Assessment of intraluminal impedance for the detection of pharyngeal bolus flow during swallowing in healthy adults

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Intraluminal impedance, the inverse measurement of intraluminal conductivity, is a modality that can be used to detect the flow of luminal contents through the gut. When impedance is measured along a segment of the gut lumen using an array of multichannel intraluminal impedance (MII) electrodes, the passage of a bolus of high conductivity (e.g., most liquids and solids) produces a propagated decrease in impedance from baseline. Conversely, the passage of a bolus of low conductivity (e.g., gas) produces a propagated increase in impedance from baseline. Hence, the speed and direction of bolus movement can be detected (1).

When measuring movement of substances within the gut using impedance, it is advantageous to simultaneously measure pressure as this enables the assessment of both motility and flow of luminal content. MII has been extensively used to detect the occurrence of gastroesophageal reflux (GER) (3, 10), and combined manometry and impedance assemblies have allowed further assessment of esophageal motor mechanisms of GER and GER volume/acid clearance (4, 8, 9). Combined manometry and impedance has also been used for the assessment of esophageal motility disorders such as hypotensive peristalsis, nonspecific motor disorder, diffuse esophageal spasm, and achalasia (10). Recent studies have used MII to reevaluate the minimal requirements for effective bolus propulsion by esophageal peristalsis (2) and suggest that effective passage of a bolus can be facilitated by esophageal pressure waves of lower amplitude than previously defined based on fluoroscopic assessments of bolus flow. Other studies have evaluated the impact of bolus type and consistency and body position on peristaltic effectiveness (3, 4, 11). Therefore, with the many competing factors that influence the effectiveness of peristalsis, the combination of manometry and impedance is better able to discriminate between normal and abnormal esophageal function than manometry or impedance alone.

In the context of neuromyogenic pharyngeal dysfunction, the determinants of the effectiveness of pharyngeal propulsive forces have received little attention. Pharyngeal intraluminal pressures, with or without simultaneous videoradiography, can provide insights into the degree of pharyngeal weakness or incoordination. However, there has been little systematic evaluation of the relationships among pressure, pressure wave velocity or coordination, and the effectiveness of bolus transport and bolus clearance. MII has been shown in the esophagus to provide such insights and might be a useful and nonradiological technique for such a purpose in the evaluation of the pharyngeal swallow. This is of particular relevance to the pediatric population, where radiological exposure time is a significant concern. The aim of this study was to use a novel combined manometry and impedance assembly to evaluate MII for the detection of bolus flow through the pharyngoesophageal segment in healthy adult volunteers, with the view to evaluating the feasibility and validity of a combined manometry and
MII assembly in the detection of bolus flow during the pharyngeal swallow in patients with oropharyngeal dysphagia.

METHODS

Subjects

We studied 10 healthy adult volunteers (5 men and 5 women) with a mean age of 24 yr (range 19–36 yr) recruited from the community by advertisement. All were screened to ensure none had swallowing difficulties, medical illnesses, or history of head and neck or gastrointestinal surgery or were taking medications that could have affected swallowing function. All subjects gave written informed consent, and the study was approved by the Human Ethics Committee of the South-Eastern Sydney Area Health Service.

Measurement Techniques

Pharyngeal manometry and impedance. Manometric data were collected using a custom-designed silicone rubber manometric assembly (outer diameter 2.5 mm) with 10 recording sideholes spaced at 1-cm intervals and 8 stainless steel electrode rings (4 mm long) spaced at 1-cm intervals at the midposition between sideholes 2–9 (Fig. 1A). Electrode rings enabled both the simultaneous measurement of impedance across recording sites as well as radiographic localization of bolus position relative to recording sites (Fig. 1B). The assembly was perfused with degassed distilled water by a low-compliance pneumatic perfusion pump (Dentsleeve; Wayville, South Australia, Australia) at 0.15 ml/min per channel. Pressures were registered for each perfused channel by 10 external pressure transducers (Abbott Critical Care Systems; Chicago, IL). Pressure and impedance signals were acquired simultaneously using two computer-based data-acquisition systems (Trace! version 1.2 videomanometry system, Prof. G. Hebbard, Royal Melbourne Hospital, Melbourne, Victoria, Australia, and Bioview impedance manometry system, Sandhill Scientific; Denver, CO). The signal acquisition rate was 10 Hz for the Trace! version 1.2 system and 50 Hz for the Bioview system.

