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High Resolution Manometry Correlates of Ineffective Esophageal Motility

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Abstract

Background—There are currently no criteria for ineffective esophageal motility (IEM) and ineffective swallow (IES) in High Resolution Manometry (HRM) and Esophageal Pressure Topography (EPT). Our aims were to utilize HRM metrics to define IEM within the Chicago Classification and to determine the distal contractile integral (DCI) threshold for IES.

Methods—The EPT of 150 patients with either dysphagia or reflux symptoms were reviewed for the breaks >2 cm in the proximal, middle and distal esophagus in the 20 mmHg isobaric contour (IBC). Peristaltic function in EPT was defined by the Chicago Classification, the corresponding conventional line tracing (CLT) were reviewed separately for IEM and IES. Generalized linear mixed models were used to find thresholds for DCI corresponding to traditionally determined IES and failed swallows. An external validation sample was used to confirm these thresholds.

Results—In terms of swallow subtypes, IES in CLT were a mixture of normal, weak and failed peristalsis in EPT. A DCI of 450mmHg-s-cm was determined to be optimal in predicting IES. In the validation sample, the threshold of 450 mmHg-s-cm showed strong agreement with CLT determination of IES (positive percent agreement 83%, negative percent agreement 90%) Thirty-three among 42 IEM patients in CLT had large peristaltic breaks, small peristaltic breaks or ‘frequent failed peristalsis’ in EPT; 87.2% (34/39) of patients classified as normal in CLT had proximal IBC-breaks in EPT. the patient level diagnostic agreement between CLT and EPT was good (78.6% positive percent agreement, 63.9% negative percent agreement), with negative agreement increasing to 92.0% if proximal breaks were excluded.

Conclusions—The manometric correlate of IEM in EPT is a mixture of failed swallows and IBC break in the middle/ distal troughs. A DCI value<450 mmHg-s-cm can be utilized to predict IES previously defined in CLT. IEM can be defined by >5 swallows with weak /failed peristalsis or with a DCI <450 mmHg-s-cm.

Keywords

high resolution manometry; esophageal pressure topography; ineffective esophageal motility

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Introduction

Ineffective esophageal motility (IEM) is defined as a swallow response associated with poor bolus transit in the distal esophagus conventional line tracing (CLT). Peristalsis is defined as an ineffective swallow (IES) if it exhibits amplitudes of less than 30 mmHg at pressure sensors positioned 3 or 8 cm above the lower esophageal sphincter (1) and the classification of IEM is made when IES account for 50% or more test swallows (2). Ineffective esophageal motility is believed to be an important pathologic feature of both gastroesophageal reflux disease (GERD) (3) and dysphagia (4) making it an important diagnosis in CLT classification schemes for esophageal manometry (5).

With the advent of high-resolution manometry (HRM) and esophageal pressure topography (EPT), came the introduction of new metrics to define esophageal motor function using quantitative criteria based on the morphology of the peristaltic contraction. Consequently, measures of peristaltic integrity and vigor shifted from peristaltic amplitude to identifying breaks in the peristaltic wavefront and the distal contractile integral (DCI). In the Chicago Classification of esophageal motility, the definition of weak peristalsis is based on the length of breaks in the 20 mmHg isobaric contour (IBC), as these have been shown to be associated with impaired bolus transit with both fluoroscopy (6) and intraluminal impedance monitoring (7). Also important in the description of weak peristalsis is the location of these breaks, as they may have distinct pathologic origins and consequences. Although the Chicago Classification has thus far utilized DCI only to define hypercontractile disorders, this measurement could be also leveraged to define ineffective swallows. Normative data suggest that the 5th percentile for DCI in normal controls is 363 mmHg-s-cm and this could be utilized as a measure of abnormally low contractility in the distal esophagus (8).

