Effect of aging on bolus kinematics during the pharyngeal phase of swallowing

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Swallowing difficulty is a common complaint in the elderly and, although there are data for the biomechanics of liquid swallows, little is known about solid bolus motion, or kinematics, in the elderly. The aims of this study were as follows: 1) to characterize and compare solid and liquid bolus kinematics in the elderly and compare the findings with those in young subjects and 2) to correlate bolus kinematics and dynamics. Concurrent manometric-fluoroscopic techniques were used to study eight young and eight elderly subjects. The subjects performed four swallows each of 0.2-cm-diameter solid barium pellets and 5 ml of liquid barium during sagittal fluoroscopy and six-channel pharyngoesophageal manometry. Images were digitized for analysis of kinematic properties such as velocity and acceleration. Dynamic pressures were recorded and coordinated with kinematic events. Image analysis showed that velocity varied as the pellet passed through the hypopharynx, pharynx, and upper esophageal sphincter. In young subjects, pellet kinematics were characterized by two zones of pellet acceleration: one over the tongue base and another as the pellet passed through the upper esophageal sphincter. Although the elderly showed a similar zone of acceleration over the base of the tongue, the second zone of pellet acceleration was not seen. Decreasing pressure gradients immediately distal to the position of the solid pellet and liquid bolus characterized dynamics for all subjects. This decreasing pressure gradient was significantly larger in elderly than in young subjects. Bolus kinematics and dynamics were significantly altered among elderly compared with young subjects. Among these differences were the absence of hypopharyngeal bolus acceleration and a significant increase in the transphincteric pressure gradient in the elderly.

Earlier studies reported significant alteration in the biomechanics of swallowing in elderly compared with young subjects. These changes involve pharyngeal peristalsis (17–19, 21), upper esophageal sphincter (UES) opening (2, 7, 16, 19), contractile function of the suprahyoid muscles (2), and deglutitive excursion of the larynx and hyoid bone (2, 7, 16, 18). Although these studies addressed the effect of aging on the dynamic aspect of oral pharyngeal phases of swallowing, i.e., forces that induce bolus movement, the motion of the bolus itself, i.e., the kinematics of the bolus, especially a solid bolus, in the elderly has not been systematically studied. The limited information about bolus kinematics generally pertains to young volunteers (8, 9), and, because the elderly frequently complain about swallowing difficulty, in general, and swallowing pills, in particular, a better understanding of bolus kinematics in this age group may help us better understand the pathophysiological bases of dysphagic symptoms in seemingly healthy elderly individuals and may have clinical ramifications. For this reason, the present study was undertaken to 1) characterize the solid pellet and liquid bolus kinematics in the elderly and compare the findings with those in young subjects, 2) characterize and compare the kinematics of solid and liquid boluses in the elderly, and 3) correlate solid and liquid bolus kinematics with their associated dynamics.

METHODS

Eight healthy young [18–40 yr of age, mean 27 (SD 6)] and eight healthy elderly [70–85 yr of age, mean 75 (SD 7)] male volunteers without a history of swallowing difficulty were studied by a concurrent manometric and videofluoroscopic technique. Studies were approved by the Human Research Review Committee of the Medical College of Wisconsin, and subjects gave informed written consent before the studies. Subjects were studied in an upright position after an overnight fast, and the nasal cavity was anesthetized with 2% topical lidocaine (Xylocaine, Astra Pharmaceuticals, Westborough, MA) applied by a cotton-tipped applicator just before insertion of the manometric probe.

For recording the pharyngo-UES intraluminal pressure phenomenon, we used a solid-state transducer assembly. Two three-site transducer probes with their pressure sensors 3 cm apart were secured side-by-side, so that the manometric recording sites were separated by 1.5 cm. The frequency response of these solid-state transducers was 20,000 Hz. The transducer assembly was passed transnasally and positioned such that, at rest, the two most proximal manometric sites were in the hypopharynx, the two middle sites were in the UES high-pressure zone, and the distal sites were in the proximal esophagus. The recording sites faced posteriorly. All pressure measurements were referenced to local atmospheric pressure. All pressure data were displayed on an 8-channel Sensormedics polygraph and concurrently recorded on a 16-channel Vetter FM tape recorder for subsequent analysis with a computerized digitization system.

