A New Era in Esophageal Diagnostics: The Image-Based Paradigm of High-Resolution Manometry

Renato Salvador, MD, FACS, Attila Dubecz, MD, Marek Polomsky, MD, Oliver Gellerson, MD, Carolyn E Jones, MD, Daniel P Raymond, MD, Thomas J Watson, MD, Jeffrey H Peters, MD, FACS

BACKGROUND: The development of high-resolution (HRM) catheters and software displays of manometric recordings in color-coded pressure plots has changed the diagnostic assessment of esophageal disease. HRM may offer advantages over conventional methods, including improved identification of motility disorders, hiatal hernia, and outflow obstruction, and ease interpretation.

STUDY DESIGN: HRM studies were obtained in 50 healthy volunteers and 106 patients. HRM was performed using a 36-channel catheter, with sensors spaced at 1-cm intervals. Manometric findings were classified into abnormalities of the gastroesophageal barrier and those of the esophageal body and validated by comparison with endoscopic and radiographic diagnostic methods.

RESULTS: The mean time for HRM was significantly lower than that for a conventional method (8.1versus 24.4 minutes; $p < 0.0001$). A structurally defective lower esophageal sphincter (LES) was present in 53 (57.3%) patients, a hypertensive LES in 6 (7.8%), and impaired LES relaxation in 17 patients (16.7%). Validating the LES findings, 86.3% (44 of 51) of patients with a defective sphincter by HRM had radiographic or endoscopic evidence of a hiatal hernia, and 80% (41 of 51) had a positive pH study, endoscopic erosive esophagitis, or Barrett's esophagus. Evidence of a hiatal hernia by HRM was seen in 33 (56%) patients; a hiatal hernia was seen in 91% (30 of 33) of these on endoscopy and 81% (17 of 21) on barium swallow. Fifty-eight patients (54.7%) had an abnormal body motility.

CONCLUSIONS: HRM studies are shorter than those using conventional methods. Interpretation is image based, and correlation with objective endoscopic and physiologic findings confirms the accuracy of interpretation. The introduction of HRM is a significant advance in the outpatient evaluation of esophageal function. (J Am Coll Surg 2009;208:1035–1044. © 2009 by the American College of Surgeons)

It has been said that progress is often made by applying new technology to old problems or, more rarely, old technology to new problems. The introduction of high-resolution esophageal manometry is an example of the former. Esophageal manometry was introduced into clinical practice in the 1970s, and although it has slowly evolved, it remains fundamentally similar to the early efforts. Techniques for recording intraluminal pressure were introduced in the late 1960s, and accurate measurements became possible with development of the low-compliance perfusion systems widely used for decades.[1] Over the past 20 to 30 years, esophageal manometry has found its place as an important tool in assessing patients with foregut symptoms. This is particularly true in surgical practice, where a fundamental understanding of esophageal physiology may have an impact on the outcomes of esophageal surgery.[2] Decisions for medical or surgical therapy are often influenced by knowledge of the patient's esophageal physiology, as are patient discussions about risks, the potential for complications or side effects, and the probability of symptom and relief. A full understanding also allows selection of the approach, procedure, and technical elements of surgery to be designed with the patient's specific characteristics in mind.

Technology introduced in the 1990s began to change the landscape of esophageal diagnostics beginning with Nguyen and colleagues'[3] description of multichannel intraluminal impedance and Clouse and colleagues'[4] introduction of the concept of high-resolution manometry

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From the Department of Surgery, Division of Thoracic and Foregut Surgery, University of Rochester, Rochester, NY.
Correspondence address: Jeffrey H Peters, MD, Department of Surgery, Box SURG, 601 Elmwood Ave, University of Rochester, Rochester, NY 14642.

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Abbreviations and Acronyms

GERD = gastroesophageal reflux disease
HRM = high-resolution manometry
LES = lower esophageal sphincter
UES = upper esophageal sphincter

(HRM). These were the first new tools in decades for clinical evaluation of patients with esophageal disease. The introduction of HRM into clinical practice, and the development of sophisticated algorithms to display the expanded manometric dataset as pressure topography plots, transformed esophageal manometry into an image-based paradigm that holds promise to offer advantages over conventional methods for both research and clinical applications.[5-7] The aim of this study was to establish normal values for HRM and assess its diagnostic utility and benefits in a cohort of patients presenting with foregut symptoms.

METHODS

The study population consisted of 50 healthy volunteers and 106 patients evaluated between September 2005 and November 2007 in the Department of Surgery, University of Rochester. The patients included 41 men and 65 women, with a mean age 53 years (range 20 to 90 years), who underwent esophageal function testing using HRM. Patients with malignant disease or earlier foregut surgical procedures were excluded. Manometric findings were classified considering each esophageal anatomic-physiologic "compartment," including components of the gastroesophageal barrier (LES), sphincter relaxation, motility of the esophageal body, and the cricopharyngeal muscle.

Normal values

Normal values were defined by recording topographic, time, and pressure events (HRM) in 50 asymptomatic healthy volunteers. There were 28 men and 22 women, with a mean age of 27 years (range, 20 to 52 years). Healthy subjects had no history of foregut or gastrointestinal symptoms or upper gastrointestinal tract surgery, were not taking antisecretory or other gastrointestinal medications, and all were without other comorbid medical conditions.[5] Radiographic or endoscopic investigation was not performed. Normal values are reported as the average of three independent readings, each performed by a surgeon with considerable experience in esophageal manometry.

Technique of high-resolution manometry

The catheter used is 4.2 mm in diameter and contains 36 solid-state circumferential sensors spaced at 1-cm intervals (Sierra Scientific Instruments).[8] This device uses pressure transduction technology (TactArray), which allows each of the 36 pressure-sensing elements to detect pressure over a length of 2.5 mm in 12 radially dispersed sectors. The pressure of each sector is averaged, making each of the 36 sensors a circumferential pressure detector, with the extended frequency response characteristic of solid-state manometric systems. The response characteristics of each sensing element are designed to record pressure transients in excess of 6,000 mmHg/second and to be accurate to within 1 mmHg of atmospheric pressure for measurements obtained in the final 5 minutes of the study, immediately before thermal recalibration. The data-acquisition frequency was 35 Hz for each sensor.[8-10] Manometric data were analyzed using ManoView analysis software (Sierra Scientific Instruments).