To date, there is no definition of IEM using HRM and EPT because HRM analysis has steered away from measurement schemes that do not consider the segmental architecture of peristalsis. Defining peristalsis with EPT using only two axial locations ignores the additional detail provided by EPT and would be akin to a radiologist ignoring thin-slice axial CT cuts and focus only on images taken every 3 to 5 cm. However, defining IEM does have historical importance and may have clinical relevance in esophageal manometry and one of the strengths of the Chicago Classification has been to bridge conventional manometry with EPT. Thus, the goal of this study was to develop a correlate of IEM using metrics developed for HRM and EPT, naturally focusing on breaks in the IBC and DCI. Additionally, we also sought to determine whether the DCI could be utilized to define threshold values for IES and failed peristalsis, as this could potentially improve both automated analysis and inter-observer agreement.

Methods

Subjects and study protocol

A database of 2,000 consecutive patients undergoing HRM from March 2006 to May 2010 was screened for study subjects. Patients were randomly selected for inclusion after excluding individuals with: 1) major motility disorders by the Chicago Classification (9) (achalasia, EGJ outflow obstruction, distal esophageal spasm, absent peristalsis, hypercontractile esophagus), 2) hiatus hernia (> 3 cm separation between the lower esophageal sphincter and crural diaphragm), and 3) esophageal stricture, eosinophilic esophagitis (endoscopic or histopathological evidence). In all, 150 patients (53 males, mean age 46.4 years, range 21 – 76) were included: 69 with dysphagia, 40 with GERD, and 41 patients with both dysphagia and reflux symptoms but without 24-hour esophageal pH monitoring. An additional randomly selected group of 100 patients (37 males, mean age 49.8 years, range 19 – 85) were selected from the same database using identical exclusion

criteria to assess the predictive value of the DCI thresholds derived from the current study. The study protocol was approved by the Northwestern University Institutional Review Board and informed consent was obtained from each subject.

Manometry Protocol

Manometric studies were done with the patients in the supine position after at least a 6-h fast. The HRM catheters were 4.2 mm outer diameter solid-state assemblies with 36 circumferential sensors at 1-cm intervals (Given Imaging, Los Angeles, CA). Transducers were calibrated at 0 and 300 mmHg using externally applied pressure. The manometric assemblies were placed transnasally and positioned to record from the hypopharynx to the stomach with at least three intragastric sensors. The manometric protocol included a 5-min baseline recording and ten 5-ml water swallows.

EPT and CLT analysis

The EPT plot of each swallow in the HRM study was analyzed for integrity of the 20 mmHg isobaric contour. Peristalsis was defined as intact if no break longer than 2 cm was observed in the IBC. Failed peristalsis was defined by minimal (<3cm) integrity of the 20mmHg isobaric contour distal to the proximal pressure trough. When the 20mm Hg isobaric contour was disrupted, the length of the break was measured using the Smart Mouse tool in ManoView™ software (Given Imaging), and the location of the break was described in relation to the troughs (P-proximal, M-middle, D-distal) as previously described by Clouse et al (10). Weak contractions were categorized as weak contraction with large breaks (>5cm in length) or weak contraction with small breaks (2–5cm in length). The break at the transition zone (P) was specifically noted given its importance as a landmark for defining the transition point between the proximal and distal segmental contractions. The Distal Contractile Integral (DCI) was calculated as the mean amplitude (greater than 20 mmHg) of the distal esophageal contraction in mmHg-s-cm (9). The final diagnosis of the EPT for every patient was made according to the 2012 version of the Chicago Classification: ‘weak peristalsis with large peristaltic defects’ if greater than 20% of swallow exhibited large (>5 cm) breaks in the 20 mmHg IBC, ‘weak peristalsis with small peristaltic defects’ if greater than 30% of swallows exhibited small (2–5 cm) breaks in the 20 mmHg IBC, or ‘frequent failed peristalsis’ if >30% but <100% of swallows were associated with failed peristalsis (9) (Table 1).

The same swallows from the same 150 patients were reviewed independently in CLT format by the same investigator (YX) who was blinded to the original EPT diagnosis. Contraction amplitudes 3, 8 and 13 cm above the LES were measured and distal esophageal amplitude was calculated as the average of contraction amplitude 3 and 8 cm above the LES. The velocity of distal esophageal contractions was measured between 8 and 3 cm above the LES. Swallows were classified as: (a) normal swallow if contraction amplitudes 3 and 8 cm above the LES were each ≥30 mmHg and distal onset velocity was <8 cm/s; (b) ineffective swallow (IES) if either of the contraction amplitudes 3 and 8 cm above the LES was <30 mmHg; (c) simultaneous swallow if contraction amplitudes 3 and 8 cm above the LES were each ≥30 mmHg and distal velocity was >8 cm/s. IEM was defined according to the 2008 criterion of Castell (≥50% manometrically ineffective (<30 mmHg) swallows) (2) (Table 1). The normal swallows were categorized as effective swallows (ES).

