Impact of fundoplication on bolus transit across esophagogastric junction

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1Division of Gastroenterology and Hepatology, Department of Medicine, and 2Department of Surgery, Northwestern University Medical School, Chicago, Illinois 60611-3053; and 3Department of Mechanical Engineering, Pennsylvania State University, University Park, Pennsylvania 16802-1413

Kahrilas, Peter J., Shezhang Lin, Anita E. Spiess, James G. Brasseur, Raymond J. Oehl, and Michael Manka. Impact of fundoplication on bolus transit across esophagogastric junction. Am. J. Physiol. 275 (Gastrointest. Liver Physiol. 38): G1386–G1393, 1998.—This study analyzed the effect of fundoplication on the mechanics of liquid and solid bolus transit across the esophagogastric junction (EGJ). The squamocolumnar junction was endoscopically clipped in seven controls, seven hiatal hernia patients, and seven patients after laparoscopic Nissen fundoplication. Concurrent manometry and fluoroscopy were done during swallows of liquid barium and a 13-mm-diameter marshmallow. The EGJ opening, pressure gradients, transit efficiency, and axial motion were measured. The axial motion of the EGJ was reduced in the fundoplication and hiatal hernia patients. The opening dimensions at the squamocolumnar junction were similar among groups, but in each case the constriction limiting flow to the stomach was at the hiatus and this was substantially narrowed with fundoplication. As a result, liquid intrabolus pressure was increased and marshmallow transit frequently required multiple swallows. We conclude that fundoplication limits the axial mobility of the EGJ and leads to a restricted hiatus opening. These alterations decrease the efficiency of solid and liquid transit into the stomach and are potential causes of dysphagia in this population.

hiatal hernia; lower esophageal sphincter; reflux disease; dysphagia

DYSPHAGIA IS A PROMINENT side effect of fundoplication, reported with a frequency of up to 43% (18, 19). In fact, patients are advised to anticipate short periods of postoperative dysphagia after laparoscopic Nissen fundoplication, with the usual disclaimer that this will resolve over time. Whether or not that “resolution” is actually a function of adaptation to an abnormal condition is not clear. Attempts to minimize postoperative dysphagia have logically focused on the impact of fundoplication on the esophagogastric junction, in particular on variables of the surgical technique, such as the size of the dilator used, the length of the wrap, and the degree to which the fundus is mobilized during surgery (5, 7). As a result, the dilator diameter used intraoperatively to gauge the tightness of the fundoplication has increased, the suggested length of the wrap decreased, and full mobilization of the fundus is advocated. Nevertheless, dysphagia remains a common side effect of fundoplication.

If there is a mechanical correlate of dysphagia after fundoplication, it likely involves impaired bolus transit across the esophagogastric junction, a region that exhibits unique attributes compared with the adjacent tubular esophagus (12). Whereas the tubular esophagus empties as a function of peristalsis, emptying of the phrenic ampulla, encompassing the esophagogastric junction, is more complex. The phrenic ampulla forms with longitudinal shortening of the esophagus during peristalsis, which tenses the gastric cardia through the hiatus (10). Once formed, the ampulla is globular in shape and uniform hydrostatic intrabolus pressure builds within it due to active contraction along the ampullary wall [including the lower esophageal sphincter (LES)]. Pulsatile flow from the ampulla into the stomach occurs between diaphragmatic contractions (10, 19). Coincident with emptying, the esophagus reestablishes its resting length, presumably achieved by relaxation of the longitudinal muscle and elastic recoil of the phrenoesophageal membrane. Clearly, the mechanics of the esophagogastric junction may be substantially altered by fundoplication, which is commonly performed for patients who had a hiatal hernia before surgery. However, the effect of fundoplication on the emptying mechanics at the esophagogastric junction has not been described. Thus this study aimed to contrast the emptying mechanics at the esophagogastric junction in normal volunteers, patients with a hiatal hernia, and patients after successful fundoplication.

METHODS

Esophageal emptying of a solid and liquid bolus was analyzed with combined videofluoroscopy and intraluminal manometry in groups of normal subjects, hiatal hernia patients, and patients after fundoplication to examine the influence of these conditions on esophageal emptying mechanics. The study protocol was approved by the Northwestern University Institutional Review Board, and written informed consent was obtained from study participants.

