Dynamics of esophageal bolus transport in healthy subjects studied using multiple intraluminal impedancometry

H. N. Nguyen, J. Silny, D. Albers, E. Roeb, C. Gartung, G. Rau, and S. Matern. Dynamics of esophageal bolus transport in healthy subjects studied using multiple intraluminal impedancometry. Am. J. Physiol. 237 (Gastrointest. Liver Physiol. 36): G958–G964, 1997 — The dynamics of a bolus transport through the esophagus are largely unexplored. To study this physiological process, we applied multiple intraluminal impedancometry in 10 healthy subjects. Three different protocols were used: 1) liquid bolus administered with subject supine, 2) liquid bolus with subject upright, or 3) semisolid bolus with subject supine. Transit of different parts of a bolus (bolus head, body, and tail) was analyzed at different anatomic segments, namely the pharynx and the proximal, middle, and distal thirds of the esophagus. A characteristic pattern of bolus transport was seen in all subjects. Impedance changes related to air were observed preceding the bolus head. The bolus head propelled significantly faster than did the bolus body and tail. Pharyngeal bolus transit was significantly faster than esophageal bolus transit. Within the esophagus, bolus propulsion velocity gradually decreased. Bolus transport was significantly accelerated in the upright position and delayed with increase of bolus viscosity. In conclusion, the dynamics of a bolus transport from the pharynx into the stomach are complex. It varies within both different anatomic segments and different parts of the bolus and depends on bolus characteristics and test conditions. The spatial and temporal resolution of a bolus transport can be obtained by the impedance technique.

In the present study, we applied multiple intraluminal electrical impedancometry to characterize the patterns and dynamic features of bolus transport through the esophagus. In addition, we determined the effects of alterations of bolus viscosity and body position on bolus transport.

MATERIALS AND METHODS

Subjects

Ten healthy subjects (7 males and 3 females, mean age 26.5 yr) without any history of gastrointestinal diseases were studied. The subjects were recruited from a group of medical students at the University of Aachen. None of the subjects took any medication, and each gave written informed consent. The study protocols were approved by the ethics committee of the University of Technology at Aachen.

Multiple Intraluminal Impedancometry

Principles. The method is based on the intraluminal measurement of electrical impedance among several closely arranged electrodes during a bolus passage using an intraluminal probe. For procedure-related details, see Silny et al. (26–27). The principles are shown in Fig. 1. Briefly, the intraluminal electrical impedance between two electrodes is inversely proportional to the electrical conductivity of the luminal contents and the cross-sectional area. Compared with the muscular wall, air has a lower electrical conductivity and yields an impedance increase. In contrast, saliva or nutrients have a higher conductivity and therefore yield an impedance drop at the corresponding measurement segments. On the other hand, a luminal dilatation (e.g., induced by bolus entry or wall relaxation) results in an impedance drop, whereas a luminal narrowing (e.g., induced by wall contraction) causes an impedance increase.

Characteristics of the impedance tracing. A bolus passage over each measuring segment yields a typical impedance tracing with a maximum of five phases and three characteristic points (Fig. 1). They are defined as follows: the F point shows the arrival of the bolus head at the corresponding segment, indicated by a return of impedance amplitude to the baseline after an increase due to air passage; the B point characterizes the moment when the maximal bolus volume is located within the corresponding segment, indicated by the lowest impedance value during phase III; the C point is facultative and represents the moment of rapid lumen occlusion, caused by a contraction wave clearing the bolus tail, indicated by the maximal impedance value during phases III to IV. The F and C points represent the bolus head and tail, respectively. Both parts are well defined. In contrast, since the bolus body is long, we represent it by the B point. Although this definition of the B point is arbitrary, it can be feasibly used, because this point is well reproducible and represents the maximal bolus volume. Because the end of the bolus tail is identical with the point of lumen-occluding contraction, its propagation represents the esophageal wall...
Fig. 1. A: principles of intraluminal impedancometry. Electrical impedance (Z) of an electric field between 2 electrodes is the ratio between applied voltage (U) and resulting current (I). B: example of a typical impedance tracing related to a bolus passage over 1 measured segment showing a maximum of 5 phases and 3 points (F, B, and C). Phase I is the resting stage of the organ; phase II represents arrival and passage of an air volume ahead of the bolus; phase III is associated with arrival and passage of a bolus; phase IV is associated with the wall contraction with facultative lumen occlusion; and phase V is the transitory stage to the resting stage. F point shows arrival of bolus head at corresponding segment, indicated by return of impedance amplitude to baseline. B point characterizes the moment when the maximal bolus volume is located within the corresponding segment, indicated by the lowest impedance value during phase III; and C point is facultative and represents the moment of rapid lumen occlusion, caused by a contraction wave clearing the bolus tail, indicated by maximal impedance value during phases III to IV. This tracing type was predominantly observed. C: determination of points of interest (different parts of a bolus) using 3 different cursor pairs. Data between each cursor pair were subsequently analyzed, and corresponding points were selected according to their definition.

