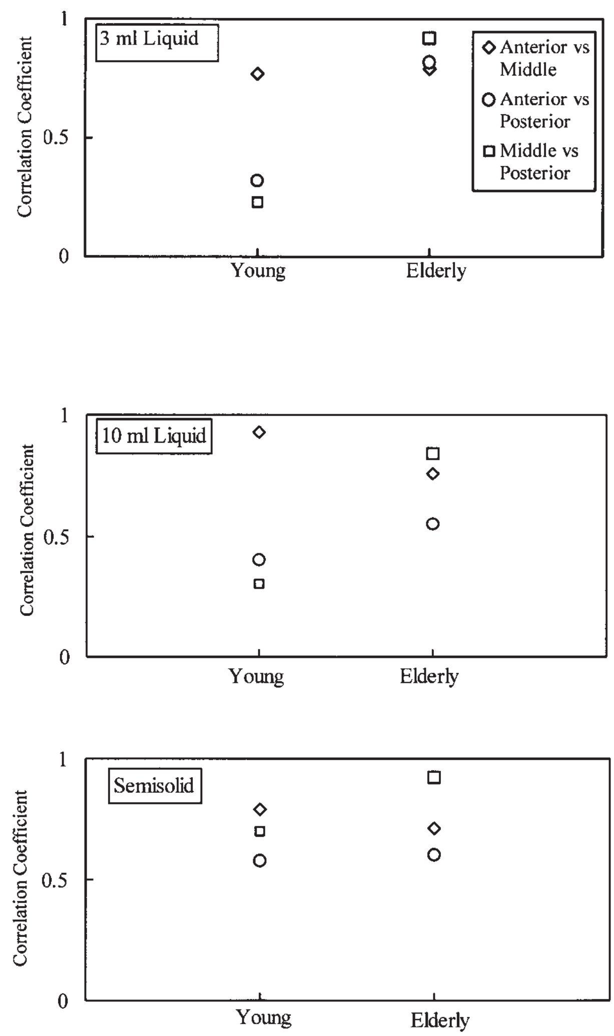

Figure 4. For both small and large liquid boluses, maximum swallowing pressures among all three bulbs tended to be correlated in the elderly group, while only pressures between the anterior and medial bulbs tended to be correlated in the young group. For semisolid boluses, pressures among all three bulbs were correlated in both groups.

to reach peak swallowing pressures varied by both bulb ($p = .0001$; anterior > middle = posterior) and bolus consistency ($p = .001$; semisolid > 3-ml liquid = 10-ml liquid in young, and semisolid = 3-ml liquid > 10-ml liquid in elderly).

Gender effect.—There were no gender differences in time to reach peak pressure for either isometric or swallowing tasks.

Multiple-Peaked Oral Pressure Waveforms

The incidence of multiple-peaked pressure waveforms is shown in Figure 6(A). Each set of three bars shows the number of individuals who demonstrated multiple peaks in the lingual pressure waveform at $\alpha = 25\%$, 50%, and 75% for a particular age group and bolus type (see Methods for definition of α). Young subjects are shown on the left and elderly subjects on the right. Note that $\alpha = 25\%$ is the most conservative level (i.e., pressure must decrease to 25% of peak value to be considered double peaked). The numbers in parentheses above each column represent the number of individuals demonstrating multiple-peaked behavior at the 25%, 50%, and 75% levels of α for that column. Although the elderly group appears to show a higher incidence of multiple lingual peaks than the young group, these differences are not statistically significant (analyzed using Fisher's Exact test).

Figure 6(B) shows the number of individuals who demonstrated the pattern of pressure building with multiple peaks, as described in the Methods section (plotted in the same way as the upper plot). Note that only elderly individuals showed this pattern on liquid swallows, while both elderly and young showed pressure building on semisolid boluses. There were no apparent gender differences in the pattern of multiple-peaked behavior.