Combined videofluoroscopy. Swallows of radioopaque boluses containing Omnipaque 300 (Amersham Health; Princeton, NJ) were recorded in the lateral projection using a 9-in. Toshiba (Kawasaki, Japan) image intensifier, and images were acquired by computer (Trace! version 1.2) at 12.5 frames/s for later analysis. Included in the field of view in the lateral projection were the incisor teeth anteriorly, the hard palate superiorly, the cervical spine posteriorly, and the proximal cervical esophagus inferiorly. Temporal correlation of videofluoroscopy (VF) images and manometric/impedance data was achieved using a synchro device (Sandhill Scientific), which imprinted a square-wave pulse on the manometric and impedance recordings in synchronicity with the in/out movement of a metal pin located within the radiographic field of view.

Experimental Protocol

Subjects fasted for at least 4 h before the study. Immediately before assembly placement, the baseline perfusion pressure offset of each channel was zeroed with the assembly placed underwater and at the level of the external transducers. The assembly was then passed transnasally until all manometric sideholes were located in the esophagus and then withdrawn in a stepwise fashion until sidehole 5 (impedance segment 3) was located above the proximal margin of the UES at rest, thus allowing capture of pressure and impedance changes occurring across the pharyngoesophageal segment (Fig. 1B). Depending on the height of the patient, the most distal impedance segment (Z6) was either in the distal UES or proximal esophagus. After a 10-min adaptation period, subjects were asked to swallow duplicates of 10 boluses comprising 2, 5, 10, and 20 ml liquid (50% Omnipaque in distilled water); 2, 5, 10, and 20 ml semisolid (50% Omnipaque in vanilla yogurt, thickened by the addition of a standard quantity of Novartis Thicken Up); and 1 and 2 cm² solid boluses (bread dipped in Omnipaque). The total fluoroscopic exposure time was <2 min.

Data Analysis

Analysis of all recordings was performed by consensus agreement of two observers who simultaneously analyzed both the VF recordings and impedance tracings. The reliability of impedance for the detection of bolus transit was assessed by comparing the timing of “known” bolus passage measured by VF with timing of the pharyngoesophageal impedance change recorded at each impedance segment (consisting of a pair of ring electrodes). True bolus movement was determined using VF. For each bolus swallowed, the time of bolus entry and the time of bolus clearance were determined at the level of each of the assembly electrode rings. Time 0 was defined as the time of bolus entry at the level of the most
proximal ring electrode. To correlate bolus movements, determined relative to individual electrode rings, with impedance patterns, determined across impedance segments consisting of pairs of electrode rings, bolus movement across each impedance segment was defined by the timing of bolus movement relative to the bottom ring electrode of each impedance segment. Pharyngoesophageal bolus transit time was therefore defined by the time from bolus entry at the level of electrode ring 2 (corresponding to impedance segment Z1) to bolus exit at the level of electrode ring 7 (corresponding to impedance segment Z6).

For each bolus swallow, the raw impedance (Ω) values at baseline (before swallow), at nadir (during bolus flow), and at the time points corresponding to (VF determined) bolus entry and bolus clearance were recorded. In addition, (VF determined) estimates of timing of bolus entry, timing of bolus clearance, and bolus transit time were correlated with impedance-derived estimates of the same parameters. Impedance-derived estimates of bolus entry were based on a fall in impedance from baseline to 50% of the baseline-nadir difference. Impedance-derived estimates of bolus clearance were based on the precise onset of impedance recovery, 25% impedance recovery and 50% impedance recovery (standard criteria). These levels of impedance recovery were chosen because they are relatively easy to derive using the semiautomated impedance analysis system provided.

The timing of pharyngoesophageal contraction was also assessed manometrically. Trace! software allowed representation of pressure in the form of a standard line plot (Fig. 2C) or as a spatiotemporal color isocontour plot. The isocontour plot provides a more detailed representation of the changes that occur in the space-time pressure structure of the pharyngoesophageal segment during swallow (12).

Raw data for impedance and parameters of bolus flow detected by both methods were nonparametric and therefore were compared using Spearman Rank Correlation and Wilcoxon Signed-Rank tests. \( P < 0.05 \) was considered statistically significant.