Following the IEM analysis of the 150 patients, the second analysis was performed to determine whether the DCI thresholds derived from the first series could accurately identify IEM in the second set of 100 patients. This analysis was performed by a different investigator (SR).

Statistical analysis

Power transformations were considered to normalize values of DCI using the Anderson-Darling test statistic as a “goodness of fit” criterion, with the square root transformation proving optimal. Generalized Linear Mixed (GLM) Models were used to assess the differences in DCI (transformed) within Chicago Classification subtypes as well as to assess the relationship between EPT metrics and CLT measurements while accounting for the clustered nature of the data (multiple swallows per subject). Summary statistics presented (means and 95% confidence intervals) have been back transformed from the least square means estimates from the GLM models. Association between EPT metrics and CLT measurements was evaluated using GLM models with the fixed effect estimate (β) presented, and data from one swallow per study subject is shown in a scatterplot. Positive and negative percent agreement rates are presented to compare patient classifications using EPT or CLT definitions as defined previously.. GLM models were further used to determine optimal thresholds of DCI from a grid of possibilities (25 through 600, by 25 mmHg-s-cm) in predicting IES and failed swallows while accounting for intra-person variability using the log Pseudo-Likelihood to evaluate fit. A validation sample was used to assess positive and negative percent agreement between DCI thresholds and CLT determination of IES. A total of 1000 bootstrap samples of a single swallow from each patient (from a possible 10^{100} possible samples) were created to estimate the positive percent and negative percent agreement of swallows and corresponding 95% Confidence Intervals for determining IES. Associations between CLT measures and transition zone defect were also assessed using GLM models, and odds ratio estimates with 95% Confidence Intervals are presented. All P values were two-tailed with the level of significance defined at 0.05. Data analysis was performed using a standard software package (SAS v. 9.2, Cary, NC).

Results

EPT correlates of IES in the Chicago Classification of HRM

Of the 1500 swallows analyzed, 444 were categorized as IES and 1054 as ES; the remaining two were simultaneous contractions and excluded from this analysis. The distribution of the Chicago Classification swallow subtypes and the DCI ranges for IES and ES are presented in Table 2. In terms of Chicago Classification swallow subtypes, IES in CLT format were a mixture of normal, weak contractions with large break, weak contractions with small break, and failed peristalsis (Figure 1). Among the 444 IES on CLT, 63 were defined as intact on EPT: 61 swallows with a peristaltic amplitude slightly less than 30 mmHg at either 3 or 8 cm above the LES on CLT, 1 with an IBC break less than 2 cm in the distal trough on EPT, and 1 with vascular artifact on EPT. Among the 1054 ES on CLT, there were 68 with weak contraction with large break in the proximal trough, 31 with weak contraction with small break in the middle or distal trough, and 182 with weak contraction with small break in the proximal trough making for a total of 281 swallows with one or another category of weak contraction. In total, 88.9% (250/281) of the ES in CLT with weak contraction on EPT had a small or large break in the proximal trough.

Distal Contractile Integral cutoff values for IES and failed peristalsis

The mean DCI of ES was significantly greater than that of IES (1239 vs 227 mmHg-s-cm, $p < 0.001$) and there was a significant association between the distal esophageal amplitude and DCI of the 1498 analyzed swallows ($\beta = 0.386$ $p < 0.001$). Figure 2 shows the relationship between distal esophageal amplitude and DCI for the first swallow from each of the 150 study subjects by swallow effectiveness. When DCI was categorized, a value of DCI < 450 mmHg-s-cm was optimal in predicting IES, and < 50 mmHg-s-cm was optimal in predicting a failed swallow. In the validation sample, the mean and 95% Confidence interval for

percent positive percent agreement for IES of the bootstrapped samples was 83.3% (73.0%, 92.9%) and the negative percent agreement was 89.7% (84.4%, 95.0%).