Subject groups. Subjects for this investigation were derived from a pool of normal volunteers, patients with symptomatic reflux disease identified as having a hiatal hernia, and patients who had laparoscopic Nissen fundoplication to treat chronic reflux disease. Neither the hiatal hernia patients nor patients who had undergone fundoplication had evidence of Barrett’s epithelium on the basis of prior, clinically indicated, endoscopic evaluation. Two of the hiatal hernia patients subsequently underwent fundoplication and were also studied in that group. Of the nine volunteers and nine hiatal...
patients whose squamocolumnar junction was <1 cm above the diaphragm.

Subjects were then studied with concurrent fluoroscopy and manometry. A 7-lumen silicone rubber manometric assembly with five side hole recording sites situated at 1.5-cm intervals, one side hole 5 cm proximal to this cluster, and one side hole 5 cm distal was used (Dentsleeve, Bowden, South Australia). The manometric assembly had radiopaque markers just distal to each side hole recording site. Each catheter lumen was perfused by a low-compliance perfusion pump at 0.3 ml/min (Dentsleeve Mark II, 16-channel model), connected to a computer polygraph set at a sampling frequency of 40 Hz (Neomedix Systems, Warriewood, New South Wales, Australia), and processed utilizing Gasstromac software (Neomedix). Response characteristics of each manometric channel exceeded 200 mmHg/s. Manometric tracings and fluoroscopic images were synchronized using a videotimer (model VC 436, Thalner Electronics Laboratories, Ann Arbor, MI) that encoded time in hundredths of a second on each video frame and sent a 1-V 10-ms pulse to an instrumentation channel of the polygraph at whole second intervals. A swallow of 10 ml of barium and a swallow of a 13-mm marshmallow along with 10 ml of dilute barium were done during suspended end expiration.

Data analysis. Initial analysis of the videofluoroscopic recordings was accomplished without reference to the manometric data. Relevant videofluoroscopic sequences were digitized and analyzed with image analysis software (13). Structural movement was quantified using an image-based coordinate system referenced to a stationary point on a vertebral body within the fluoroscopic field. Data were corrected for fluoroscopic magnification using the known 1.5-cm distance between the manometric sensors. Motion and opening diameter of the squamocolumnar junction were determined by tracking the motion of the mucosal clip. "Vertical" motion was quantified relative to an axis drawn through the center of the esophageal lumen with the point of hiatal crossing designated as position 0, proximal locations recorded as positive distances, and distal locations recorded as negative distances. A horizontal axis was then drawn perpendicular to the vertical axis, intersecting the esophageal wall at the attachment point of the clip. The esophageal opening diameter was measured as the distance between opposing esophageal walls along this horizontal axis. The luminal diameter of the esophagus/gastric cardia as it crossed the hiatus was also measured by this method. Videofluoroscopic data were analyzed in conjunction with the manometric recordings to discern intrabolus pressure (that obtained from within a bolus-filled luminal segment), closure pressure (intraluminal pressure at the instant that luminal closure is first achieved), and maximal contact pressure (obtained from a closed, bolus-free segment) (4). All manometric pressure values were referenced to atmospheric pressure.

Data values within test conditions were averaged and expressed as means ± SE, except for the occurrence of retrograde flow or impaired transit, which was expressed as a percentage of the total number of trials. Statistical comparisons among groups were made using the unpaired t-test.

RESULTS

Axial movement and opening of squamocolumnar junction. Esophageal emptying across the esophagogastric junction exhibited distinct characteristics within each subject group. Figure 1 illustrates a typical example of emptying mechanics for a normal subject, a hiatal hernia patient, and a patient after fundoplication.
In each case, the traced fluoroscopic images in Fig. 1 illustrate the position of the squamocolumnar junction before swallow, after swallowing but immediately before initial opening at the squamocolumnar junction, at the time that the squamocolumnar junction was maximally distended, and at the time of closure at the squamocolumnar junction. It is evident from Fig. 1 that the axial motion of the distal esophagus during emptying is greatest in the normal subject, intermediate in the hernia patient, and least in the fundoplication patient. It is also apparent from Fig. 1 that the narrowest passage for entry into the stomach is at the diaphragmatic hiatus rather than at the squamocolumnar junction and transhiatal luminal diameter is markedly diminished with fundoplication. One consequence of this is impaction of the swallowed marshmallow at the superior aspect of the fundoplication, as evident in Fig. 1 (bottom right). In all instances of failed marshmallow transit, the site of hang up was at the superior aspect of the fundic wrap.