The procedure is performed by a trained esophageal laboratory nurse in conjunction with an esophageal fellow. The patient is prepared and the catheter passed by the nursing staff. The fellow is responsible for accurate conduct of the study, assuring correct catheter placement spanning the two sphincters, appropriate patient swallowing, and concurrent interpretation to allow a technically acceptable study. At the outset of each procedure, transducers are calibrated to 0 and 100 mmHg using externally applied pressure. Studies were done in the supine position after at least a 6-hour fast. Most esophageal studies are performed in a body position to accentuate abnormalities, ie, lying flat (increasing sensitivity). This is true of radiographic evaluation and motility. The HRM assembly is passed transnasally and the 36 sensors positioned to record from the hypopharynx to the stomach, including a minimum of 4 intragastric sensors. The catheter is then fixed in place by taping it to the nose.[8] Data acquisition begins with a 20-second swallow-free period used in the software analysis phase to assess the basal pressure and length characteristics of the lower and upper esophageal sphincters (landmark frame). This is followed by 10 consecutive swallows of 5 mL saline more than 25 seconds apart to evaluate the esophageal body motility and lower esophageal sphincter (LES) relaxation. Normal saline, with its standardized concentration of electrolytes, is used to facilitate proper catheter function.

Analysis

Manometric data were analyzed using ManoView analysis software. Analysis begins by using the landmark frame to obtain baseline reference values for the upper esophageal sphincter (UES), LES, and pressure inversion point. Measurements of the LES were established by dragging the individual corresponding icons (ie, LES, LES upper border, LES lower border) up or down on the right side of the

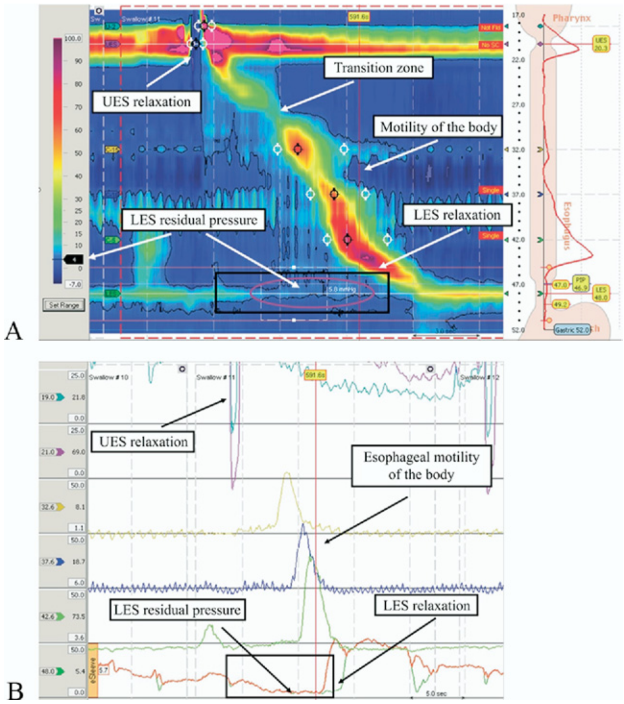


Figure 1. (A) High-resolution manometry image of esophageal pressure activity in a normal subject. The spatiotemporal plot presents the same information as is present in the line plots. (B) The segmental functional anatomy of esophagus with progressive contraction (peristaltic waves) can be clearly seen. The synchronous relaxation of the upper esophageal sphincter (UES) and lower esophageal sphincter (LES) is highlighted with the arrows. LES relaxation pressure was measured by scaling down the isobaric contour tool to the pressure level at which the isobaric lines become discontinuous, which represents the minimal pressure imaged. In this example, the LES residual pressure is 4 mmHg. (B) The same study by conventional manometry picture, with pressure range values from 0 to 50 mmHg.

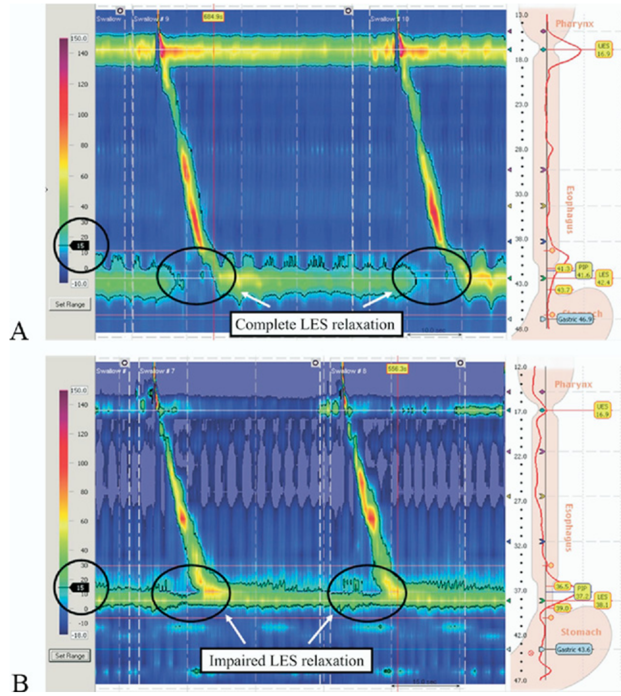


Figure 2. Isobaric contour tool. A high lower esophageal sphincter (LES) residual pressure can be readily identified by slowly decreasing the isobaric contour pressure. (A) Example of complete sphincter relaxation and residual pressure < 15 mmHg using an isobaric tool value set at 15 mmHg (95th percentile of normal value). The dark lines outlining the sphincter high-pressure band can be seen to be discontinuous, indicating a pressure below 15 mmHg. (B) Example of LES residual pressure higher than 15 mmHg. Here, with the isobaric tool value set at 15 mmHg, the dark lines outlining the sphincter high-pressure band are continuous, indicating the pressure never drops below 15 mmHg, a clear example of impaired LES relaxation.

screen in the Pressure Profile panel to the appropriate level imaged from the recording (Fig. 1).