Chicago Classification correlates of IEM

The comparative diagnoses of the 1500 swallows from the 150 patients in the primary analysis interpreted in CLT and EPT format are shown in Figure 3. Among the 42 patients with IEM in the CLT format, 33 had ‘weak peristalsis with large defects’, ‘weak peristalsis with small defects’, or ‘frequent failed peristalsis’ on EPT analysis and the remaining 9 were normal. Among the nine of these that were normal, two had swallows with distal IBC break shorter than 2 cm, three had distal peristaltic amplitudes slightly less than 30 mmHg in every ineffective swallow, and four had more than 5 swallows with either weak peristalsis or failed peristalsis but of insufficient number to achieve a Chicago Classification diagnosis of weak peristalsis or ‘frequent failed peristalsis’. Of the 108 patients classified as normal in the CLT format, 39 had an abnormality according to the Chicago Classification with the majority (87.2%, n=34) having IBC-breaks in the proximal pressure trough. Among the other 5 patients, two had frequent failed peristalsis and three had weak peristalsis with small defect in the distal trough. Utilizing a combination of ‘weak peristalsis with large defect’, ‘weak peristalsis with small defect’ and ‘frequent failed peristalsis’ as criteria for IEM, the positive percent agreement was 78.6% and negative percent agreement was 63.9%. However, when the comparison is restricted to include only ‘weak peristalsis with large defect’ and ‘weak peristalsis with small defect’ localized in the middle and distal pressure troughs, the negative percent agreement improved to 92.0% (with positive percent agreement remaining at 78.6%). The median (IQR) number of swallows with failed peristalsis, large IBC-breaks (>5 cm) and small IBC-breaks (2–5 cm) in IEM patients were 3 (1, 5), 2 (1, 4) and 2 (0, 3) respectively. Interestingly, in the validation sample, the agreement between patient diagnosis of IEM determined by CLT or by those with >5 swallows with DCI<450mmHg-s-cm, was stronger (85.7% positive percent agreement, and 92.3% negative percent agreement).

Transition zone defects

One of the early discoveries resultant from the application of the EPT format to the analysis of peristalsis was of the transition zone (and transition zone defects) between the peristaltic contraction in the proximal and distal esophagus. Subsequently, this has been defined as a break in the 20 mmHg IBC greater than 2cm (11). Among the 1500 swallows in the primary analysis, a transition zone defect was found in 616. Among these, 342 also fulfilled criteria for IES using CLT analysis. Alternatively, the pressure amplitude at the channel 13 cm above the LES was also assessed to determine how well this measurement could identify transition zone defects. Among the 1500 swallows in the primary analysis, 517 had a peristaltic amplitude of less than 30 mmHg at the LES +13 cm site. Among these 517 swallows, 401 swallows had a transition zone defect in the EPT (Table 4) (Figure 4), in fact the odds ratio estimate for peristaltic amplitude of less than 30 mmHg at the LES +13 cm site among swallows with a transition zone defect relative to those without was 24.26 (15.61, 37.70).

Discussion

Ineffective esophageal motility, characterized by low amplitude peristalsis in the distal esophagus, is associated with poor bolus transit. Although IEM was defined within the construct of CLT manometry, it is logical that it could also be described using metrics derived for HRM and EPT analysis based on breaks in the IBC and the DCI. Thus, we sought to develop criteria for IEM within the EPT paradigm. Using the Castell criteria for an IES, we found that most of the IES on CLT (86%) was classified as either failed peristalsis or swallows with small or large breaks in the middle or distal pressure trough on EPT.

Additionally, we determined that swallows with a DCI < 450 mmHg-s-cm had a high likelihood of being classified as an IES on CLT. Given these findings, IEM could be identified in EPT in either of two ways: 1) 50% or more swallows with any combination of failed peristalsis, weak contraction with small break or weak peristalsis with large break in the middle/distal esophagus or 2) 50% or more swallows associated with a DCI < 450 mmHg-s-cm.