The computer system for analyzing the manometric data consisted of a personal computer-compatible computer operating the system driving analog-to-digital (A/D) conversion hardware and software (DATAQ Instruments, Toledo, OH). The A/D program (CODAS) is a menu-driven capture-and-analysis package that allows for the asynchronous concurrent capture of up to 16 channels of data. The maximum sampling frequency of the system is 50 kHz, which exceeds the frequency requirements for sampling pharyngeal-UES pressure activity. The A/D conversion hardware and CODAS software allowed for capture and analysis of the six-channel pressure transducer signals at sampling frequencies higher than the limitations of the polygraph recording pens (30 Hz), as well as analysis of the captured manometry...
ric data in time scales unattainable in a conventional polygraph paper-and-pen recording.

To record bolus motion during swallowing, we studied the subjects concurrently by videofluoroscopy. The subject sat in a chair, positioned laterally to the face of the image intensifier. The subject was instructed to hold his head in a neutral position. Videofluoroscopic recordings were obtained at 90 keV with a 22.86-cm (9-inch) image intensifier mode and appropriate collimation so that a lateral image of the posterior mouth, pharynx, and pharyngoesophageal region was obtained. Fluoroscopic images were recorded on a super-VHS video-cassette recorder (AG-1960 Proline, Panasonic, Tokyo, Japan) that recorded 60 fields/s. The manometric and fluoroscopic recordings were synchronized by means of a specially designed timer (Thalnier Electronics, Ann Arbor, MI). The timer, video recorder, and polygraph were electrically connected. The timer generates two simultaneous signals: one provided a video-displayed time signal in hundredths of a second on the fluoroscopic images, and the other generated a 1-Hz, 5-V-amplitude timing pulse that was recorded on the chart paper used for manometric recording. For each swallow, the first pulse marked on the manometric recording paper was noted and logged, along with the elapsed tape count displayed on the video cassette recorder. The chart paper was run at a speed of 50 mm/s; thus each millimeter on the paper represented 20 ms. The timer signal also allowed synchronization of morphological events recorded on videofluoroscopic images, with the manometric events recorded on the FM tape recorder.

The computer analysis system used for analyzing the videofluoroscopic data consisted of a computerized system driving an A/D conversion board and program specifically designed for image capture and analysis. The image analysis-and-capture software (JAVA, Jandel Scientific, San Mateo, CA) allows capture of standard raster scan video images and morphological analysis of digitized image data. The digitized images were stored as computer files for any subsequent recall or analysis.

All subjects were studied during four swallows of each of the following: 1) a barium pellet (0.2-cm-diameter spherical pills) and 2) 5 ml of liquid barium and three dry swallows. Each barium pellet was swallowed without mastication, and no additional fluid, except the ambient saliva present during deglutition, was swallowed. For all swallows, we determined the velocity and acceleration of the barium pellet and the head and tail of the barium liquid bolus as they traversed the pharynx, UES, and subsphincteric area of the esophagus. The videofluoroscopic images were digitized by the computer image analysis system at a rate of one video field every 60th of a second. The video analysis software was used to mark the x-y coordinates of the center of the pellet and boundaries of the liquid barium bolus head and tail as the bolus moved through the pharynx and UES. The image analysis program in spreadsheet format stored the time-dependent coordinates. Thus, for any stored set of swallow sequence images, a time-dependent (x-y) mapping of bolus head and tail location was obtained. The bolus head and tail coordinates were numerically differentiated with respect to time to yield the velocity and differentiated twice to yield acceleration of the bolus head and tail. Along with the bolus kinematic data, we also determined, on fluoroscopy, the positions of the barium pellet and liquid barium bolus head and tail relative to the instant that the epiglottis appeared to make contact with the arytenoid cartilages at the posterior larynx (laryngeal vestibular closure) and relative to the instant of separation of the anterior and posterior walls of the pharyngoesophageal segment (UES opening).