In the DISCUSSION includes all of these parts.

**Movement.** In contrast, the propagation of the bolus head and body represents the bolus propagation. Thus the term bolus used by us in the discussion includes all of these parts.

**Instruments.** In this study, a custom-made flexible polyvinyl catheter of 2.6-mm outer diameter and 2.5 m length with 17 electrodes was used. The electrodes were 4 mm long and positioned 1.6 cm apart from each other. Bipolar impedance measurements were performed between adjacent electrodes, thus yielding 16 recording segments of 2 cm length (between the midpoints of each electrode pair) over a total distance of 32 cm.

The data acquisition was achieved by a mobile computer-based system similar to that previously described (26). After analog-to-digital conversion, impedance signals were stored on-line on the hard disk of a personal computer (sample frequency 100 Hz). A self-developed software was used for data acquisition, analysis, and graphic presentation.

**Study Protocols**

The subjects were asked to fast for at least 8 h before recording. The impedance catheter was passed through the nose into the esophagus. The two distal channels were positioned into the stomach, which is easily recognized by a drop in the basal impedance amplitude due to an increase of the cross-sectional area around the catheter and the higher conductivity of stomach contents. The final position of the catheter was radiologically confirmed. After a resting period of 30 min, the study procedures were performed as follows: 10 ml of a test substance were placed into the mouth with a syringe, and the subjects were asked to swallow on command by the investigators. Between each application of the test substance, the esophagus was cleared by two administrations of 5 ml water swallowed at intervals of at least 60 s. Three protocols were used, each consisting of eight swallows: 1) a standard protocol using a liquid bolus (Osmolite formula diet, Abbot, Wiesbaden, Germany) studied with subjects in a supine position; 2) a second protocol studying the effects of changes in bolus viscosity to bolus transport using a liquid bolus (Osmolite) with subjects in an upright position; and 3) a protocol studying the effects of changes in bolus viscosity to bolus transport using a semisolid bolus (yogurt) with subjects in a supine position. Resting intervals lasted 20 min between each protocol.

**Data and Statistical Analysis**

Excluding the stomach region (channels 15-16) and the lower esophageal sphincter region (channels 13-14), we defined four different regions of interest according to the position of the electrode pairs: 1) the pharyngeal region, including the upper esophageal sphincter (channels 1-4), 2) the proximal third of the esophagus (channels 4-7), 3) the middle third of the esophagus (channels 7-10), and 4) the distal third of the esophagus (channels 10-13).

Each swallow was individually analyzed. The F point (bolus head), B point (bolus body), and C point (lumen-occluding contraction or bolus tail, respectively) were determined at the corresponding channels using a self-implemented computer program. Three different cursor pairs were sequentially placed by the investigator as shown in Fig. 1C. The data between each cursor pair were subsequently ana-
lyzed, and the corresponding points were selected according to their definition. The obtained absolute time values were consecutively written to ASCII files. Subsequently, time intervals between corresponding channels were individually calculated for these points.