Although it may seem logical to abandon the diagnosis of IEM in HRM and EPT due to its reliance on only two recording sites, IEM is a widely accepted concept with potential clinical significance in GERD and dysphagia. Additionally, one of the objectives in developing the Chicago Classification for HRM was to bridge the old with the new, thereby requiring a correlate for IEM. Current Chicago Classification diagnoses relevant to the concept of IEM are 'weak peristalsis with large peristaltic defects', 'weak peristalsis with small peristaltic defects', and 'frequent failed peristalsis' but the number of swallows required to meet criteria for these entities were based on normative ranges and it was clear that IEM would involve an overlap among these categories. Hence, in the current analysis we applied CLT and EPT analyses to the same studies to devise criteria for IEM in EPT. However, EPT enhances the classification of IEM by providing further detail regarding the mechanism of the ineffective swallow, including the recognition of transition zone defects, which confound any analysis limited to the distal esophagus.

Evident from the comparison of CLT and EPT analyses, IES are heterogeneous, comprised of both failed peristalsis and swallows with small or large breaks in the middle/distal pressure troughs. Thus, IEM could be a combination of these or dominated by one or the other. Although there are minimal data to substantiate that differentiating these entities has clinical significance, they are likely different in terms of pathogenesis (7). Failed peristalsis may result from an intermittent defect in triggering distal esophageal peristalsis that may or may not be associated with weak peristalsis once it is triggered. Hence, the clinical circumstance in which failed peristalsis is encountered runs the spectrum from a variant of normal to complete smooth muscle failure analogous to that seen with achalasia or scleroderma. In contrast, weak swallows characterized by small or large breaks in the IBC generally have defects that persist in the middle and distal pressure troughs with normal triggering of distal segment peristalsis. These breaks, especially when large have persistent implications regarding bolus transit with potentially specific clinical significance (7).

Our findings also demonstrate the advantage of EPT in the accurate assessment of transition zone defects. Transition zone defects were the first defined aberration of esophageal motility based on the segmental architecture of the peristalsis as initially reported by Clouse and Staiano (12). In a pivotal study, Fox et al subsequently described the effect of transition zone defects in abnormal bolus transit and highlighted the apparent benefit HRM had above conventional manometry in identifying these defects (13). Additional studies corroborated the clinical and pathophysiologic significance of transition zone defects suggesting that these should be considered in any analysis of bolus transit (14, 15). Results from the current study demonstrate that transition zone defects are common in both patients with and without IEM implying that their identification should be an outcome of interest in the clinical assessment of dysphagia.

Another interesting finding from this study was of defining DCI threshold values for IES and failed peristalsis. The DCI is a reasonable metric to define IES as the measurement boundaries are limited to the second and third contractile segments, which are also assessed by recording sites 3 and 8 cm above the LES. We found that a cutoff of 450 mmHg-s-cm could be utilized for defining a swallow as ineffective and 50 mmHg-s-cm could be used to define failed peristalsis. These cutoff values can be used in the automated analyses of

peristaltic function. However, the utilization of a single number cutoff negates the detail of EPT and it is possible that identifying more specific swallow subtypes may have clinical implications beyond the global effect that these abnormalities have on bolus transit.

One potential limitation of the proposed definitions of IEM in EPT could be related to the fact that weak peristalsis is defined using the 20 mmHg isobaric contour while IEM utilizes 30 mmHg as the threshold amplitude for an effective swallow. The 20 mmHg cutoff appears to be more appropriate considering previous analyses using simultaneous manometry with impedance. Using an ROC analysis to discern the best threshold amplitude for bolus transit on intraluminal impedance, Tutuian et al reported that normal bolus transit could be found in patients with amplitudes less than 30 mmHg(16). This was also substantiated in more recent work by Roman et al where a cutoff of 20 mmHg was utilized for determining various degrees of weak peristalsis (7). That study revealed that a break of 5 cm or more in the 20 mmHg IBC was always associated with impaired bolus transit whereas breaks of between 2 and 5 cm had variable proclivity to impaired bolus transit. Regardless of the difference in thresholds, the current data demonstrate that we could reliably define IEM with EPT metrics based on the 20 mmHg IBC.