RESULTS

Two hundred boluses were administered. Eighteen were not evaluable due to poor positioning of the region of interest in the X-ray field of view or because the video was turned off before the bolus had completely passed. Evaluable swallows comprised 76 liquid, 70 semisolid, and 36 solid boluses. All subjects exhibited normal swallowing, and the pharyngoesophageal pressure measurements rendered appropriate patterns of intrabolus pressure generation, UES relaxation, initiation of the

Fig. 2. Patterns of pressure and impedance during bolus swallowing. A: radiological image of the combined assembly in situ in a healthy volunteer. B: Top: “true” bolus passage illustrated by radiological images at different phases of the swallow. Bottom: impedance pattern recorded across segments Z1–Z6. C: pressure patterns recorded across sideholes 1–10 (SH1–SH10). Note that manometric sideholes 3–7 (black) are located at the midpoint of impedance segments Z1–Z6, respectively. D: comparison of pressure and impedance patterns recorded at positions SH4/Z2 in the pharynx. E: comparison of pressure and impedance patterns recorded at positions SH8/Z6 at the distal margin of the UES HPZ. Note the following. First, the timing bolus head entry (H) corresponds closely to the timing of onset of intrabolus pressure on the manometric tracings as well as the timing of the impedance drop to 50% on the impedance tracings. Second, the timing of bolus tail clearance (T) corresponds closely to the onset of the upstroke of pharyngeal contraction and the upstroke of UES tone. Third, in the pharynx in particular, the timing of impedance recovery to 25–50% of baseline occurs well after the bolus has cleared. Instead, the recovery of impedance is clearly associated with the offset of pharyngeal contraction some 0.8 s after passage of the true bolus tail. Fourth, the onset of the small step-up increase in pharyngeal impedance from nadir that can been seen is associated with the peak of the pharyngeal pressure wave. Finally, in the UES, the timing of bolus tail clearance is associated with impedance recovery to 25%.
pharyngoesophageal stripping wave, and recovery of UES pressure to baseline.

The baseline measurements of impedance varied along the length of the pharyngoesophageal segment; there was usually an axial drop in baseline impedance that was most marked across the impedance segment straddling the transition from distal pharynx to the UES, and the lowest levels of impedance were recorded at impedance segment Z5, which was usually located at the level of the UES high-pressure zone (Fig. 1C). The median baseline impedances recorded across all swallows by different impedance segments are shown in Table 1.

The typical impedance pattern recorded during bolus swallowing consisted of a propagated drop of impedance from baseline to nadir (Table 1), which was followed by a recovery of impedance to at least 50% of baseline (Fig. 2B). An abrupt increase in impedance of >10,000 Ω often preceded the impedance drop; this increase being due to swallowed air travelling in front of the bolus head. At the level of the UES, the impedance increase signified the timing of UES opening. In the case of liquid boluses, air was often observed within the body of bolus itself on VF. Air within the bolus caused the impedance readings to be higher and fluctuate during bolus transit. making analysis more difficult than other bolus types. Overall, semisolid and solid boluses produced a cleaner and more reliably interpretable impedance signature than liquid. The volume of the bolus did not significantly influence the magnitude or nadir characteristics of the impedance drop recorded during swallowing.

At the time of bolus entry, the median impedance recorded along the assembly dropped to levels of between 29% and 55% from baseline (Table 1). The bolus entry time determined by a 50% impedance drop correlated with bolus determined by VF. Correlation coefficients for the bolus entry time determined for all boluses combined were $r = 0.206$ ($P < 0.005$), $r = 0.435$ ($P < 0.0001$), and $r = 0.388$ ($P < 0.0001$) at impedance segments Z2 (pharynx), Z4 (UES), and Z6 (UES/proximal esophagus), respectively. Subanalyses based on bolus type showed that the bolus entry of semisolid ($r = 0.291$, $P < 0.05$; $r = 0.737$, $P < 0.0001$; and $r = 0.758$, $P < 0.0001$, respectively) and solid boluses ($r = 0.342$, $P < 0.05$; $r = 0.642$, $P < 0.0001$; and $r = 0.758$, $P < 0.0001$, respectively) were accurately detected, but the bolus entry of liquid boluses was poorly detected and did not reach statistical significance ($r = 0.101$, $r = 0.034$, and $r = 0.017$, all not significant, respectively).

Unlike the pattern of impedance drop, the pattern of impedance recovery associated with bolus clearance was more complex and varied dependent on the axial location of the impedance segment. For impedance segments located within the pharyngeal lumen (Z1 and Z2), the median impedance recovered to only 9–13% of baseline when the bolus cleared (Table 1) and the recovery of impedance to the standard level of 50% of baseline occurred well after the true bolus had cleared. (Fig. 2D). Estimates of the timing of pharyngeal bolus clearance that were based on standard 50% impedance criteria did not correlate with VF (Table 2).