Isobaric contour tool

The analysis software includes an interpretation aid known as the isobaric contour tool. This can be activated by selecting the appropriate software menu option and allows "boundaries" to be drawn around any designated pressure value (Fig. 2). This can be useful to assess adequate sphincter relaxation. Choosing this tool at a setting of, for example, 15 mmHg, results in software construction of "boundary lines" delineating pressures above and below 15 mmHg. Focusing on the high-pressure band of the LES, if the lines do not come together, the pressure never drops below 15 mmHg. Given the finding that LES residual pressure values > 15 mmHg are abnormal (see Results section), this indicates inadequate relaxation. Figure 2 shows an example assessment of sphincter relaxation and residual pressure using a set value of 15 mmHg. Successful relaxation below this level (Fig. 2A) can be seen as occurring when the boundary lines are discontinuous. In contrast, failure to relax below 15 mmHg can be seen in Figure 2B, as isocontour boundary lines that completely encompass the sphincter area (ie, never fall below 15 mmHg). The isobaric contour was used to visualize and estimate LES relaxation duration and pressures, LES-crural diaphragm separation, configuration of esophageal body motility, and intrabolus pressures.

Each of the 10 subsequent swallow frames includes UES contraction, UES relaxation, and esophageal body contraction. Postswallow esophageal function is analyzed by placing spatial markers at the start, peak, and end of the relaxation and contraction for each specific channel. The esophageal body contraction can be clearly visualized by its colored contour, facilitating placement of the spatial markers. These pressure data are transformed into a topographic (color contour) plot, which provides a continuous depiction of pressure along the entire recording segment throughout time. This allows a complete spatial and temporal analysis of esophageal motor events.[4]

Definitions

Abnormal values were defined as those above or below the 5th and 95th percentiles of values obtained from normal volunteers. A structurally defective LES was defined as having any one of the following abnormalities:[11] overall length < 2.4 cm, abdominal length < 0.9 cm, and resting pressure < 9.8 mmHg. A hypertensive LES was defined as a resting pressure above 49.8 mmHg. Impaired relaxation was considered present when either the LES residual pressure was > 14.7 mmHg or the percent LES relaxation was below 57.5%.

Failed contraction waves were defined as complete failure of the contraction, with no pressure domain above 30 mmHg (by isobaric contour). The proximal body segment was defined hypotensive when the amplitude was between 25 and 29.8 mmHg and hypertensive with amplitude > 126.2 mmHg. The distal body segment was defined as hypotensive when contraction amplitudes were between 30 and 43.2 mmHg and hypertensive when the contraction amplitude was > 180.2 mmHg. Ineffective esophageal motility was defined as more than 3 peristaltic contractions with any combination of: failure of wave progression, contraction amplitudes ≤ 30 mmHg, or failed

Table 1. Normal Values in 50 Healthy Volunteers Who Underwent High-Resolution Manometry

Characteristics	Mean	SD	Median	5th–95th percentile
Normal lower esophageal sphincter				
Length overall, cm	3.2	0.5	3.2	2.4–4.0
Abdominal length, cm	1.9	0.59	1.9	0.9–2.7
Resting pressure, mmHg	27.7	12	26.7	9.8–49.8
Residual pressure, mmHg	5.7	4	5	0.2–14.7
Normal esophageal body				
Distal body amplitude, mmHg	98.03	43.6	91	43.2–189
Distal body duration, s	3.77	0.65	3.6	2.8–4.9
Proximal body amplitude, mmHg	48.5	20.4	45.2	29.8–126
Proximal body duration, s	3.19	0.62	3.2	2.6–4.1
% peristaltic waves	96.6	8.4	100	80–100
Normal upper esophageal sphincter				
Resting pressure, mmHg	73.8	25.48	70.4	35.5–113
Residual pressure, mmHg	−1.01	5.6	−0.5	−9.4–9.7

Values are an average of three independent readings by experienced manometric fellows.