To study the effects of body position and bolus viscosity on global bolus transit, pharyngeal-gastric transit time of a bolus (bolus head and body) was determined, which is defined as the time course of corresponding points F1 to F14 or B1 to B14, respectively.

To study the dynamics of bolus transport, the propagation velocity of each bolus part (bolus head, body, and tail) was calculated at the different anatomic segments, by dividing the distance between the segments by the time interval between their activation. The effects of alterations of body position and bolus viscosity were evaluated.

The data of each individual subject represent mean values of eight swallows for each parameter obtained. Each parameter of esophageal chyme transport represents the mean of 10 individual subjects. Comparisons were made using Student's t-test for paired samples, with $P < 0.05$ considered significant. All values are given as means ± SE.

RESULTS

Patterns of Bolus Transport

Characteristic impedance patterns induced by a single swallow were found for the transport of boluses of different viscosity and body position. The form of the bolus head seemed to be dependent on body position and bolus viscosity (Fig. 2, A-C). We called such an impedance pattern a primary peristalsis pattern, since a bolus is continuously transported from the pharynx into the stomach. Deducted from the typical impedance increases, air was observed preceding the bolus head.
This phenomenon was seen throughout the esophagus but was predominantly observed in the distal third of the esophagus and in the supine position (Fig. 2A, horizontal arrows). Furthermore, belching with gas movement from the stomach into the pharyngeal region yielded an impedance pattern similar to that shown in Fig. 2D. In some cases, reflux of gas from the stomach into the distal esophagus could be deduced by a retrograde increase of impedance amplitude (Fig. 2, A and C, vertical arrows). Using the above-described algorithm, we found that air preceding the bolus head did not significantly influence the determination of the bolus head. In all cases, it has been clearly identified.

Parameters of Bolus Transport and Effects of Body Position and Bolus Viscosity on Bolus Transport

Mean pharyngeal-gastric transit time of the bolus head using a liquid bolus with subjects supine was 3,127 ± 500 ms. Change of body position from supine to upright resulted in accelerated transit (2,169 ± 278 ms, P < 0.05), whereas an increase of bolus viscosity resulted in delayed transit (4,521 ± 401 ms, P < 0.05). Compared with the bolus head, mean pharyngeal-gastric transit time of the bolus body was significantly longer (5,659 ± 252 ms, P < 0.05). It was not significantly affected by alteration of body position from supine to upright (5,058 ± 275 ms, not significant) but by increased bolus viscosity (6,621 ± 375 ms, P < 0.05). The corresponding mean propagation velocities are shown in Table 1.

Independent of anatomic segments, bolus viscosity, and body position, the bolus head had the fastest propagation velocity compared with bolus body and bolus tail (Fig. 3). The bolus head traversed across the pharyngeal region with a mean velocity of 37.1 ± 1.1 cm/s. Its pharyngeal propulsion was not affected by change in body position (38.8 ± 2.4 cm/s) but was slower after increasing bolus viscosity (28.3 ± 2.1 cm/s, P < 0.05). Within the esophagus, bolus head propulsion velocity was significantly slower at entry into the proximal third of the esophagus and gradually decreased further during transport toward the stomach (33.6 ± 1.4 vs. 20.3 ± 1.8 vs. 13.7 ± 2.5 cm/s, proximal vs. middle vs. distal esophagus, respectively). Esophageal bolus head propulsion velocity significantly increased by changing the body position from supine to upright, but declined by increasing bolus viscosity (Table 1).

Table 1. Mean propagation velocities of various parts of a bolus through the esophagus

<table>
<thead>
<tr>
<th>Bolus Parts</th>
<th>Liquid Bolus</th>
<th>Semisolid Bolus, Supine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supine</td>
<td>Upright</td>
</tr>
<tr>
<td>Head</td>
<td>9.6 ± 1.4</td>
<td>14.2 ± 2.2*</td>
</tr>
<tr>
<td>Body</td>
<td>5.0 ± 0.4†</td>
<td>5.2 ± 0.8†</td>
</tr>
<tr>
<td>Tail</td>
<td>4.1 ± 0.1†</td>
<td>4.7 ± 0.2†</td>
</tr>
</tbody>
</table>

Values are means ± SE (in cm/s). *P < 0.05 compared with liquid bolus, supine. †P < 0.05 compared with bolus head.

