Bolus transit patterns in healthy subjects: a study using simultaneous impedance monitoring, videoesophagram, and esophageal manometry

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Impedance monitoring has been recently introduced to measure esophageal transit, whereas manometry is the gold standard for esophageal motility. These two tests are performed on different occasions and settings, and findings may be contradictory as a result (2, 9). A test evaluating both esophageal transit and motility simultaneously would address this limitation, and a transit test without radiation exposure would be desirable.

Impedance monitoring was recently introduced to measure bolus transit (11) by detecting changes in resistance to current flow when a bolus traverses an electrode pair, and can distinguish liquid (low impedance) from gas (high impedance) boluses. Incorporating electrode pairs on a commercially available solid-state pressure transducer also had electrode pairs 2 cm apart embedded around each sensor to record impedance. The catheter was connected to a personal computer with specialized software (Bioview, Sandhill Scientific) for acquisition, analysis, and storage of impedance data. Synchronization of videoesophagram to the impedance changes occur with these abnormal barium transit patterns, this would be useful in interpretation of impedance monitoring. Furthermore, impedance values at baseline, nadir and recovery after bolus exit have not been reported in peer-reviewed literature.

The aim of this work is to correlate bolus transit patterns determined by videoesophagram with bolus transit patterns identified by impedance monitoring and compare them with concomitant manometric findings. In addition, analysis of the barium bolus relative to the radiopaque electrode pair and pressure site will assess the relationship of barium entry and exit to impedance and pressure changes. Finally, baseline impedance values throughout the esophagus will be presented.

Materials and Methods

Part A. Bolus Transit Patterns in Normal Subjects

We studied 15 healthy volunteers (4 men, 11 women; mean age, 43 yr; range, 33.5–51 yr). They had no esophageal symptoms, and were receiving no medications affecting motility. The protocol was approved by the Cleveland Clinic Foundation Institutional Review Board on October 7, 2003, and all subjects gave written informed consent.

Videoesophagram was performed at a rate of 30 frames/s (OEC General Electric Medical Systems, Salt Lake City, UT). A 9-channel catheter (Fig. 1) allowed simultaneous impedance and manometry monitoring. It was passed per nares such that circumferential solid-state pressure transducers were placed at the LES and 5 cm above the LES, and three unidirectional pressure transducers were 10, 15, and 20 cm above the LES (Konigsberg Instruments, Pasadena, CA). The proximal four pressure sensors also had electrode pairs 2 cm apart embedded around each sensor to record impedance. The catheter was connected to a personal computer with specialized software (Bioview, Sandhill Scientific) for acquisition, analysis, and storage of impedance data. Synchronization of videoesophagram to the impedance monitoring tracing was achieved by a custom-made device (Sandhill Scientific) that allowed their correlation at a 0.03-s interval.

All subjects were studied recumbent by simultaneous videoesophagram and impedance monitoring for ~2 min. They received 5–6

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similar to saline (247 vs. 270 of water because the barium-saline mixture had an impedance value saline given at 20- to 30-s intervals. Normal saline was used instead successive swallows of 10 ml of 45% barium sulfate mixed with 0.9%
(LES;itoring is shown. Five pressure sensors measure lower esophageal sphincter
pressure sensors.
to measure impedance to current flow surround the four intraesophageal
P5
1cm Site in the Distal Esophagus

Part A. Bolus Transit Patterns in All Normal Subjects

Correlation between videosophagram and impedance. We analyzed a total of 86 swallows from 15 healthy volunteers (Table 1). In 97% (83/86) of swallows, the two methods were in agreement with one of three bolus patterns identified in this study: 1) normal bolus transit, 2) bolus stasis, and 3) retrograde escape.

Normal bolus transit. Most swallows (71%, 61/83) had normal bolus transit by impedance and videosophagram (Fig. 2). Manometry found in all 61 swallows both normal propagation of peristalsis and contraction amplitude ≥ 30 mmHg at all sites.

Baseline impedance before bolus entry was higher (P < 0.02) at the 5-cm site above the LES than the proximal three sites and was a median (range, 25 to 75th percentile) of 2,172 Ω (1465, 2784 Ω). Bolus nadir tended to be lower at the 5-cm site than the proximal three sites (Table 2), and was 205 Ω (191, 226 Ω). Impedance recovered from the nadir to > 90% of the original baseline at sites 20, 15, and 10 cm above the LES, and ≥ 77% of the original baseline at the site 5 cm above the LES.