We determined the intraluminal pressure relative to the location of the barium pellet and liquid barium bolus head and tail. From the videofluoroscopic images, the position of the bolus relative to the manometric recording sites was determined throughout the swallow sequence. With use of the timing signal that coordinated the fluoroscopic images and manometric events for every video field, the pressure phenomenon proximal and distal to the bolus was determined for all barium pellet and barium liquid swallow sequences. For the purposes of the present study, we have used the term pressure gradient to refer to the spatial distribution of pressure from the most proximal to the most distal manometric recording site. The pressure between all adjacent sites will be evaluated to test the hypothesis (by ANOVA) that there are spatial differences in the measured absolute pressure among the manometric sites spanning the UES.

Results were analyzed for wave duration and nadir pressure and were compared with subatmospheric pressures recorded from the pharynx-UES area. Within-age group statistical analysis was done by ANOVA with repeated measures. Between-age group analysis was done by unpaired t-test and ANOVA. Values are means (SD) unless stated otherwise.

RESULTS

Solid pellet and liquid bolus dynamics in young and elderly subjects. Analysis of the manometric recording showed, with each swallow, a peristaltic pressure wave that propagated from the most proximal transducer site distally. Analysis of concurrent videofluoroscopic recordings showed that, at the peak of deglutitive UES and laryngeal excursions, the most proximal manometric recording site was positioned within the hypopharynx in the vicinity of the laryngeal inlet; three sites were in the pharyngoesophageal junction (90% of the total analyzed swallow sequences), and the remaining two sites were positioned in the proximal esophagus.

In addition, analysis of the pressure phenomenon within the pharynx, UES, and proximal esophagus showed, during each swallow, immediately before arrival of the pharyngeal peristaltic pressure wave at the most proximal manometric site, a transient pressure decline at all six transducer sites for dry swallow as well as liquid barium and liquid barium swallows.

Analysis of concurrent videofluoroscopic recordings of pellets and barium swallows showed that development of this pressure decline was concurrent with anterior displacement of the hyoid-larynx-cricoid complex and occurred in the hypopharynx, UES, and proximal esophageal recording sites located caudal to the luminal closure induced by the peristaltic wave. Distribution of this transient pressure decline through the pharyngoesophageal junction is shown in Figure 1. In 83% of solid pellet and 55% of liquid barium swallow for young subjects and 53% of solid pellet and 41% of liquid barium swallow for elderly subjects, the ambient pressure distal to the peristaltic pressure wave decreased to subatmospheric ("negative") pressure. The incidence of subatmospheric pressure distal to the peristaltic pressure wave during pellet swallows was significantly higher in young than in elderly subjects ($\chi^2 = 5.16, P = 0.023$); however, no statistical differences in the incidence of negative pressure values during liquid bolus swallows were found between young and elderly subjects ($\chi^2 = 0.77, P = 0.38$). The transsphincteric pressure behavior during pellet swallow in the elderly subjects was different from that in the young subjects, in that the nadir of pressure decline was significantly higher in the elderly than in the young subjects (Fig. 1).