Mean pharyngeal propulsion velocity of bolus body (9.6 ± 1.0 cm/s) was significantly affected by alterations of body position (8.2 ± 0.8 cm/s, P < 0.05) and bolus viscosity (7.6 ± 0.4 cm/s, P < 0.05). Similar to the bolus head, esophageal propulsion velocity of bolus body was significantly slower than pharyngeal propulsion velocity (5.0 ± 0.4 vs. 9.6 ± 1.0 cm/s) and showed a gradual decrease within the esophagus (7.8 ± 0.9 vs. 5.6 ± 0.6 vs. 4.9 ± 0.5 cm/s, proximal vs. middle vs. distal esophagus, respectively). It was significantly affected by increased bolus viscosity (Table 1).

Typical impedance signals associated with a rapid lumen-occluding contraction (C point) were intermittently missed in the channels 11-13. The tracings showed a slow increase of impedance values as depicted in Fig. 4. In contrast to the bolus head and body, the bolus tail propelled through different esophageal segments with similar velocities (3.9 ± 0.2 vs. 4.4 ± 0.3 vs. 4.0 ± 0.3 cm/s; proximal vs. middle vs. distal esopha-
gus, respectively), and alterations of body position and bolus viscosity did not significantly affect its propagation velocity (Table 1).

DISCUSSION

A new procedure for intraluminal recording of chyme transport by simultaneous measurement of electrical impedance was used to quantitatively characterize bolus transport through the esophagus in healthy subjects. In all subjects, a highly characteristic impedance pattern related to the transport of a bolus has been observed in the present study in agreement with initial data (10, 26, 27). In contrast, several chyme transport patterns were described in human duodenum (20). This discrepancy can be explained by the role of the esophagus as a transit organ through the chest without any additional physiological functions such as mixing or stirring of nutrients.

Under the experimental conditions used in our study, air was observed to be swallowed together with a bolus and propelled ahead of the bolus, similar to the findings of Ergun et al. (9). This phenomenon was predominantly seen in the distal third of the esophagus. In a well-conducted study using ultrafast computerized tomography, Poudreux et al. (22) reported that swallowed air was separated at the head of a bolus while traversing the esophagus and then accumulated at the ampullary region. Poudreux et al. (22) did not observe any significant reflux of gas simultaneously with sphincter relaxation. In contrast, our data clearly indicate such a phenomenon, which, however, occurred only intermittently (Fig. 2, A and C). Because only a small number of experiments were performed and analyzed in the study by Poudreux et al. (22), the intermittent gas reflux might have been missed, and this may explain the discrepancy between the two studies.

The bolus head was injected from the pharynx into the esophagus with a high velocity up to 37 cm/s, comparable with results obtained using ultrafast computerized tomography (9). The bolus body traversed the pharynx with a mean velocity of 9.6 cm/s, within the range reported using scintigraphy (2). The pharyngeal propulsion of both bolus head and body was significantly affected by an increase in bolus viscosity, similar to data obtained by Dantas et al. (5).

We showed that various parts of a bolus have different propulsion behavior, and the bolus propulsion showed significant regional differences. The results imply that mechanisms regulating the dynamics of bolus propulsion from pharynx into stomach are complex. Because the pharynx ejects a bolus into the esophagus with a high velocity, the pharyngeal bolus transport and the propulsion of the bolus head were proposed to largely result from the chamber pump function of the oropharynx and the high-velocity bolus ejection from the pharynx into the esophagus (2, 9). In contrast, mechanisms regulating bolus transport in the esophagus are more complex. Esophageal bolus propulsion is induced by a sequence of peristaltic contractions (7), which clears the bolus tail (14, 23). It can be accelerated in the proximal third by the high-velocity pharyngeal propulsion (2) and slowed down in the distal third by increased abdominal pressure (23).