Bolus stasis. Bolus stasis by videosophagram was persistence of all or part of the barium bolus in the esophagus (Fig. 3). Impedance defined stasis as a lack of bolus exit, because impedance either did not return to 50% of the original baseline or fell after transient recovery (i.e., <5 s). Bolus stasis by both methods was detected in 10% (8/83) of swallows, and was present in two patterns. In 7 of 8 swallows, there was stasis only in the proximal esophagus. In 6 of 7 swallows, there was a small barium residue at the 15- or 20-cm site above the LES, and in 1 of 7 swallows, there was a large barium pool at the 15-cm site. The low impedance value with stasis persisted until the next bolus entry at a mean of 649 Ω (442, 768 Ω). Despite bolus stasis by impedance and videosophagram, manometry showed normal peristalsis in all seven swallows and a contrac-

Table 1. Correlation of barium esophagram and impedance in detecting bolus transit patterns in 86 barium/saline swallows

<table>
<thead>
<tr>
<th>Impedance</th>
<th>Normal</th>
<th>Stasis</th>
<th>REscape</th>
<th>Not seen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>61</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Stasis</td>
<td>1</td>
<td>8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>REscape</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>Not seen</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

REscape, retrograde escape.
tion amplitude $\geq 30$ mmHg in most (4/7) swallows at the pressure site with stasis.

The second pattern of bolus stasis seen in 1 of 8 swallows was bolus entry but no exit throughout the esophagus by barium and at all four impedance sites. This swallow had aperistalsis by manometry.

**Retrograde escape.** Retrograde escape (Fig. 4) was defined by videoesophagram when barium escaped proximally from the bolus into an area of the esophagus previously cleared and by impedance as bolus entry being retrograde rather than antegrade. Retrograde escape by both methods was detected in 17% (14 of 83) of swallows. Despite the retrograde escape, manometry showed normal peristalsis and a peristaltic contraction amplitude $\geq 30$ mmHg with all swallows.

In every occurrence, the same bolus transit pattern was seen by barium: 1) normal bolus transit to the distal esophagus; 2) clearing of most, but not all, of the barium bolus from the distal 2–3 cm of the esophagus; 3) when the next swallow occurred 20–23 s later, the barium residue “escaped” from the distal esophagus proximal for 5–10 cm. However, impedance found normal antegrade bolus entry only in the proximal three sites. At the site 5 cm above the LES, impedance fell prematurely; i.e., immediately after the next swallow and before the bolus reached the proximal esophagus (see Fig. 4). As the videoesophagram showed, this was a result of the residue “escaping” from just above the LES to the site 5 cm above the LES. However, impedance found normal bolus exit at all four sites.

**Abnormal transit by only one method.** Only 3 of 86 (3%) swallows had divergent results by esophagram and impedance monitoring. One swallow had retrograde escape by barium that was not detected by impedance. Two swallows had stasis (a small residue at site 15 cm above LES) by impedance because recovery after nadir did not return to the 50% value of the original baseline; however, no retention was detected by barium.

**Other observations.** In 47 of 86 swallows, impedance detected air in the bolus traversing the esophagus when the following sequence of events occurred (Fig. 5): First, there was an initial, sudden increase in impedance $>3,000$ $\Omega$ (typically to an absolute value $>10,000$ $\Omega$) due to air at impedance sites as the bolus advanced through the esophagus. Second, in the distal esophagus impedance $>7,000$ $\Omega$ persisted a mean of 3.6 s (range, 2.7–4.5) as air accumulated and remained there. Third, impedance sharply decreased to $<300$ $\Omega$ as the barium filled the distal esophagus after air clearing. Liquid total bolus transit time [time (mean $\pm$ SE) from liquid entry at the site 20 cm above LES to liquid exit 5 cm above the LES] of boluses with air transit and accumulation was only 0.5 s longer than boluses without air transit (10 $\pm$ 0.3 vs. 9.5 $\pm$ 0.3; $P > 0.05$). Videoesophagram confirmed the passage of air throughout the esophagus and accumulation in the distal esophagus. The subjects had no symptoms during the air transit.

A trivial amount of barium stasis (estimated to be $<0.3$ ml) was seen remaining at the site 15 or 20 cm above the LES after 9 of 86 (10%) of swallows, and typically was a thin linear layer of barium next to the catheter that was hard to visualize. Impedance returned to $>50\%$ of the original baseline with these swallows. Manometry showed normal peristalsis in all nine swallows, and contraction amplitude $\geq 30$ mmHg in 8 of 9 swallows.