For 74% of swallows, a small stepwise increase in pharyngeal impedance from nadir was observed preceding the main recovery in impedance (as shown in Fig. 2D). Manometric recordings indicated that the onset of this stepwise increase was associated with the peak of the pharyngeal pressure wave (Fig. 2D). The timing of the onset of the impedance recovery correlated significantly with the timing of bolus clearance determined by VF (Table 2).

For impedance segments located within the UES and esophageal lumen (Z3–Z6), the median impedance recovered to 26–29% of baseline at the time of bolus clearance. Hence, UES and esophageal bolus clearance estimates based on a 25% impedance recovery correlated most significantly with VF.
compared with either standard 50% impedance recovery criteria or criteria based on the timing of the precise onset of impedance recovery (Table 2). For these impedance segments located in the UES and esophagus, manometric recordings showed that impedance recovery coincided with the upstroke of UES pressure (postrelaxation) and the upstroke of the esophageal stripping wave (Fig. 2E).

Pharyngoesophageal bolus transit time determined by VF was most accurately estimated by impedance when criteria of a 50% drop from baseline, to indicate bolus entry at Z1, was combined with 25% recovery of impedance, to indicate bolus clearance at Z6 (Table 3 and Fig. 3). For all bolus types, standard 50% recovery impedance criteria significantly overestimated the median pharyngoesophageal bolus transit time while the onset of impedance recovery from baseline underestimated bolus transit time (Table 3).

**DISCUSSION**

This study utilized a novel combination of impedance and high-resolution manometry techniques. By simultaneously evaluating patterns of pharyngoesophageal impedance and pressure change during deglutition and correlating these patterns with actual bolus flow measured fluoroscopically, we were able to validate the technique of impedance measurement as a nonradiological tool for the detection of bolus transport through the pharyngoesophageal segment. We found that the pattern of pharyngeal impedance drop corresponded to pharyngeal passage of the bolus head; however, the pattern of pharyngeal impedance recovery did not correspond to pharyngeal bolus clearance, and, therefore, intraluminal impedance measurement did not accurately reflect the bolus transit in the pharynx. In contrast, the pattern of impedance drop and recovery in the UES and proximal esophagus was an accurate reflection of bolus transit in this region.

We observed that baseline levels of impedance were highest in the pharynx but decreased at the level of the proximal margin of the UES and below. Average impedance values were also lowest at the axial position corresponding to the midpoint of the UES high-pressure zone (usually Z5). As the radiographic image in Fig. 1 shows, the pharynx is “open” in the resting state, and, therefore, there is only partial circumferential mucosal contact between electrode pairs, whereas at the level of the UES and below, there is complete circumferential mucosal contact. In the resting state, mucosal contact bridges current flow between electrode pairs, which are otherwise electrically isolated from each other. This marked variation in baseline impedance along the pharyngoesophageal segment can therefore be explained by the degree of mucosal-electrode contact being partial in the pharynx and circumferential at the level of the UES and below. The lowest levels of baseline impedance overall were at the level of the UES high-pressure zone, which is likely to be due to the combination of complete circumferential mucosal contact and increased compression of the UES mucosa against the assembly electrodes due to UES resting tone.

The pattern of intraluminal impedance change recorded in the pharynx during bolus swallowing was far more complex than that previously reported for the esophageal lumen. Starting from a high level of baseline impedance, as described above, we observed that the impedance dropped from baseline to nadir in association with bolus entry into the impedance segment. This drop in impedance is caused when the bolus itself bridges current flow between the ring electrodes. The timing of bolus entry of semisolid and solid boluses was accurately estimated using standard impedance criteria; in contrast, bolus entry of liquids was poorly estimated, most probably due to the effect of air within the bolus, which obscures the impedance signature, making analysis more difficult.

In the pharynx, contact between the tongue base and the posterior pharyngeal wall obscured normal recovery of impedance that, below the pharynx, is associated with bolus clearance. Pharyngeal bolus clearance was associated with the onset of the pharyngeal stripping wave, but recovery of impedance to

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**Table 3. Comparisons of pharyngoesophageal bolus transit times calculated by VF and estimated by intraluminal impedance using both standard and modified criteria**