In summary, IEM can be defined in EPT by 5 or more swallows with any combination of failed peristalsis or weak contraction with large or small break in the middle or distal pressure troughs. Alternatively, IES can be identified by a contraction with a DCI <450 mmHg-s-cm which may prove very useful in automated analysis software. However, we propose continuing to utilize the Chicago Classification format of more specifically defining the characteristic of IES as we believe these may have specific pathophysiological and clinical implications. Similarly, although transition zone defects are not part of the definition of IEM, these defects are a common cause of impaired bolus transit and their recognition should be an outcome of interest. Thus, although EPT metrics can be utilized to reliably identify IEM as previously defined in CLT manometry, the current analysis demonstrates the heterogeneity of that diagnosis and emphasizes the importance of the added detail in the assessment of esophageal motility provided by EPT.

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Study highlights

1. What is current knowledge?
 - Ineffective esophageal motility, characterized by low amplitude peristalsis in the distal esophagus, is associated with poor bolus transit in conventional line tracing manometry.
 - The length of peristaltic breaks in the 20 mmHg isobaric contour and distal contractile integral were utilized to define the bolus transit in the esophageal pressure topography in high resolution manometry within the Chicago Classification.
 - There are no criteria for ineffective esophageal motility within the EPT paradigm.
2. What is new here?
 - The manometric correlate of ineffective esophageal motility in esophageal pressure topography is a mixture of failed swallows and swallows with IBC break in the middle and distal troughs.
 - Ineffective swallows can be identified by a contraction with a DCI <450 mmHg-s-cm, which could be used in the automated analyses of peristaltic function
 - Ineffective esophageal motility can be defined in esophageal pressure topography by 5 or more swallows with any combination of failed peristalsis or weak contraction with large or small break in the middle or distal pressure troughs.

Figure 1.

Examples of 3 swallows with conventional line tracing (CLT) superimposed on esophageal pressure topography (EPT). The three white lines from bottom to top are pressure tracings recorded at 3, 8 and 13cm above LES on CLT. **Panel A** illustrates a swallow with large break in the 20 mmHg isobaric contour (IBC) on EPT; the pressure amplitude at 3 and 8 cm above LES were 17 and 10 mmHg respectively, indicating that the break on EPT correlated with the weak peristaltic amplitude on CLT. The DCI was 257 mmHg-s-cm. **Panel B** illustrates failed peristalsis on EPT; the pressure amplitude at 3 and 8 cm above LES was 12 and 10 mmHg respectively indicating that the break on EPT correlated with the weak

peristaltic amplitude on CLT. The DCI was 0 mmHg-s-cm. **Panel C** illustrates a swallow with a small break in the distal pressure trough in the 20 mmHg IBC; the peristaltic amplitudes at 3 and 8cm above LES were 53 and 73 mmHg respectively indicating that the break on EPT was not correlated with weak amplitude peristalsis on CLT. The DCI was 438 mmHg-s-cm.

Figure 2.

Mean amplitude, as measured by Conventional Line Tracing (CLT) and the square root transformation of distal contractile integral (DCI) from esophageal pressure topography (EPT) from first swallow of 150 patients. Generalized linear mixed models accounting for multiple swallows from each individual show significant association between mean amplitude and square root of DCI ($\beta=0.386$, $p<0.001$).

Figure 3.

Categorization of IES and ES in EPT in EPT terms (**top**) and of IEM and normal in CC diagnoses (**bottom**). Ineffective swallow represented a mixture of weak contractions and failed peristalsis. Slightly over 255 of effective swallow in CLT were categorized as weak in EPT. The 42 diagnoses of IEM likewise represented a mixture of normal, frequent failed peristalsis, weak peristalsis with large peristaltic defects and weak peristalsis with small peristaltic defects in EPT terms. Again, over 25% of studies categorized as normal in CLT manometry had one or another manifestation of weak peristalsis in EPT.

Figure 4.