<table>
<thead>
<tr>
<th>Site above LES</th>
<th>Impedance Baseline</th>
<th>Impedance Nadir</th>
<th>Impedance Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 cm</td>
<td>1570 (1,176.8–1,926)</td>
<td>282.5 (265.3–308.4)</td>
<td>1,569.3 (1,213.8–1,923.3)</td>
</tr>
<tr>
<td>15 cm</td>
<td>1326.3 (1,143.9–1,554.9)</td>
<td>243.3 (233.9–267)</td>
<td>1,274.5 (984.8–1,487)</td>
</tr>
<tr>
<td>10 cm</td>
<td>1605 (1,503–1,883.5)</td>
<td>228.3 (215.1–244.5)</td>
<td>1,278.3 (1,240–1,896.3)</td>
</tr>
<tr>
<td>5 cm</td>
<td>2172.5 (1,465.1–2,784.3)*</td>
<td>205.3 (191–226.7)</td>
<td>1,669.8 (1,287.5–2,758.6)</td>
</tr>
</tbody>
</table>

Data presented in ohms as median and (range, 25–75%); $n = 61$ barium saline swallows with normal transit. LES, lower esophageal sphincter. *$P < 0.02$ 5-cm site vs. all other sites.
The lowest impedance value occurred when the barium bolus covered both electrodes and maximally distended the esophagus (Fig. 6). Impedance began to fall from baseline and began to rise from nadir when the bolus reached the top electrode of the electrode pair on entry and exit, respectively. The 50% impedance value with entry occurred as the barium bolus head approached the bottom electrode having covered the top electrode, and the 50% value with exit occurred just after the bolus tail left the bottom electrode.

Two distinct small increases in intraesophageal pressure (each ~5 mmHg) occurred during barium bolus presence, i.e., intrabolus pressure. The first occurred as barium initially filled the esophagus at the site of the pressure sensor, and the second occurred as the bolus became “compressed” between the advancing esophageal contraction proximal and the unopened LES distal. The contraction upstroke began as the barium tail reached the pressure sensor. The contraction continued while no barium was present at the pressure site and reached a maximum of 160 mmHg.

DISCUSSION

There was an excellent correlation between videoesophagram and impedance monitoring in assessing normal and abnormal patterns of bolus transit in normal volunteers. This supports impedance monitoring as a valid measure of bolus transit in normal individuals. Three bolus transit patterns were found: 1) normal bolus transit, 2) stasis, and 3) retrograde escape.

Normal bolus transit was the most common bolus transit pattern. Not only could no residue of barium be identified throughout the esophagus after barium transit, but impedance baseline after bolus clearance returned to near the prebolus baseline and remained relatively stable until the next bolus entry at all four sites. We found median prebolus baseline 5 cm above the LES to be 2,172 Ω, which is very similar to a preliminary report of 2,227 Ω (10).

Fig. 3. Proximal stasis despite normal esophageal peristalsis. A: barium esophagram during the first swallow shows retention of barium at the site 20 cm above the LES that persists despite normal transit of most of the bolus to the stomach. B: impedance tracing with the same swallow shows normal bolus exit at the distal 3 sites. However, there is stasis at the 20-cm site because impedance falls to <500 Ω after transient (<5 s) clearing. Manometry shows normal peristalsis with a contraction amplitude >30 mmHg. The second swallow shows a normal bolus transit pattern, and normal esophageal peristalsis with contraction amplitudes >30 mmHg.

Fig. 4. Retrograde escape despite normal esophageal peristalsis. A: barium esophagram during the 1st swallow shows normal bolus transit to the distal 2–3 cm of the esophagus where most, but not all, of the barium bolus is cleared. When the 2nd swallow occurred 20 s later, the barium residue “escaped” 5 cm proximal. B: impedance tracing shows normal bolus exit at all four sites with the 1st swallow. However, antegrade bolus entry was seen only in the proximal 3 sites. At the site 5 cm above the LES, impedance fell prematurely; i.e., immediately after the 2nd swallow and before the bolus reached the proximal esophagus. Manometry shows normal esophageal peristalsis with contraction amplitudes >30 mmHg for both swallows.
A small residue of barium that decreased impedance >50% at the 15–20 cm site above the LES occurred with 6 of 86 swallows and a trivial residue without a decrease in impedance in another 9 of 86. Because simultaneous manometry found normal peristalsis in all 15 swallows with small or trivial stasis and normal contraction amplitude with most, we believe this finding is clinically unimportant and should be viewed as a normal variant. However, 5-cm manometric spacing could miss focal peristaltic dysfunction. Our results are similar to Tamhankar et al. (13) who found with videoesophagram that 15% of normals had proximal escape of one-fifth of their swallows. However, this study did not use concomitant manometry. Although Massey et al. (6) and Hewson et al. (3) found proximal escape at the level of the aortic arch when hypotensive peristaltic waves <20 mmHg occurred in a group of patients with esophageal dysmotility, our report shows that proximal stasis can occur despite normal peristalsis and contraction amplitude.

Retrograde escape occurred in 16% of swallows. Videoesophagram found this was because a small portion of the bolus did not clear the distal esophagus before the next swallow. Impedance monitoring found normal bolus exit at all four sites. However, normal bolus exit from the esophagus did not occur because barium residue was in the “gap” below the last impedance site 20 cm above the LES and the LES (see Fig. 3). Impedance monitoring was also abnormal, however, because premature bolus entry was noted at site 4 as the residue escaped retrograde from the most distal esophagus to the site 5 cm above the LES. We found that no swallow had retrograde bolus escape when the interval between swallows was 30 s, and suggest that 30 s is the optimal interval for swallows.