Pellet kinematics in young and elderly subjects. Analysis of the videofluoroscopic recordings showed that, during each swallow, the velocity of the pellets varied as they traversed the pharynx, UES, and proximal esophagus. The velocity variability was location dependent. There were two distinct zones of
increasing velocity. The average velocity of the pellet traversing the dorsum of the tongue was 18.4 (SD 1.3) and 17.2 (SD 3.1) cm/s for the young and elderly subjects, respectively. This velocity increased to 39.5 (SD 3.1) and 32.1 (SD 3.1) cm/s in the young and elderly subjects, respectively, while the pellet traversed the base of the tongue to the level of the inverted epiglottis (supraglottic region). During this time, the larynx had reached its maximum elevation and the epiglottis had assumed its horizontal orientation. The pellet velocity decreased significantly \((P < 0.05)\) to 8.9 (SD 3.1) and 13.2 (SD 3.7) cm/s in the young and elderly subjects, respectively, while it traversed the area between the tip of the horizontal epiglottis and the posterior pharyngeal wall (pharyngoepiglottic space). After the pellet passed this area, its velocity increased to an average of 31.8 (SD 2.4) cm/s in the young subjects \((P < 0.05)\) but remained at 13.2 (SD 1.7) cm/s in the elderly subjects \((P = \text{not significant})\) while it passed through the pharyngo-UES area to enter the proximal esophagus. After the pellet entered the esophagus, its velocity decreased to 11.8 (SD 1.2) and 10.7 (SD 3.0) cm/s in the young and elderly subjects, respectively \((P < 0.05 \text{ and } P = \text{not significant, respectively})\). This proximal esophageal pellet velocity was measured in 21 instances in which the pellet could reliably be seen moving through the proximal esophagus in the young subjects and in 19 instances in the elderly subjects. In the other subjects, the pellet remained in the subepiglottic region of the esophagus until it was cleared by a subsequent water swallow. A composite time history of average pellet velocity is shown in Fig. 2. In the elderly subjects, the second acceleration of the bolus that was observed in the subepiglottic hypopharyngeal region in all the young subjects was absent.

Liquid bolus kinematics in young and elderly subjects. Videofluoroscopic analysis of liquid bolus kinematics showed that, during each swallow, the kinematic behavior of the head of the liquid barium bolus was significantly different from that of the tail of the bolus in both groups. The velocity of the liquid barium bolus head showed a similar difference between the young and elderly subjects in acceleration of the bolus. In both groups, the anatomic locations of the two acceleration zones were identical. The average bolus head velocity over the posterior aspect of the tongue was 19.1 (SD 2.9) and 17.1 (SD 4.3) cm/s in the young and elderly subjects, respectively. At the supraepiglottic region, the bolus head velocity reached 37.6 (SD 8.1) and 35.5 (SD 5.9) cm/s in the young and elderly subjects, respectively. The bolus head decelerated to 20.1 (SD 3.6) and 10.2 (SD 4.9) cm/s in the young and elderly subjects, respectively, at the pharyngoepiglottic space. In the infraepiglottic region in the young subjects, it accelerated to 35.4 (SD 3.7) cm/s, but in the elderly subjects, similar to pellet movement, the velocity averaged 11 (SD 3.6) cm/s. The bolus head velocity was not significantly different from the pellet velocity in the regions described above. The average tail velocity of the bolus as it traversed the pharynx and passed through the UES was relatively constant at 10.3 (SD 3.0) and 10.0 (SD 5.2) cm/s in the young and elderly subjects, respectively (Fig. 2). Similar to pellet kinematics, bolus head kinematics in the elderly subjects were significantly different from those in the young subjects, in that there was no second acceleration in the hypopharyngeal subepiglottic area.

Pellet kinematics and dynamic interrelation. Analysis of the concurrent manometric and videofluoroscopic recordings showed that, in both groups, the pellet traveled ahead of the
peristaltic pressure wave. The distance between the pellet and the peristaltic front was 1.4 (SD 0.2) and 1.1 (SD 0.2) cm for the young and elderly subjects, respectively, when the peristaltic contraction wave reached the most proximal manometric site in the pharynx. The acceleration of the barium pellet was associated with incrementally decreasing pressure distal to the location of the pellet in the hypopharynx and across the UES. As the pellet passed each manometric recording site, the concurrent pressure at each site distal to it showed a progressive decline (Fig. 3).

Liquid bolus kinematic and dynamic interrelation. Analysis of concurrent manometric and videofluoroscopic recordings
showed that the kinematic and dynamic characteristics of the bolus head were significantly different from those of the bolus tail. As with the pellet swallows, there was an incrementally decreasing pressure distribution distal to the bolus head. The temporal and spatial pressure distributions in the regions distal to the head of the barium bolus were similar to those for pellet swallows.