Examples of 2 swallows with transition defects on EPT superimposed with conventional CLT manometry. The three white lines from bottom to top are pressure tracings recorded at 3, 8 and 13 cm above the LES. **Panel A** illustrates a swallow with a transition zone defect (4.8cm) in the 20 mmHg isobaric contour in the proximal trough on EPT; the peristaltic amplitude on CLT 13 cm above LES was 16 mmHg, indicating that the transition zone defect on EPT correlated with weak amplitude peristalsis at the LES +13cm site on CLT.

Panel B illustrates a swallow with a transition zone defect (3.1cm) in the 20 mmHg isobaric contour in proximal trough on EPT. The pressure amplitude at the LES +13 cm site was 39 mmHg, indicating that the transition zone defect on EPT was not correlated with normal amplitude peristalsis at the LES +13cm site.

Table 1

The terminology utilized in esophageal pressure topography and conventional line tracing

	Terminology	Criteria
Esophageal pressure topography (EPT)		
Individual swallow	Weak contraction	Large break in the 20mmHg isobaric contour(>5cm in length) Small break in the 20mmHg isobaric contour(2–5cm in length)
	Failed peristalsis	Minimal(<3cm) integrity of the 20mmHg isobaric contour distal to the proximal pressure trough
	Rapid contraction	Contractile front velocity more than 9cm/s
	Intact contraction	20mmHg isobaric contour without large or small break (not greater than 2cm)
Diagnosis	Weak peristalsis with large peristaltic defects	Mean IRP <15 mmHg and >20% swallows with large breaks in the 20 mmHg isobaric contour (>5cm in length)
	Weak peristalsis with small peristaltic defects	Mean IRP <15 mmHg and >30% swallows with small breaks in the 20 mmHg isobaric contour (2–5cm in length)
	Frequent failed peristalsis	>30%, but <100% of swallows with failed peristalsis
Conventional line tracing format (CLT)		
Individual swallow	Normal swallow	contraction amplitudes 3 and 8 cm above the LES were each 30 mmHg and distal onset velocity was <8 cm/s
	Simultaneous swallow	contraction amplitudes 3 and 8 cm above the LES were each 30 mmHg and distal onset velocity was >8 cm/s
	Ineffective swallow	either of the contraction amplitudes 3 and 8 cm above the LES was <30 mmHg
Diagnosis	Ineffective esophageal motility	50% manometrically ineffective (<30 mmHg) swallows

Table 2

DCI values (mmHg-s-cm) for ineffective and effective swallows categorized in Chicago Classification subtypes

	Ineffective		Effective	
	n (%)	Mean (95% CI) DCI*	n (%)	Mean (95% CI) DCI*
Total	444	227 (179, 282)	1054	1239 (1135, 13470)
EPT type				
Intact	63(14.2)	447 (380, 518)	766(72.6)	1418 (1294, 1547)
Weak contraction	205(46.2)	206 (177, 236)	281(26.7)	780 (676, 891)
Failed peristalsis	176(39.6)	12 (6, 21)	---	
Other	---	---	7(0.7)*	2278 (1756, 2868)

* Mean and 95% Confidence Interval (CI) are based on back transformed least square means of transformed DCI data.

* Five hypertensive swallows (mean DCI 3233 mmHg-s-cm) and 2 swallows with a rapid contraction (mean DCI 690mmHg-s-cm).

The agreement between CLT and EPT in the diagnosis of IEM in the second analysis of 100 patients alternatively using the Chicago Classification criteria of five swallows with failed peristalsis or weak peristalsis in the distal pressure troughs or five swallows with a DCI less than the threshold of 500 mmHg-s-cm to predict IEM status.

Table 3

		IEM status predicted by failed peristalsis or weak peristalsis		IEM status predicted by DCI < 500 mmHg-s-cm	
		IEM	non-IEM	IEM	non-IEM
CLT Diagnoses	IEM	24	8	30	2
	non-IEM	1	67	5	63
Total		25	75	35	65

Table 4

Transition zone defect correlates of weak pressure amplitude in the channel 13cm above LES among 1500 swallows in HRM

CLT Analysis	EPT Analysis		Total
(LES +13 cm)	Transition zone defect	No transition zone defect	
Amplitude <30mmHg	401	116	517
Amplitude >30mmHg	215	768	983
Total	616	884	1500