Figure 1 suggests that deglutitive axial motion at the squamocolumnar junction is diminished in both hiatal hernia and fundoplication patients compared with normal subjects. Figure 2 summarizes group data on mobility and opening of the squamocolumnar junction. The scheme of Fig. 2 is similar to that of Fig. 1 in that the initial and extreme axial positions of the squamocolumnar junction as well as its maximal opening dimension are indicated. Evident from the summary data, opening dimensions at the squamocolumnar junction are greatest among the hiatal hernia patients and least among the normal subjects, whereas a comparison of normal subjects to hiatal hernia patients to fundoplication patients shows that deglutitive axial motion is progressively attenuated. The other major distinguishing feature of the fundoplication patients is the reduced opening dimension across the diaphragmatic hiatus (Table 1). Associated with the diminished opening dimension is impaired marshmallow transit across the esophagogastric junction; while there were no...
FUNDOPICATION AND EGJ TRANSIT

Fig. 2. Summary data on opening and axial movement of the SCJ among subject groups. As in Fig. 1, only incremental movement of the SCJ before opening and from initial to maximal opening (top) and from maximal opening to closure and descent after closure (bottom) is shown. Position of the SCJ is shown as follows. Top: □, at rest; ○, before luminal opening; ●, at maximal distension. Bottom: ●, at maximal distension; ○, at luminal closure; □, after descent. Closure vector indicates direction of luminal movement during closure; 0° is vertical and 90° is horizontal. Data are means ± SE for each subject group. *P < 0.05 vs. normal. †P < 0.05 vs. hiatal hernia.

instances of impaired transit among the normal subjects or hiatal hernia patients, this was observed in four of seven fundoplication patients (Table 1).

Mechanics of liquid transit across esophagogastric junction. Along with the altered deglutitive mechanics of the esophagogastric junction among subject groups, there were differences in the pressure characteristics of esophageal emptying. Figure 3 depicts concurrent manometric and fluoroscopic data for a normal subject. The traced fluoroscopic images in Fig. 3 show the anatomic configuration at the time of luminal closure at each recording site, and the manometric tracings depict the activity at the corresponding times at each recording site. Moving from the proximal to the distal sensor, the pattern of emptying shifts from that characteristic of the esophagus, with slight intrabolus pressure and relatively large amplitude contact pressures during the peristaltic contraction, to that characteristic of the ampulla with higher, sustained intrabolus pressure and no subsequent peristaltic contraction (12). Thus Fig. 3 (manometric tracings) indicates the pressures that are built up within the bolus to overcome the frictional pressure drop associated with the narrowing of the lumen as it traverses the hiatus.

Figures 4 and 5 are analogous to Fig. 3, illustrating examples of a hiatal hernia patient and a postfundoplication patient, respectively. In each of these cases, the pressure characteristics generated on the bolus as it traverses the hiatus are different from those of the normal subject. In the hiatal hernia patient, the magnitude of intrabolus pressure at the second and third manometric sites is low. On the other hand, in the fundoplication patient (Fig. 5), there was a rapid increase in intrabolus pressure at the fourth manometric site immediately before luminal closure. However, with fundoplication, Table 1 shows the transhiatal luminal diameter to be significantly reduced. The other distinctive feature of fundoplication was the sustained, repetitive esophageal contraction, as evident at the sixth recording site shown in Fig. 5. Table 2 summarizes data on ampullary intrabolus pressure and esophageal contractile activity among the subject groups. The functional consequence of these altered pressure dynamics

Table 1. Opening duration at the SCJ, total axial movement of the SCJ, and marshmallow transit across the EGJ in subject groups