The forces related to bolus tail kinematics were associated with the peristaltic pressure wave. Comparison of peristaltic pressure wave velocity, measured manometrically, and bolus tail speed, measured fluoroscopically, showed that the two phenomena were virtually identical: 11.0 (SD 0.3) and 10.9 (SD 0.5) cm/s, respectively, in the elderly subjects and 10.5 (SD 0.5) and 10.6 (SD 0.5) cm/s, respectively, in the young subjects. Also, analysis of the concurrent manometric and fluoroscopic recordings showed that the upstroke of the peristaltic pressure wave velocity, measured manometrically, and fluoroscopic recordings showed that the kinematic and dynamic characteristics of the swallowed bolus. A: barium pellet at the level of manometric site 1. B: liquid bolus swallow. Head of the liquid bolus is visible near manometric site 4.

DISCUSSION

In this study, we compared the kinematics and dynamic characteristics of solid and liquid bolus movement between young and elderly subjects. To study the solid bolus, we used a small barium pellet that, to some extent, could represent pharmaceutical tablets commonly used by the elderly population. For study of solid bolus kinematics and dynamics, use of this small pellet allowed for accurate identification of its location without uncertainty inherent to defining the precise interface of the barium liquid bolus with the tissue and air.

Two significant differences between the elderly and young subjects have been revealed in regard to solid and liquid bolus kinematics and dynamics: 1) Although in young individuals there are two zones of bolus acceleration in the pharynx, in the elderly the distal acceleration zone just above the UES is absent. 2) The downhill transsphincteric pressure gradient had a significantly higher nadir level in the elderly than in the young subjects. The presence of a decreasing pressure gradient throughout the pharyngoesophageal segment ahead of the swallowed bolus has been previously reported in young healthy individuals (8). Subsequent studies demonstrated the presence of similar gradients in intrabolus pressure as liquid boluses traverse this segment (13, 20). The differences observed in the present study add to the list of previously reported significant reduction in biomechanical events, such as anterior laryngeal excursion and the UES opening in the elderly.

Studies of chewing performance of food or synthetic material have shown that the diameters of the masticated particles range from 0.85 to 2.00 mm during optimal mastication (12). Studies of the physical characteristics of solid food during normal oral ingestion and mastication reported particle sizes of 5–1,500 μm for bread and 2.5–30 mm for spaghetti (6) and 30–500 μm for bread and 0.8–6.2 mm for spaghetti (5). Studies of oropharyngeal sensitivity reported a correlation in the perception of 4- to 9-mm-diameter spheres and the size of normally chewed food particles (4). Furthermore, in studies of
pill swallowing, particle diameters of 2.1–2.9 mm for freely masticated solid, nondissolving pills have been reported (1). Although the 2-mm pellet used in our study is seemingly small, it is within the range of values reported for solid particles swallowed during normal physiological mastication and deglution.

Difficulty swallowing, especially a solid bolus and pills, is a common complaint of elderly individuals in whom no cerebrovascular accidents or neuromuscular diseases have been documented. Alterations found in this study of healthy elderly volunteers provide some explanation for the mechanisms that might contribute to the increased prevalence of these symptoms in this age group. When the pellet bolus failed to exit the pharynx, two simultaneous differences were observed (Fig. 5): 1) The anterior excursion of the larynx during these failed swallows was significantly less than that during successful swallows. 2) The downstream prebolus pressure gradient was absent and, in addition, exhibited a significantly higher nadir. It is reasonable to assume that the prebolus pressure gradient is induced by and reflects the rapid expansion of the pharyngo-
esophageal junction induced by the pulling contractions of the suprahyoid muscles responsible for anterior laryngeal movement and UES opening. If this assumption is true, our finding represents another important function of suprahyoid muscle contraction during deglutition, in that forceful contraction of these muscles induces rapid expansion of the UES lumen, resulting in a rapid decline in intraluminal UES pressure, which facilitates bolus transit through the pharyngoesophageal junction.