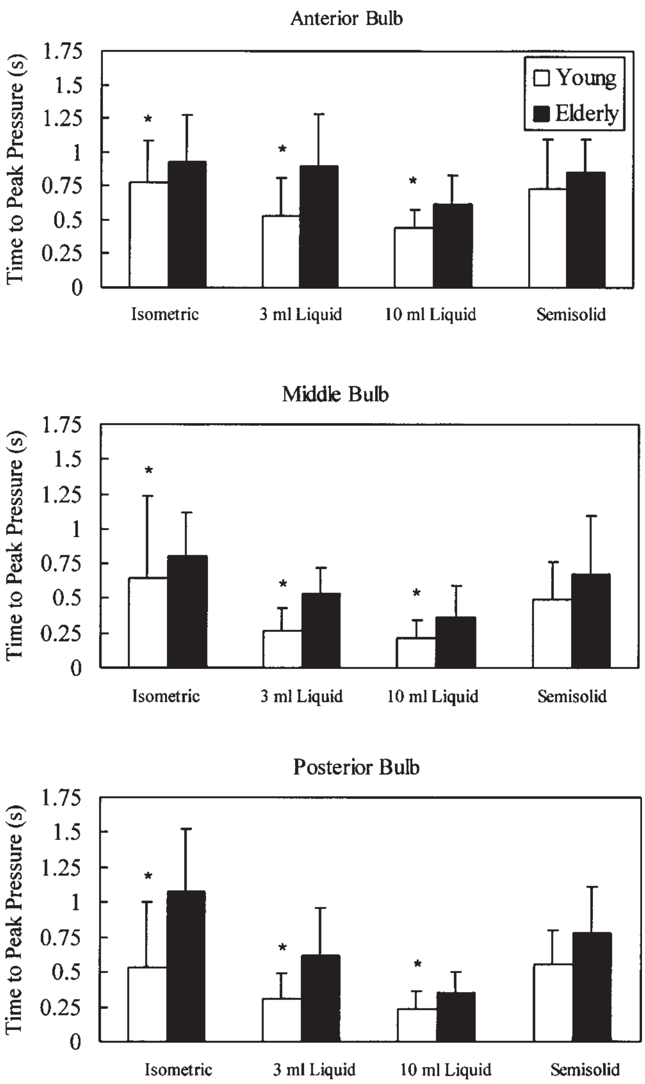

Figure 5. Time to reach peak pressure was reduced with age for both the isometric task and liquid swallows, with no difference found for semisolids. *Indicates significant difference between young and elderly age groups by ANOVA across bulb, within task/consistency ($p < .05$).

Discussion

The decrease in tongue strength with increased age found in the current study is consistent with previous reports (15,16) and reflects a general age-related decline in skeletal muscle strength (21,22). This decline, termed sarcopenia (23,24), results from a decrease in the size and number of muscle fibers (25) and an increase in noncontractile tissue (26,27). The data presented here, along with data showing increased amyloid deposits in human tongues with increased age (28), suggest that similar changes to those reported in limb musculature may be occurring in the tongue.

Despite decreased lingual strength, there were no significant differences in peak swallowing pressure between the young and elderly age groups, also consistent with previous reports (15) and showing that available lingual "pressure reserve" (the difference between isometric and swallowing pressures) is reduced with age. This reduction may leave older individuals more vulnerable to insults to the swallowing system (e.g., stroke or trauma) for which a younger individual may be able to functionally compensate.

For liquid swallows, pressures at all bulb sites were correlated in the elderly group, whereas only at the anterior and middle bulbs in the young group. This difference may reflect age-related material property changes, such as increased connective tissue relative to muscle, leading to a "stiffer" tongue (as in other muscle tissue [29,30]). Other possibilities are neuromuscular changes, such as an increased number of muscle fibers per motor neuron (as in other muscle tissue [31]). Such changes may lead to larger regions of muscle acting as a unit, decreasing the lingual "degrees of freedom." These changes may lead to decreased adaptability of the swallowing system to insults with age. Correlation of pressures at all bulbs for semisolids in both age groups likely reflects greater effort required for more viscous boluses relative to liquids.

Unchanging peak swallowing pressure with increased age, along with an increased oral phase duration (8), led Robbins and colleagues to suggest that older individuals may require more time to build the pressures necessary (and equivalent to young) for oropharyngeal bolus transport (15). In the current study, time to reach peak swallowing pressure was significantly increased with age for liquids but not semisolids. Note that older individuals aspirate most commonly on liquid as opposed to other types of materials (32).

To understand the contrast between age effects on the different boluses, patterns of lingual pressure generation were studied, focusing on multiple-peaked pressure waveforms. Both age groups often reached maximum pressure with the first peak, followed by a lower peak after the bolus had exited the oral cavity (where the separation between the oral cavity and pharynx was operationally defined as the most posterior aspect of the ramus of the mandible, as in [9]). A different pattern, in which maximum pressure was *not* reached on the first peak, led to increased time to reach peak pressure and was termed "pressure building." Only elderly individuals showed pressure building for liquids, while both age groups showed this pattern for semisolids, contributing to the differential effect of age on time to reach peak pressure.

Pressure building has important clinical implications, especially for liquids. Indeed, the only individual (an elderly person) who showed pressure building on all three bulbs in the same (liquid) swallow aspirated on this swallow. The initial pressure peak propelled part of the bolus into the pharynx before onset of the fluoroscopically visible mechanisms of airway protection; this material was aspirated, illustrating the potential danger of pressure building. Indeed, among all our elderly subjects, premature entry of the bolus into the pharynx often accompanied this pattern, although in these normal individuals the bolus was usually contained within the vallecula and not aspirated. Although both age groups showed pressure building for semisolids, this pattern is not dangerous, because semisolids are rarely aspirated.