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Normal</th>
<th>Hiatal Hernia</th>
<th>Fundoplication</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCJ opening duration, s</td>
<td>9.2 ± 0.9</td>
<td>13.4 ± 1.3*</td>
<td>12.5 ± 0.8*</td>
</tr>
<tr>
<td>SCJ axial excursion, cm</td>
<td>2.9 ± 0.3</td>
<td>1.8 ± 0.2*</td>
<td>1.3 ± 0.2†</td>
</tr>
<tr>
<td>Maximal transhiatal diameter, cm</td>
<td>1.6 ± 0.1</td>
<td>1.8 ± 0.1</td>
<td>0.8 ± 0.1†</td>
</tr>
<tr>
<td>Success of marshmallow transit</td>
<td>7/7 (100%)</td>
<td>7/7 (100%)</td>
<td>4/7 (57%)</td>
</tr>
</tbody>
</table>

Values (except for marshmallow transit) are means ± SE. Marshmallow transit was scored as all or none after a single swallow; values are given as no. of successful trials per total no. of trials, with % given in parentheses. SCJ, squamocolumnar junction. EGJ, esophagogastric junction. *P < 0.05 vs. normal. †P < 0.05 vs. hiatal hernia.

Table 2. Closure, intrabolus, and contact pressures in subject groups

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Normal</th>
<th>Hiatal Hernia</th>
<th>Fundoplication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closure pressure at the SCJ, mmHg</td>
<td>24 ± 3</td>
<td>18 ± 3*</td>
<td>38 ± 5†</td>
</tr>
<tr>
<td>Intrabolus pressure integral, mmHg/s</td>
<td>98.0 ± 5.4</td>
<td>73 ± 4.6*</td>
<td>164 ± 8.6†</td>
</tr>
<tr>
<td>Esophageal closure pressure, mmHg</td>
<td>8.2 ± 1.2</td>
<td>8.4 ± 1.7</td>
<td>10.9 ± 1.9</td>
</tr>
<tr>
<td>Esophageal contact pressure integral, mmHg/s</td>
<td>84 ± 6.2</td>
<td>68 ± 4.8*</td>
<td>124 ± 7.4†</td>
</tr>
<tr>
<td>Incomplete esophageal emptying</td>
<td>1/7 (14%)</td>
<td>2/7 (29%)</td>
<td>3/7 (43%)</td>
</tr>
</tbody>
</table>

Pressure values are means ± SE. Esophageal emptying was determined fluoroscopically; incomplete emptying was evident by residual barium within esophageal lumen at end of swallow sequence as shown in Fig. 4. Emptying values are given as no. of incomplete bolus transfers per total no. of trials, with % given in parentheses. Closure pressures are intraluminal pressure at instant of luminal closure at the SCJ or at esophageal recording site. Intrabolus pressure integral corresponds to shaded areas on manometric tracings from recording site proximal to the EGJ exhibiting greatest closure pressure; for example, recording sites 5, 2, and 4 in Figs. 3, 4, and 5, respectively. Integrals are indicative of work required to achieve luminal closure proximal to hiatus. Esophageal contact pressure integral was for area under the curve of the entire contractile complex at the most distal esophageal recording site above ampulla; for example, sites 7, 5, and 6 in Figs. 3, 4, and 5, respectively. Integrals are reflective of contractile activity of distal esophagus. *P < 0.05 vs. normal. †P < 0.05 vs. hiatal hernia.
among groups is evident in Table 2; incomplete esophageal emptying occurred in three of seven fundoplication patients and two of seven hiatal hernia patients. Figure 6 summarizes the data on closure pressure at each luminal location relative to the squamocolumnar junction, indicating that these were significantly decreased in the hiatal hernia patients and significantly increased in the fundoplication patients. Note transition from peristaltic pattern of emptying in tubular esophagus (recording site 7), characterized by high-amplitude propagated contraction, to that of the ampulla (recording sites 4 and 5), characterized by a sustained low-amplitude contraction during restoration of esophageal length (distal migration of clip at the SCJ).