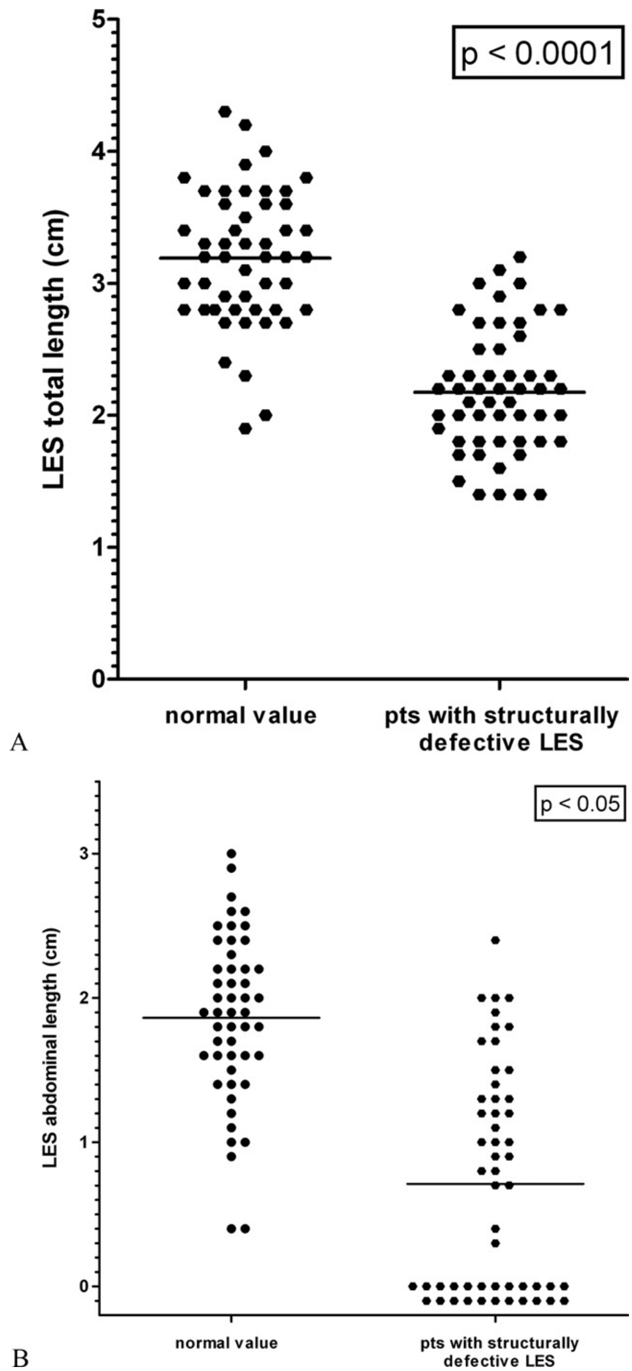


Figure 3. (A) Scatterplot of lower esophageal sphincter (LES) total length in 50 healthy volunteers and in 53 patients with structurally defective LES ($p < 0.0001$). (B) Scatterplot of LES abdominal length in 50 healthy volunteers and in 53 patients with structurally defective LES ($p < 0.05$).

Table 2. Comparison of Endoscopic and Radiographic Evidence of Hiatal Hernia in Patients with Two Distal High-Pressure Zones on High-Resolution Manometry

	High-resolution manometry, n	
Variables	**Manometrically evident two high-pressure zones**	**No manometrically evident two high-pressure zones**
Endoscopy		
Evidence of hernia	30	28
No evidence of hernia	3	20
Barium swallow		
Evidence of hernia	17	17
No evidence of hernia	4	20

peristalsis over a segment of the distal esophagus. Diffuse esophageal spasm was defined as ≥ 20% (2 of 10) contraction waves, with velocities > 8 cm/second over the distal 3 segments of the esophagus. The assessment of the esophageal body was based on 10 swallows.

Statistical analysis

Normal value results are reported as mean, median, standard deviation, maximum, minimum, and 5th to 95th percentile. Fisher's exact test and *t*-test were used to compare categorical data. Statistical significance was determined at $p < 0.05$.

RESULTS

Normal values

Values for LES total and abdominal length, resting and residual pressure, esophageal body contraction wave amplitude, duration, and propulsion and UES resting pressure obtained from the 50 normal volunteers are shown in Table 1.

Indications and conduct of the procedure

The primary symptoms for which patients were referred for esophageal function testing were: heartburn in 95 (89.6%), regurgitation in 92 (86.8%), cough in 60 (56.6%), chest pain in 41 (38.6%), hoarseness in 40 (37.7%), dysphagia in 22 (20.7%), wheezing in 17 (16%), and epigastric pain in 15 (15%). Procedure times for 40 random patients undergoing either HRM or 10 swallows of a conventional impedance manometry (MII EFT) were compared. The mean procedure time for HRM was 8.2 minutes, ranging from 6 minutes, 49 seconds to 11 minutes, 01 second. This was markedly less than that for the MII EFT procedure (excluding 10 viscous swallows), which averaged 24.42 minutes and ranged from 17 minutes, 19 seconds to 37 minutes, 01 second ($p < 0.0001$). HRM findings were abnormal in 91 (85.8%) of the 106 patients. Only 15 patients (14.2%) had normal manometric findings.

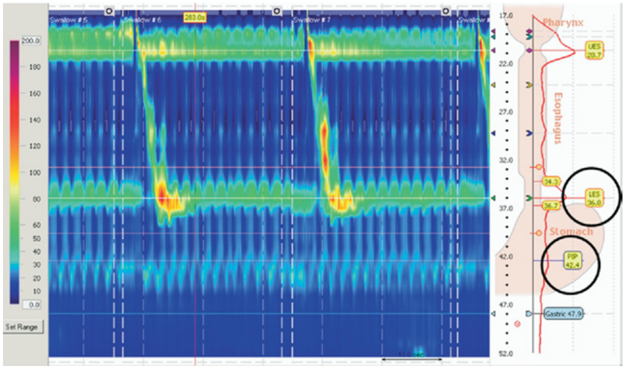


Figure 4. Identification of a hiatal hernia. Two distal high-pressure zones can be readily seen as color bands across the lower portion of the tracing. The most distal high-pressure zone is the location of the diaphragmatic crus, and the more proximal zone is the high-resolution manometry image of the lower esophageal sphincter.

Assessment of the lower esophageal sphincter

Resting pressure and total and abdominal lengths of the lower esophageal sphincter were assessed by analyzing a 30-second landmark frame at the onset of the procedure. Abdominal length is determined by identifying the pressure inversion point with software assistance as the icon is scrolled into the thorax from the abdomen.

Abnormal LES measurements were detected in 71 (68.9%) of 103 patients in whom the sphincter could be assessed. It was structurally defective in 53 (57%), hypertensive in 6 (6%), and had impaired relaxation (residual pressure > 14.7 mmHg) in 17 (17.5%) of the patients. A short total length was the most common cause of a defective sphincter (Fig. 3A), present in 39 of 53 (73.6%) patients, followed by a short abdominal length (Fig. 3B) in 31 of 53 (58.5%), and low resting pressure in 15 of 53 (28.3%). In an effort to validate the sphincter measures, Table 2 shows the relationship of a structurally defective sphincter to other clinical features of patients with gastroesophageal reflux disease (GERD). Eighty-six percent (44 of 51) of patients with a defective sphincter by HRM had radiographic or endoscopic evidence of a hiatal hernia, 78.6% (22 of 28) had an abnormal esophageal pH study, and 78.4% had endoscopically confirmed erosive esophagitis or Barrett's esophagus. The sphincter was hypertensive in 6 patients (5.9%), 4 of whom had achalasia (66.7%).