Within the body, it is mainly determined by the functional neuroanatomy and the peristaltic mechanisms of the esophagus (7, 16, 30). The proximal esophagus mainly consists of striated muscle, the distal esophagus mainly consists of smooth muscle, and a combination of both muscular types occurs in the middle third of the esophagus (18). These muscle types show different behaviors related to innervation configuration, response to vagal simulation, neurotransmitters for contraction, and mechanisms of peristalsis (7, 30). Using topography plots of the contraction waves, Clouse and Staiano (3) suggested at least three separate neuromuscular contraction units within the esophagus.

It has been shown that the dynamics of an esophageal bolus transport were affected by bolus characteristics and testing conditions; transit time and propagation velocity of a bolus were accelerated in upright position and decelerated with increased bolus viscosity. Similar observations were reported by Palugay (21) using fluoroscopy. As studied by intraluminal manometry, alterations of bolus viscosity and body position were shown to significantly affect esophageal peristalsis, in particular the myogenic part including amplitude and duration of contractions (8, 12, 13, 15, 25). In addition, the pressure profile generated by the esophageal musculature to propel a bolus was shown to depend on bolus characteristics and testing conditions (4, 23, 24). Thus the results on esophageal bolus transport observed in the present study can be addressed to previously reported data on esophageal peristalsis. On the other hand, since a viscous bolus tends to remain compact during its propulsion (2), an increase of bolus viscosity will result in an increase of intraluminal resistance during bolus propulsion and, therefore, slow its transport. In contrast, the addition of the gravity to the pharyngeal propulsion will accelerate the transit in an upright position. The results correspond to fluid flow mechanisms in tubular organs such as the esophagus (1).

The propagation velocity of the lumen-occluding contraction or the bolus tail was not significantly different between the various segments of the esophagus. Using concurrent manometry and videofluoroscopy, Ren et al. (23) showed that esophageal transit of a bolus tail was nearly constant except at the ampullary region. Lin
et al. (16) showed that the bolus transit through this region is very slow and seems to be driven by a hydrostatic pressure difference between the ampullary region and the stomach rather than by a peristaltic contraction. These results explain our findings that typical impedance changes related to a rapid lumeno
ccluding contraction were intermittently missed in the present study. On the other hand, an exact interpretation of the manometric data should consider the fact that different pressure domains can be recorded intraluminally during bolus transport (23). Thus our results are not comparable with previous manometric data. In a similar experimental design, Dooley et al. (8) showed that a significant change in contraction wave velocity was seen with boluses of high viscosity, whereas boluses of medium viscosity yielded similar responses. Our data indicate that the neuronal part of an esophageal response on swallowing a bolus can remain constant. The neural control mechanisms of a primary peristaltic wave are considered to be autonomic, which are mainly regulated by the central nervous system and can be modulated by the myenteric plexus (7, 30).

In a previous work done by Frieling et al. (11), comparing impedancometry with manometry, it was shown that considering esophageal wall contraction velocity, both techniques provided similar results. By contrast, considering bolus front movement, impedancometry is a reliable technique to differentiate between transit of wet and semisolid boluses. In reflux patients, impedancometry has recently demonstrated a delayed transit of wet and semisolid boluses as in the present study. On the other hand, an exact interpretation of the manometric data should consider the fact that different pressure domains can be recorded intraluminally during bolus transport (23). Thus our results are not comparable with previous manometric data. In a similar experimental design, Dooley et al. (8) showed that a significant change in contraction wave velocity was seen with boluses of high viscosity, whereas boluses of medium viscosity yielded similar responses. Our data indicate that the neuronal part of an esophageal response on swallowing a bolus can remain constant. The neural control mechanisms of a primary peristaltic wave are considered to be autonomic, which are mainly regulated by the central nervous system and can be modulated by the myenteric plexus (7, 30).

In conclusion, the dynamics of a bolus transport from the pharynx into the stomach are shown to be complex and vary within different anatomic segments, as well as within different parts of the bolus. The physical characteristics of the bolus and the test conditions alter bolus transport.

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