Fig. 3. Fluoroscopic and manometric data on emptying across the EGJ in a representative normal subject. Fluoroscopic tracings at left depict anatomic configuration at the time of luminal closure at manometric recording sites 7, 6, 5, and 4 corresponding to t_7, t_6, t_5, and t_4, respectively. Similarly, at right, the corresponding timing of these images is indicated on manometric tracings by labeled vertical lines. As such, t_7, t_6, t_5, and t_4 represent the transition from recordings of intrabolus pressure (shaded on the manometric tracings) to recordings within a closed lumen for manometric recording sites 7, 6, 5, and 4, respectively (indicated by circled areas on manometric tracings). Note transition from peristaltic pattern of emptying in tubular esophagus (recording site 7), characterized by high-amplitude propagated contraction, to that of the ampulla (recording sites 4 and 5), characterized by a sustained low-amplitude contraction during restoration of esophageal length (distal migration of clip at the SCJ).

Fig. 7 illustrates the changes in closure pressure at each luminal location relative to the squamocolumnar junction. As noted, closure pressure was significantly increased in the fundoplication patients and decreased in the hiatal hernia patients. Note transition from peristaltic pattern of emptying in tubular esophagus (recording site 7), characterized by high-amplitude propagated contraction, to that of the ampulla (recording sites 4 and 5), characterized by a sustained low-amplitude contraction during restoration of esophageal length (distal migration of clip at the SCJ).

DISCUSSION

The esophagogastric junction is anatomically specialized to permit seemingly contradictory actions. During swallow-induced relaxation, it facilitates esophageal emptying while simultaneously preventing the reflux of gastric contents that is favored by the positive abdomen-to-thorax pressure gradient. At rest, it must episodically permit belching or vomiting but prevent frequent gastric reflex. This physiological balance is accomplished by the interplay of several anatomic and physiological variables, including the position of the LES relative to the diaphragm (22), the pattern of crural contraction during LES relaxation (17), and the repositioning of the LES relative to the diaphragm by longitudinal muscle contraction of the esophagus (10). Two circumstances during which esophagogastric junction anatomy is altered are the hiatal hernia and fundoplication. Previous studies (9, 15, 22) have shown that one consequence of a hiatal hernia is compromise of retrograde competence during swallow-induced LES relaxation. Fundoplication is performed to correct the retrograde incompetence of the esophagogastric junction both at rest and during swallow. However, improved retrograde competence may come at the expense of compromising antegrade flow. The present study suggests that fundoplication significantly alters the axial mobility of the esophagogastric junction and narrows the hiatal canal; each of these has potential negative consequences on esophageal emptying.

Eosophageal peristalsis entails both a lumen-obliterating contraction and shortening. In the tubular esophagus, shortening results from longitudinal muscle contraction (23, 24), and the magnitude of axial propulsive force as measured with a balloon tethered to a tension-sensing transducer is proportional to the magnitude of shortening in the area of the balloon (21). This mechanism of generating axial propulsive force is accentuated in the upper esophageal sphincter, a region characterized by profound clearing ability (20). Axial motion
accompanies peristalsis at the esophagogastric junction by a somewhat different mechanism; ascent is attributable to longitudinal muscle contraction but descent depends on relaxation of the longitudinal muscle and the elastic recoil of the phrenoesophageal attachments. Viewed as such, the phrenic ampulla is a small, reducing hiatal hernia (1, 8). With progressive loosening of the phrenoesophageal ligament, the phrenic ampulla first enlarges to a reducing hiatal hernia and then evolves into a persistent, nonreducing hiatal hernia (6, 10, 25). Consistent with this concept of the hiatal hernia, axial motion at the esophagogastric junction during peristalsis is quantitatively reduced with a hiatal hernia (10). Findings from the present study show an even greater decrement in axial motion after fundoplication. Figures 2 and 6 show that the most profound decrease in axial motion observed in the fundoplication group was in the descent phase of emptying. During this phase, the lumen is closed by circular muscle contraction, while esophageal length is reestablished. Conceptually, this is analogous to the grabbing effect observed within the upper esophageal sphincter during which propulsive force is maximal (20). The impaired marshmallow transit observed in the fundoplication patients suggests that decreased axial motion of the esophagogastric junction is functionally significant. This hypothesis is also consistent with the clinical observation that postfundoplication dysphagia correlates more closely with the degree of intraoperative fundic mobilization than with the completeness of the wrap itself (7).