Evidence of a hiatal hernia was present when 2 distal high-pressure zones were identified on the high-resolution images (Fig. 4). This was seen in 33 (56%) of the patients, and, when present, it was always associated with a structur-

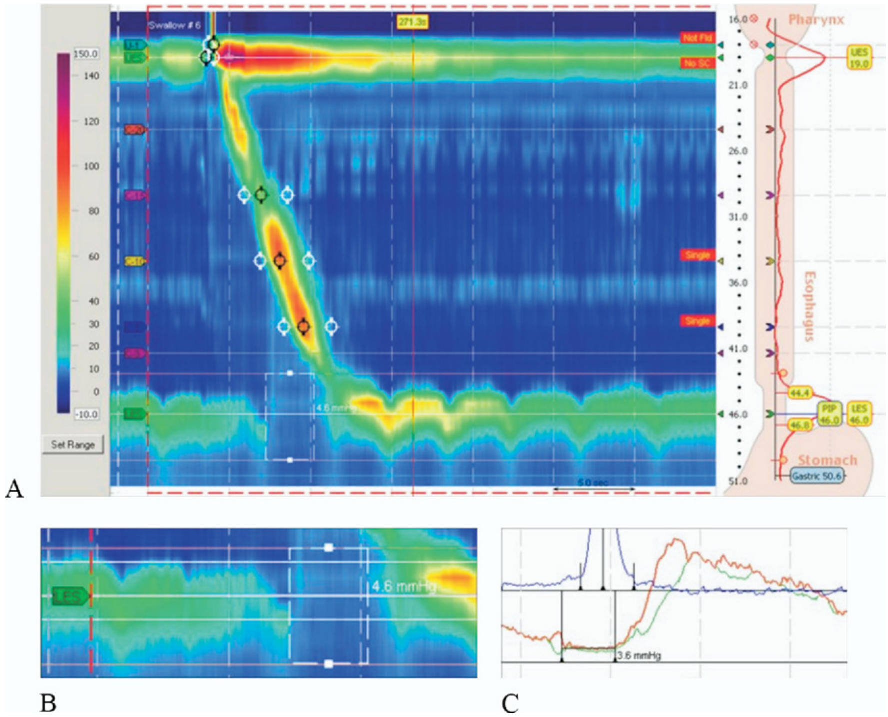


Figure 5. Assessment of lower esophageal sphincter (LES) relaxation and esophageal body function. (A) The white box, a 3-second software marker used to assess LES relaxation, is placed over the area corresponding to LES relaxation. This area appears between the pharyngeal contraction and the end of the esophageal body contraction and is visually apparent by having a darker hue of blue color representing decreased pressure of the LES. Esophageal body contraction amplitudes are assessed during the swallow frame analysis by selecting channels 5 cm, 10 cm, and 15 cm above the LES. Body contractions are clearly visualized and identified by their colored contour as progressive waves of higher amplitude from the upper esophageal sphincter (UES) high-pressure zone to the LES high-pressure zone. Spatial markers are placed at the start, peak, and end of the body contraction for each specific channel level. (B) Magnified view of the LES relaxation area. (C) Conventional line tracing mode showing a horizontal bar within this box positioned at the lowest point of the tracing to obtain LES residual pressure.

ally defective LES. All 33 patients with a hernia configuration on HRM had upper endoscopy, and 21 a barium swallow. A hiatal hernia was confirmed in 30 of 33 (91%) patients on upper endoscopy and 17 of 21 (81%) on video barium swallow.

LES relaxation and residual pressure were assessed during swallow frame analysis, as described in the Methods section (Fig. 5). LES relaxation was incomplete in 17 patients (16.7%). When relaxation was incomplete, 76.5% had a final diagnosis of achalasia (Fig. 6). The percent LES relaxation was below normal in 17 of 18 patients with diagnosis of achalasia (94.5%; $p < 0.0001$). A receiver-operator curve of the sensitivity and specificity of LES residual pressure in the diagnosis of achalasia is shown in Figure 7. A value of 15 mmHg will distinguish achalasia from nonachalasia patients with a specificity of 72% and a sensitivity of 96%. Three patients had impaired relaxation without achalasia; each had evidence of esophagitis and a positive pH study, suggesting the possibility of scarring or stricture (Table 3).

Assessment of the esophageal body

Esophageal body parameters were assessed for each of 10 swallows during the swallow frame analysis, as described in the Methods section. Body contractions were clearly visualized and identified by their colored contour as progressive waves of higher-amplitude color from the UES high-pressure zone to the LES high-pressure zone. It was considered ineffective if 3 or more peristaltic contractions had failure of wave progression, contraction amplitudes $\leq$ 30 mmHg. Diffuse esophageal spasm was defined as $\geq$ 20% contraction waves, with velocities $>$ 8 cm/second over the distal 3 segments of the esophagus. Fifty-eight (54.7%) of the 106 patients had abnormal motility of the esophageal body. Classic motility disorders were present in 34 patients, achalasia in 20 (18.8%), ineffective esophageal motility in 9 (8.5%), nut-

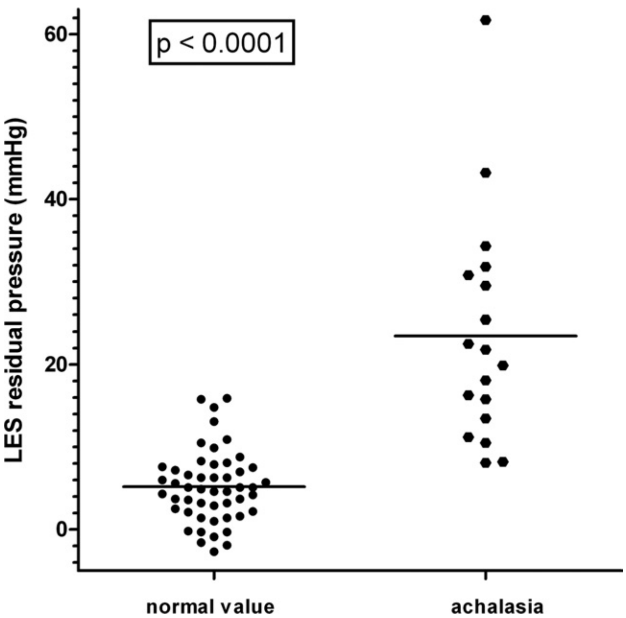


Figure 6. Scatterplot of lower esophageal sphincter (LES) residual pressure in 50 healthy volunteers and 18 patients with diagnosis of achalasia ($p < 0.0001$).