Previous studies have shown an increased delay between bolus entry into the pharynx and the initiation of hyoid elevation with increased age (9,11) as well as a link between premature bolus entry into the pharynx and aspiration (33). These findings likely relate to pressure building, as the ini-

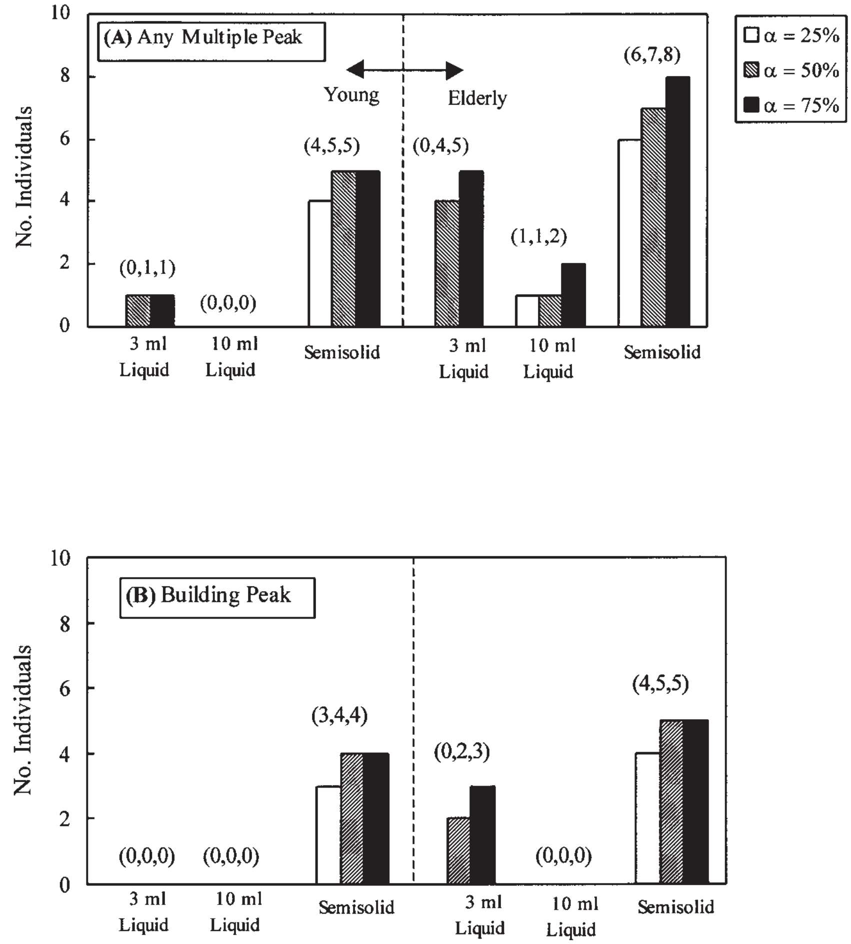

Figure 6. Number of individuals showing multiple-peaked pressure waveforms (**A**) and pressure building behavior (**B**) for each bolus type and level of α (see Methods for definition of α). Young subjects are shown on the left and elderly subjects on the right. The numbers in parentheses above each column represent the number of individuals at the 25%, 50%, and 75% levels of α for that bolus type and age group.

tial, submaximal pressure peak typically preceded the onset of hyolaryngeal elevation.

The underlying cause of this lingual behavior is not clear. In context with multiple hyoid gestures, Sonies and colleagues (10) suggested subtle neurologic changes associated with swallow initiation, a hypothesis supported by Robbins and colleagues (34) who studied multiple lingual gestures in Parkinson patients. Alternatively, this pattern may be related to neuromuscular changes within the tongue (reflected by decreased strength and rate of force development), such as decreased motor unit discharge rate, decreased ratio of motor neurons to muscle fibers, and a reduced number of synaptic pathways. Such alterations may lead to changes in muscle recruitment and subsequent force development patterns. Finally, these patterns may relate to central processes that occur with aging. For example, Robbins and colleagues (35) showed that increased periventricular hyperintensitites (believed to represent white matter lesions) were related to slower swallowing.

As swallowing outcomes in older healthy subjects are likely multifactorial, future studies are required to shed light on the relationships between age-related changes in anatomy and physiology and the resulting patterns of oral pressure generation. Such work may have important bearing on the development of rehabilitative techniques for dysphagic patients, particularly those who are geriatric. For now, it is clear that alterations in lingual function with age may have profound effects on swallowing safety.

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Address correspondence to Jo Anne Robbins, PhD, GRECC (11G), William S. Middleton VA Hospital, Madison, WI 53705.

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