Ampullary emptying of liquids and semisolids is altered by both fundoplication and a hiatal hernia. Rather than by peristalsis, the ampulla normally empties during expiration by a combination of elevated sustained circular muscle tension and relengthening of the esophagus (10, 12). The elevated wall tone is necessary to create a sufficient back pressure to overcome both the elevated pressure within the stomach relative to the esophagus and the frictional pressure drop associated with a narrowed hiatus. The generation of intrabolus pressure within the ampulla, the resistance to flow across the narrowed hiatal segment separating the ampulla from the stomach, and the rate of flow across the esophagogastric junction are mechanically interrelated by a form of Newton's law of motion applied to flow (assuming that frictional and pressure forces dominate over inertial and gravitational forces): 

$$
\Delta P = CV(Q/D^4) \Delta L$$

(4, 11). In this formula, $\Delta P$ is the pressure drop from the esophagus to stomach over a luminal segment of axial extent $\Delta L$, $Q$ is the volumetric rate of flow through the segment, $D$ is the average diameter of the segment, $V$ is the bolus fluid viscosity, and $C$ is a constant that depends on the cross-sectional geometry of the segment. Note that there must always be a drop in pressure in the direction of flow when friction dominates and that the required ampullary pressure that must be generated is proportional to $1/D$ to the fourth power. Thus, given that gastric pressure was nearly identical among subject groups (Fig. 6), small decreases in the hiatal diameter create large differences in the pressure drop across the hiatus even...
if the physiological system responds to increased resistance by decreasing the rate of flow and extending the time for esophageal emptying. Thus the 12.5% increase in hiatal diameter in the hiatal hernia group and the 50% reduction in the fundoplication group (Table 1) are associated with respective reduction and increase in the intrabolus pressure integral of these groups (Table 2). Increased intrabolus pressure proximal to fundoplication of similar magnitude has recently been reported by Mathew et al. (14).

A change in intrabolus pressure within the ampulla implies also a change in "clamping" pressure required to maintain luminal closure at the tail of the ampulla (for example, recording site 6 at time 6 in Fig. 5). Figure 6 illustrates the differences among groups in the pressure required to maintain ampullary closure during emptying. Closure pressures are greatly increased in the fundoplication group and reduced (with a more proximal peak) in the hiatal hernia group. Physiologically, increased ampullary pressure implies increased active tension within the circular muscle of the esophageal wall surrounding the ampulla. This statement is based on the application of "Laplace's law" ($T = \frac{1}{2}P \times D$) where $T$ is tensile force per axial length of circular muscle, $P$ is the intrabolus pressure relative to thoracic pressure, and $D$ is the luminal diameter. If the muscle of the distal esophagus is incapable of providing the required increment in tone, the rate of flow through the esophagogastric junction must be reduced or a failure of emptying will occur, evidenced by retrograde flow of the bolus (Table 2). A similar effect is observed in an esophagus obstructed by a diameter-limiting ligature (16); the esophagus proximal to the partial obstruction...
exhibits repetitive sustained contractions as evident by the tracing at the sixth recording site in Fig. 5 and by the esophageal contraction integral values in Table 2. This pattern of repetitive contractions is not normally seen at the esophagogastric junction even in the case of outflow obstruction by a Müller maneuver, because the esophageal segment normally generating the intrabolus pressure (the phrenic ampulla) exhibits a sustained tonic contraction rather than a propagated peristaltic one (2, 3, 12). Thus the occurrence of these spasm-like esophageal contractions is another consequence of decreased mobility of the esophagogastric junction after fundoplication.

In conclusion, functional alterations of the esophagogastric junction are evident with both a hiatal hernia and fundoplication. With a hiatal hernia, there is a major defect in retrograde competence during peristalsis (15, 22). Findings from the present study suggest that fundoplication impairs antegrade transfer of both solids and liquids at least in part because of decreased mobility of the esophagogastric junction during peristalsis and narrowing of the transhiatal passage. Although the subjects in this investigation did not report clinically significant dysphagia, they exhibited objective evidence of impaired bolus transfer that was attributable to the altered mechanics of the esophagogastric junction consequent from fundoplication. Further work will be necessary to determine the relationship between these observations and clinically significant postfundoplication dysphagia.

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