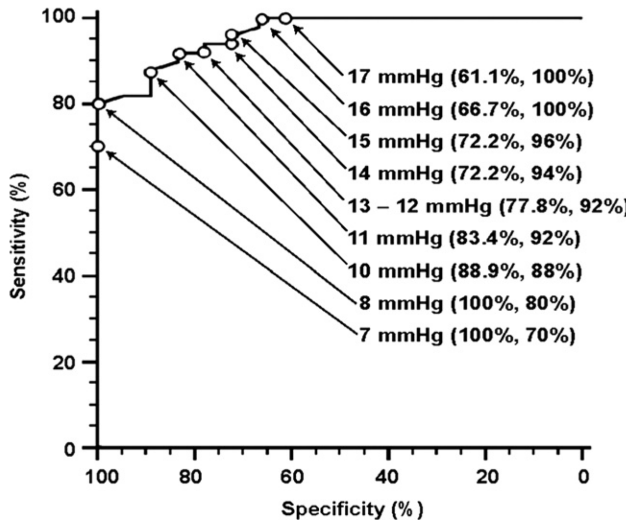


Figure 7. Receiver-operator curve analysis of the sensitivity and specificity of various high-resolution manometry measured values of the lower esophageal sphincter residual pressure in 18 patients with achalasia.

cracker amplitudes in 4 (3.8%), and diffuse spasm in 1 (0.9%).

Wave progression abnormalities, defined as ≥ 20% of the 10 swallows, were present in 34 (32.1%) patients and contraction amplitude abnormalities, defined as the average of 10 contraction amplitudes above or below normal values, in 42 (39.6%) of the 106 patients. As can be seen in Figures 12–15, the image-based analysis of the high-resolution data makes identification of these abnormalities readily evident. Esophageal contraction waves were simultaneous or failed (Fig. 8) in 34 patients; 20 of these had a final diagnosis of achalasia (Fig. 9), and 1 had diffuse esophageal spasm. Of the 13 remaining patients, 3 had delayed contractions (Fig. 10), 9 had ineffective esophageal motility, and 1 had scleroderma.

Abnormal segmental amplitudes were seen in 42 patients, 14 of whom were abnormally high (33.3%) and 28 abnormally low (66.7%). Nutcracker esophagus was detected in 4 patients (Fig. 11).

Table 3. Manometric Diagnosis in Patients with Impaired (Residual Pressure > 14.7 mmHg) and Normal Lower Esophageal Sphincter Relaxation

	Abnormal, n = 17 (16.7%)		Normal, n = 85 (83.3%)	
Variable	**n**	**%**	**n**	**%**
Total	17	16.7	85	83.3
Achalasia	13	76.4	5	5.9
Other motility disorders	2	11.8	39	45.9
Normal motility	2	11.8	41	48.2

DISCUSSION

HRM is a new technology introduced into the world of esophageal investigation. This new methodology is a variant of conventional manometry, in which multiple recording sites are used, in essence creating a "map" of the esophagus and its sphincters. Pressure sensors are placed in such close proximity to each other that, by interpolating between sensors, intraluminal pressure becomes a spatial continuum.[12] Published reports using HRM technology, particularly those comparing it with conventional study, are scarce, because the technique is new. This article suggests that HRM is an improvement over conventional manometry in clinical practice, allowing shorter procedure times; accurate detection of LES structural parameters and the relationship of the sphincter to the diaphragmatic crura; assessment of LES relaxation; and image-based interpretation of esophageal body motility, underlying motility abnormalities, and outflow obstruction. Basic cricopharyngeal function can also be assessed, although sophisticated analysis of cricopharyngeal function through HRM is not yet well established. As such, we have not focused on upper sphincter assessment in this article.

Simultaneous acquisition of data for the UES, esophageal body, LES, and gastric pressure minimizes the movement artifacts and study time associated with conventional esophageal manometry. Our results show that the time for the high-resolution procedure is shorter than that for a

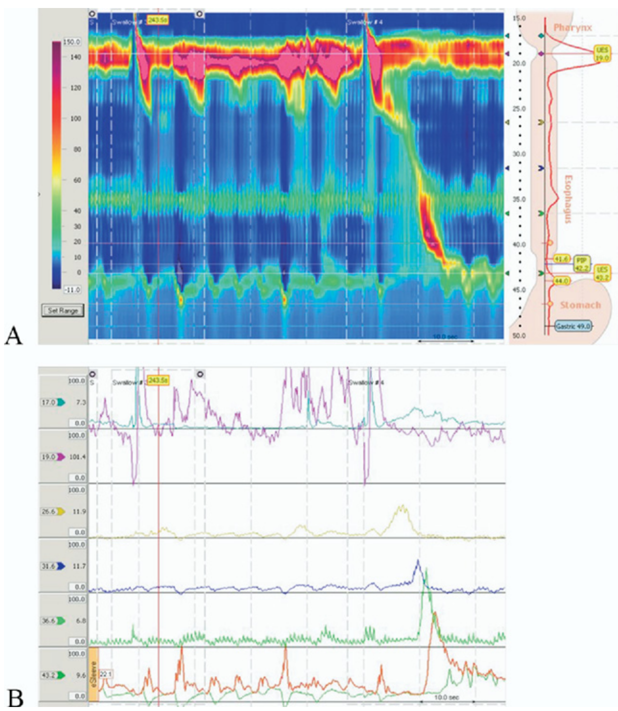


Figure 8. Failed contractions. (A) The failed contraction is evident after the first pharyngeal contraction, and the normal contraction is clear after the second pharyngeal contraction. (B) Conventional line tracing of the same patient.