Earlier studies reported significant differences in several deglutitive biomechanical events between young and elderly subjects. The UES opening is significantly smaller in elderly than in young individuals (7, 18). Anterior hyoid and laryngeal excursion has reported to be shorter in elderly than in young individuals (7). Similarly, intrabolus hypopharyngeal pressure, an indicator of resistance to flow, has been reported to be higher in elderly than in young individuals, whereas the hypopharyngeal peristaltic wave amplitude and duration are accentuated in elderly compared with young individuals (7, 17, 21). If we consider the fact that dynamic forces of the deglutitive apparatus determine bolus kinematics, it can be postulated that the documented alterations of bolus kinematics in the elderly, reported in the present study, could be the consequence of changes in the dynamics of bolus flow induced by changes in the biomechanical deglutitive events in the elderly (see above).

Furthermore, hyoid and laryngeal displacement during deglutition are closely linked to tongue movement (11, 14), especially with regard to the efficient formation and handling of nonliquid boluses just before deglutition. Previous reports have shown age-related impairment of lingual function (10, 15). These changes could potentially contribute to the mechanisms of our finding of age effects on solid bolus kinematics. Better definition of the interrelation between alterations in lingual function and changes in bolus kinematics in elderly individuals warrants further investigation.

Our finding of two acceleration zones measured in young subjects corroborates findings of previous studies (8). These two zones include the region at the posterior tongue and the hypopharynx and were separated by a zone of deceleration at the level of the inverted epiglottis. Our finding of the proximal acceleration zone in the elderly suggests preservation of the mechanisms that contribute to the acceleration in this area. Conversely, the absence of the distal acceleration zone in the elderly suggests alteration in the mechanisms associated with development of this acceleration. These mechanisms may include the contractile function of the suprahyoid muscles involved in hyolaryngeal excursion and UES opening as well as the lingual and pharyngeal contributions to pressure generation across the hypopharynx and UES.

Our study findings also show that in the elderly, similar to previous reports in young volunteers (8), the kinematics of the solid particles are similar to those of the head of the liquid bolus, but both are significantly different from kinematics of the tail of the liquid bolus.

In addition, findings of the present study in the elderly are consistent with those of previous reports in young subjects of three different pressure zones in the hypopharynx and pharyngoesophageal axis: 1) the peristaltic pressure, which reflects the lumen-obliterating contraction of the musculature, 2) the intrabolus pressure, which reflects the inertia and resistance to

Fig. 7. Transsphincteric pressure gradients in elderly and young subjects during pellet swallows with and without entrapment. There was no pressure gradient in cases of pellet entrapment, but pressure gradients were substantial in swallows without pellet entrapment.
the flow of the bolus, and 3) the pressure phenomenon in the region ahead of the bolus, which exhibits a downhill gradient across the segment induced by rapid expansion of the pharyngoesophageal junction.

Previous manofluorographic studies of elderly subjects swallowing liquid boluses have measured the velocity of the liquid bolus head traversing the oropharynx and UES (3). These studies reported bolus head velocities in the oropharynx and hypopharynx for young subjects similar to those reported in the present study; however, the findings of these studies in elderly subjects show similar oropharyngeal and hypopharyngeal bolus head velocities compared with young volunteers. The discrepancies between these previous reports and the present study may represent differences in experimental technique, catheter configuration and placement, and analysis methodology.

During the pharyngeal phase of swallowing, three of the four routes to the pharynx, i.e., the oral cavity, the nasopharynx, and the larynx, are sealed, while the fourth route, i.e., the UES, is open to remove the bolus. At the apogee of swallow, when the bolus reaches the hypopharyngeal opening of the UES, the development of a transspincteric pressure gradient, which may facilitate the direction and entry of the bolus into the UES and proximal esophagus, occurs ahead of the bolus. Our observation in this study that pellet entrapment in the hypopharynx was accompanied by reduced anterior laryngeal excursion (Fig. 6) and the absence of a transspincteric pressure gradient (Fig. 7), in contrast to the situation in the case of no bolus entrapment, supports this notion. It is conceivable that this transspincteric pressure gradient is influenced by the phases of respiration and intrathoracic pressure; therefore, swallowing in end inspiration could potentially enhance the transspincteric gradient and facilitate flow. This issue merits volition, volume and viscosity in humans. Gastroenterology 108: 1418–1426, 1995.

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References