<table>
<thead>
<tr>
<th>Bolus Type</th>
<th>VF</th>
<th>Onset of Recovery</th>
<th>25% Recovery</th>
<th>50% Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>0.72 (0.56, 0.88)</td>
<td>0.61 (0.50, 0.72)*</td>
<td>0.71 (0.63, 0.90)</td>
<td>0.89 (0.74, 1.24)*</td>
</tr>
<tr>
<td>Semisolid</td>
<td>1.04 (0.78, 1.28)</td>
<td>0.67 (0.54, 0.87)*</td>
<td>0.94 (0.72, 1.25)</td>
<td>1.28 (1.09, 2.30)*</td>
</tr>
<tr>
<td>Solid</td>
<td>0.76 (0.68, 1.90)</td>
<td>0.62 (0.55, 0.75)*</td>
<td>0.78 (0.70, 1.06)</td>
<td>1.08 (0.90, 1.36)*</td>
</tr>
<tr>
<td>All boluses</td>
<td>0.80 (0.64, 1.04)</td>
<td>0.62 (0.53, 0.80)*</td>
<td>0.80 (0.67, 1.04)</td>
<td>1.10 (0.86, 1.52)*</td>
</tr>
</tbody>
</table>

Data are expressed as median pharyngoesophageal bolus transit times (in s) (interquartile range). *Multichannel intraluminal impedance significantly different from VF using the Wilcoxon signed-rank test ($P < 0.001$).
>50% of baseline did not occur until the end of the swallow when pharyngeal pressures returned to baseline and the pharyngeal lumen reopened. As such, the pattern of impedance recorded reflects the period of opening of the pharyngeal swallowing chamber. A small stepwise impedance increase was observed that appeared to be associated with the decrease in level of pharyngeal compression of the impedance electrodes, which follows the attainment of peak pharyngeal pressure. The onset of this stepwise impedance recovery significantly correlated with pharyngeal bolus clearance on VF, suggesting that it may nevertheless be a useful marker of the timing of pharyngeal clearance.

Bolus tail passage at the level of the UES and proximal esophagus was more readily detected using impedance criteria. We found impedance estimates of bolus tail timing and bolus transit time based on standard criteria, previously developed for the esophagus, did correlate significantly with fluoroscopic estimates. Nevertheless, modification of these criteria to reduce the threshold of impedance recovery to 25% (rather than the standard 50%) improved the accuracy of our assessments.

This study shows that the pattern of impedance change recorded along the pharyngoesophageal segment during bolus swallowing is influenced by more than just the presence or absence of bolus in contact with the impedance electrodes. In the pharynx in particular, factors such as the presence/absence of contact between impedance electrodes and the mucosa and the extent of circumferential contact between the impedance electrodes and the mucosa as well as the degree of luminal compressive squeeze on the impedance electrodes confound the pattern of impedance recorded. These factors make the methodology inaccurate for assessment of the timing bolus clearance from the pharynx. Despite this limitation, our study does indicate that the impedance technique can accurately estimate pharyngoesophageal bolus transit time during swallowing, which is based on recognition of bolus head timing in the pharynx and bolus clearance timing in the esophagus. Accurate assessment of pharyngoesophageal transit time is, however, dependent on the administration of boluses of appropriate consistency and the use of appropriate analysis criteria. The current study indicates that solid and semisolid boluses produce a “cleaner” and therefore more easily analyzed impedance waveform. Thin liquids, such as water or saline, are problematic due to entrapment of air within the bolus during swallowing. For calculation of bolus transit time, we recommend criteria of a 50% drop in impedance from baseline to estimate bolus entry in the pharynx and 25% impedance recovery to estimate bolus clearance in the proximal esophagus.

Although impedance-based estimates of bolus transit through the pharyngeal lumen are inaccurate, it remains to be determined if pharyngeal impedance measurement can nevertheless detect the presence of pharyngeal bolus residues resulting from failed bolus clearance. In this circumstance, the presence/absence of pharyngeal bolus residue, rather than timing of bolus transit, may be more diagnostically relevant. Pharyngeal residue is likely to lead to a reduction in pharyngeal impedance postswallow and therefore may be detected as a delay in recovery of pharyngeal impedance postswallow.

MII may prove useful for the assessment of bolus flow in dysphagia, where pharyngeal and lingual tissue contact and closure pressures might be quite low and the presence of a bolus might have a proportionately greater impact on the pattern of intraluminal impedance recorded. The technique may be particularly useful in children, where dysphagia is common and prolonged and repeated exposure to ionizing radiation is a significant concern. Given the inadequacy of standard impedance-based criteria, as determined in the current study, the appropriateness of standard impedance criteria for detection of failed pharyngeal bolus clearance (bolus residue) will need to be validated. Further studies in patients with oropharyngeal dysfunction to assess the clinical utility of pharyngeal impedance measurements in the assessment of swallowing dysfunction are therefore warranted.

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