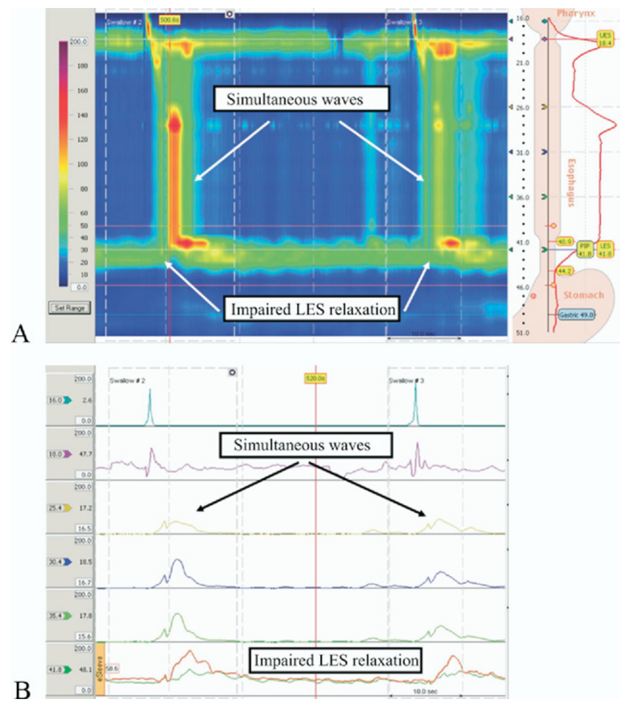


Figure 9. Achalasia. (A) The simultaneous isobaric esophageal pressurization and absent contractions of the esophageal body motility are readily seen in a patient with achalasia. Impaired lower esophageal sphincter (LES) relaxation can also be easily seen as a continuous high-pressure band across the lower portion of the image. (B) Conventional manometry picture of the same patients.

conventional study. In fact, the longest time to perform a high-resolution study (11minutes, 1 second) was shorter than the fastest time of a conventional study (17 minutes, 19 seconds). This should improve acceptance and compliance of patients for the procedure. Although HRM clearly simplifies the performance of a motility study, there is a considerable learning curve for accurate interpretation. In fact, there are aspects of the image that remain poorly defined, such as identification and measurement of a "bolus pressure." Traditional manometry often identified a ramp or bolus pressure as a pressure "hump" just preceding the esophageal contraction wave. This is thought to represent the resistance encountered by the bolus as it is squeezed down the esophagus and can be high in patients with various manifestations of outflow obstruction, such as those that can be caused by a stricture or earlier operation. Methodology to identify and measure this physiologic feature through HRM, which has clinical relevance, is lacking at present.

Normal values defined in our laboratory were similar, although not identical, to those defined by the Northwestern group.[8] We found somewhat higher mean basal LES pressures (27 mmHg [University of Rochester] versus 16 mmHg [Chicago]) and corresponding 5^{th} to 95^{th} percentile normal ranges (9.8 to 49.8 mmHg [University of Rochester] versus 5.0 to 31.6 mmHg [Chicago]). The difference may be from subjectivity in the analysis and/or patient population differences (likely the former) and further standardization of LES analysis is needed. Esophageal body contraction amplitudes were similar to those reported by the Northwestern group.

HRM facilitates assessment of both the LES and esophageal body characteristics. It eliminates the need for the cumbersome pull-through procedure during the study, and we found the image-based assessment of sphincter competence readily evident. As in interpretation of a chest radiograph and other medical images, the difference between normal and abnormal is easily seen. For example, the presence of 2 high-pressure bands along the lower portion of the tracing often indicates the presence of a hiatal hernia (Fig. 7). Our data suggest that this is a reasonably specific finding in that 80% to 90% of the time it was seen, a hernia was confirmed by upper endoscopy or barium study, although not likely very sensitive, as can be seen from the data in Table 2. The absence of a hernia configuration on HRM does not indicate that a hernia is not present.

In fact, HRM may offer insights not otherwise available on conventional manometry. Our data agree with the suggestion of Pandolfino and colleagues[13] that a separate clas-