Clinical applications of impedance monitoring have been recently published. A multicenter study using the same catheter as this study recently provided normal values for esophageal function testing. Complete bolus transit of liquid and viscous boluses by impedance was defined as normal bolus entry (50% fall from baseline to nadir) at the site 20 cm above the LES and bolus exit (return to 50% value defining bolus entry) at sites 5, 10, and 15 cm above the LES, and normal was defined as complete bolus transit of ≥79% liquid swallows and ≥69% of viscous swallows (15). Our study supports this report by confirming the validity of the 50% of baseline value as defining bolus entry and exit and confirming that the site 20 cm above the LES should not be used to define normal bolus exit as well as providing an explanation (i.e., presence of small bolus residues). However, we did find retrograde escape to 5 cm above the LES resulted in a premature fall in impedance, and feel antegrade entry at sites 5, 10, and 15 cm above the LES should be added to this definition of normal.

The ability of impedance to assess bolus composition allowed us to identify air transit throughout the esophagus, and especially accumulation and persistence for several seconds in the distal esophagus until cleared from the esophagus after LES relaxation. However, because liquid rapidly cleared the esophagus following air emptying, liquid total bolus transit time was minimally delayed. Thus this finding is not clinically important. Other studies have assessed gas transit. Pouderoux et al. (7) used ultrafast computed tomography and demonstrated that swallowing of air (8–23 ml) occurs along with the liquid bolus, and this mixture disperses in the esophagus with the air ahead of the liquid bolus to the level of the ampulla. Kahrilas et al. (5) identified repeated gas reflux by fluoroscopy that caused chest pain due to failure of upper esophageal sphincter opening and gas venting.

The comparative analysis of individual frames during videoesophagram with impedance and manometry allowed a close examination of the relationship among barium entry, presence, and exit to the radiopaque impedance electrode pair and pressure site. Traditionally, impedance monitoring defines bolus entry as a 50% fall from baseline, and exit as a 50% increase between nadir and the original baseline (15). Our study shows that the 50% values are reasonable choices for bolus entry and exit supporting previous findings of others (12). Furthermore, the 50% value facilitates computer analysis of bolus entry, presence, and exit. The association of barium entry with intrabolus pressure has been previously described, as has the clearance of bolus from the esophagus at the onset of the esophageal contraction (8). This study supports those findings.
Tutuian et al. (14) recently reported combined manometry and impedance monitoring, termed esophageal function test (EFT) in 350 consecutive patients. They found that all scleroderma and achalasia patients and 50% of patients with diffuse esophageal spasm (DES) and ineffective esophageal motility (IEM) had 80% liquid and/or 70% viscous swallows with complete bolus transit as defined previously. Bolus transit patterns were not described for the various motility disorders. However, we have described in a preliminary report using simultaneous barium esophagram, impedance, and manometry that patients with a tight wrap have a characteristic bolus transit pattern by impedance confirmed by videosophagram. The bolus transits normally to the distal esophagus where most of the barium collects above the wrap; retrograde escape usually ≥10 cm then occurs before the next swallow due to obstruction. These findings are present despite normal esophageal peristalsis and peristaltic contraction amplitude (4). Thus this is different than retrograde escape in the normal subjects in this study, where escape occurs after the next swallow. We are studying patients with other disorders to determine whether characteristic patterns of abnormal bolus transit may be present. This may give additional information to the traditional interpretation of the EFT that assesses only the number of swallows with incomplete bolus transit.

There are limitations to impedance monitoring. First, the catheter used in this study has a gap between the LES and site 5 cm above the LES, which does not allow detection of a bolus. As a result, only simultaneous videosophagram could determine that the fall in impedance 5 cm above the esophagus was due to retrograde escape from bolus stasis in the gap rather than gastroesophageal reflux. Additional impedance sites in this critical area would allow this important distinction. Second, impedance baselines were high in these normal volunteers, but may not be in patients with motility disorders. Studies in GERD patients with 24-h impedance pH have shown that retrograde bolus transit (gastroesophageal reflux) determination is difficult and occasionally not possible in the presence of a low baseline with Barrett’s esophagus (10). Antegrade bolus transit may also be affected if a low baseline is present, although this has yet to be studied.

In conclusion, videosophagram and impedance have excellent correlation in identifying bolus transit patterns. Normal transit is the most common transit pattern in healthy subjects. However, retention of barium residue in the proximal esophagus may occur even with normal peristaltic contractions and amplitude, as can retrograde escape from an incompletely cleared bolus if the next swallow is <30 s. These findings support impedance monitoring as a radiation-free transit test.
and provide normal bolus transit patterns for comparison to patients with esophageal motility disorders.

REFERENCES