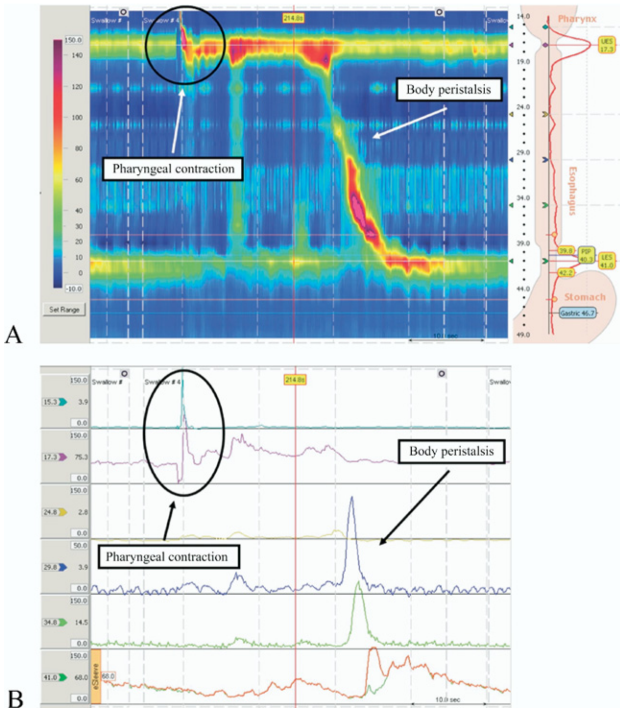
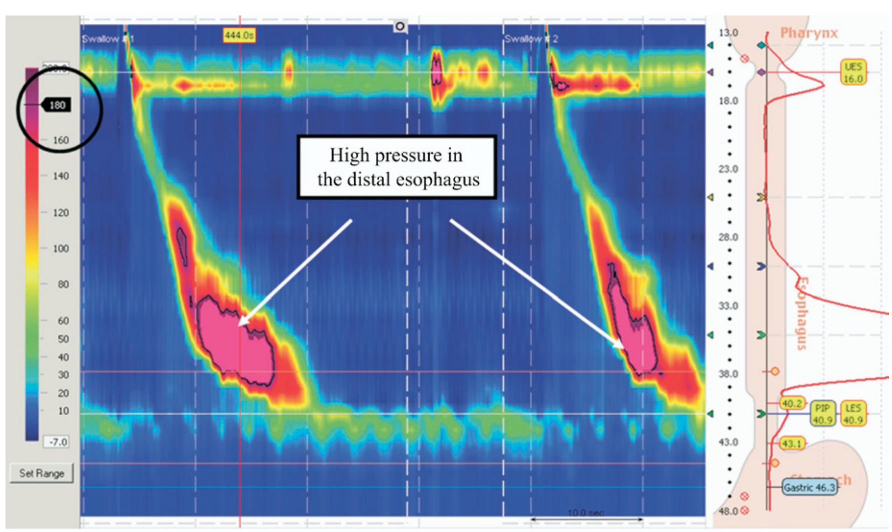


Figure 10. Delayed contractions. (A) Esophageal body contraction is evident 20 seconds after the pharyngeal contraction. (B) Conventional line tracing of the same patient for comparison.

sification of vigorous achalasia may be in error. Five of our 20 patients with a final diagnosis of achalasia had "contraction pressures" in the esophageal body of > 60 mmHg. These values would define vigorous achalasia in conventional manometric interpretation. Careful inspection of the images shows that each of these five patients had identical pressure values in every channel, more accurately reflecting esophageal pressurization than "vigorous" muscular contraction of the esophagus. In fact, we reviewed video barium swallows of these patients, and 4 of 5 had no evidence of esophageal muscular contraction. These HRM observations call into question the concept of vigorous achalasia.

These benefits of HRM are supported by the recent publication of Pandolfino and associates.[13] Reporting an analysis of HRM in 400 patients, the authors concluded that HRM offers new insights into the physiology of esophageal spastic disorders by distinguishing between spasm (a rapidly propagated lumen obliterating contraction) and compartmentalized pressurization (pseudospasm). The Northwestern group suggested that by this new distinction, vigorous achalasia and diffuse esophageal spasm are quite rare, reclassifying the majority of these patients to groups best managed with treatments directed at the esophagogastric junction. They have further shown that HRM, with its imaged-based detail compared with conventional manometry, adds new insights to the early stages of hiatal hernia development and its association with GERD. Focusing on crural diaphragm function and its relation to the LES, they compared HRM tracings of 75 controls and 156 esophagogastroduodenoscopy or pH-positive GERD patients.[5] HRM pressure tracings facilitated identification of functional LES-crural diaphragm separation in the early stages of GERD, which correlates with objective measures, including erosive esophagitis and



A B

Figure 11. Nutcracker esophagus. (A) High-amplitude distal esophageal body contractions represented by the high-pressure red contour of the esophageal body contraction. In this example, contraction amplitudes are well above 180 mmHg. (B) Conventional line tracing of the same patient for comparison.

pathologic esophageal acid exposure. These authors concluded that the reduced inspiratory augmentation of esophagogastric junction pressure afforded by abnormal crural diaphragm-LES integrity is a better predictor of positive esophageal pH findings than LES resting pressure alone.

Assessment of LES relaxation is arguably the most difficult and potentially artifactual component of conventional esophageal manometry. We found interpretation of LES relaxation on HRM to be more intuitive than with a conventional study, where the waveforms often don't explain the spatio/temporal events of sphincter movement. The use of software-based isobaric contour tool (lines drawn around any set pressure value) facilitates assessment of relaxation normality or abnormality. For example, setting the value to 15 mmHg will draw a boundary around all values 15 mmHg or greater. If the sphincter area does not have a component below these values, relaxation is abnormal (Fig. 2). Similarly, this isobaric contour tool can be used to delineate the anatomic and temporal borders of the LES high-pressure zone and esophageal body, facilitating the graphic visualization of LES and esophageal body abnormalities.

Development and introduction of a practical manometry device with 36 solid-state circumferential sensors spaced at 1 cm each permit visualization of esophageal motility as a continuum along the length of the esophagus.[12] This allows a clear, graphic visualization of segmental and global abnormal motility or outflow obstruction, often allowing identification of motility abnormalities limited to a portion of the esophageal body that may be missed by pressure sensors placed farther apart. More examples can be seen in Figure 15. The ready identification of high-pressure waves (nutcracker esophagus), diffuse spasm, and ineffective esophageal motility on HRM is in contrast to the difficulty often present in conventional manometry, where analysis by an expert may be required for recognition. HRM readily identifies the "transition zone," an often "hidden" part of the esophageal body corresponding to the transition from striated to smooth muscle in the proximal esophagus.

In conclusion, we believe that the introduction of HRM is a significant advance in the ambulatory evaluation of esophageal function, bringing it into the realm of "image"-based studies. HRM has the potential to improve the science of esophageal manometry and improve clinical outcomes. It simplifies interpretation and increases patient acceptance, both of which may lead to greater use in surgical practice.

Author Contributions

Study conception and design: Salvador, Dubecz, Polomsky, Jones, Raymond, Watson, Peters
Acquisition of data: Salvador, Dubecz, Polomsky
Analysis and interpretation of data: Salvador, Dubecz, Polomsky, Peters
Drafting of manuscript: Salvador, Dubecz, Polomsky, Peters
Critical revision: Salvador, Peters

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