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Improved Assessment of Bolus Clearance in Patients With Achalasia Using High-Resolution Impedance Manometry

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Abstract

Background & Aims—Esophageal retention is typically evaluated by timed barium esophagram in patients treated for achalasia. Esophageal bolus clearance can also be evaluated using high-resolution impedance manometry. We evaluated the associations of conventional and novel high-resolution impedance manometry metrics, esophagram, and patient-reported outcomes (PRO) in achalasia.

Methods—We performed a prospective study of 70 patients with achalasia (20–81 years old, 30 female) treated by pneumatic dilation or myotomy who underwent follow-up evaluations from April 2013 through December 2015 (median 12 months after treatment; range, 3–183 months). Patients were assessed using timed-barium esophagrams, high-resolution impedance manometry, and PROs, determined from Eckardt scores (the primary outcome) and the brief esophageal dysphagia questionnaire. Barium column height was measured from esophagrams taken 5 min after ingestion of barium (200 ml). Impedance-manometry was analyzed for bolus transit (dichotomized) and with a customized MATLAB program to calculate the esophageal impedance integral (EII) ratio.

Results—Optimal cut points to identify a good PRO (defined as Eckardt score of 3 or less) were esophagram barium column height of 3 cm (identified patients with a good PRO with 63% sensitivity and 75% specificity) and EII ratio of 0.41 (identified patients with a good PRO with

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83% sensitivity and 75% specificity). Complete bolus transit identified patients with a good PRO with 28% sensitivity and 75% specificity. Of the 25 patients who met these cut points for both esophagram barium column height and EII ratio, 23 (92%) had a good PRO. Of the 17 patients who met neither cut point, 14 (82%) had a poor PRO (Eckardt score above 3).

Conclusions—In a prospective study of 70 patients with achalasia, we found EII ratio to identify those with good PROs with higher levels of sensitivity (same specificity) than timed-barium esophagram or impedance-manometry bolus transit assessments. EII ratio should be added to achalasia outcome evaluations that involve high-resolution impedance manometry as an independent measure and to complement timed-barium esophagram.

Keywords

outcome; symptom; esophagram; swallow

Introduction

Achalasia is the prototypical esophageal motor disorder and is characterized by impaired deglutitive lower esophageal sphincter relaxation and absent peristalsis.^{1, 2} Bolus clearance is the fundamental function of the esophagus, which when disrupted by the motility abnormalities of achalasia results in esophageal retention and symptoms of esophageal dysphagia, chest pain, and regurgitation. Symptomatic improvement is an essential objective and often the primary outcome measure for gauging treatment response in achalasia. Nevertheless, discordance is often observed between patient symptoms and objective radiographic and manometric measures of esophageal function.³⁻⁵ Esophageal retention, as measured by timed-barium esophagram (TBE), was shown to be more predictive of treatment failure in achalasia than symptom severity.³ Therefore, in patients with previously treated achalasia, it is recommended that follow-up evaluations involve intermittent objective assessments, including TBE and/or manometry.²

Esophageal manometry is considered the primary method to assess esophageal motility and, when combined with multichannel intraluminal esophageal impedance sensors, the esophageal function evaluation can be enhanced by assessing the interplay between esophageal motility and bolus transit.^{6, 7} Use of esophageal impedance-manometry, however, was limited by its dichotomous qualitative evaluation of bolus clearance as complete or incomplete.^{6, 7} Advances in high-resolution impedance manometry (HRIM) offer an improved quantitative evaluation using a novel HRIM measure, the esophageal impedance integral (EII) ratio.⁸ By utilizing high-resolution impedance topography plots (Z-plots), the proportion of retained bolus can be *quantified* to better characterize esophageal bolus clearance.

We recently reported that the EII ratio outperformed other impedance-manometry metrics in correlating with symptoms among patients with dysphagia, but without a major esophageal motility disorder.⁹ Given the benefits of assessing achalasia outcomes with TBE, we hypothesized that assessing achalasia patients during follow-up after treatment with the EII ratio would benefit the outcome evaluation. Thus, we aimed to evaluate the value of TBE, via barium column height, and HRIM, via the traditional, dichotomized bolus transit and the

novel EII ratio, in assessing patient-reported outcome (PRO) in patients with achalasia following intervention.

Methods

Subjects

Patients with achalasia and previous treatment with pneumatic dilation, laparoscopic Heller's myotomy (often with Dor or Toupet fundoplasty), and/or per-oral endoscopic myotomy (POEM) returning for follow-up or referred from elsewhere were prospectively recruited and evaluated. 70 consecutive patients (without hiatal hernia > 2 cm) evaluated between April 2013 and December 2015 that completed HRIM, symptom questionnaires, and TBE were included in the analysis; these patients have been previously described, although 5 patients from that report were excluded from this analysis due to technical issues with impedance sensors that prevented reliable analysis of HRIM-measures of esophageal retention.¹⁰ The time interval between evaluation and most recent pneumatic dilation or myotomy was noted. When available, HRM performed prior to intervention was evaluated according to the Chicago Classification to provide an achalasia subtype.¹ When pre-treatment manometry was not available, the diagnosis of achalasia was assumed based on reported manometry findings and subsequent treatment. The study protocol was approved by the Northwestern University Institutional Review Board.

Symptom assessment

Symptoms were assessed by patient completion of written questionnaires at the time of HRIM. Questionnaires included the Eckardt score and the Brief Esophageal Dysphagia Questionnaire (BEDQ).¹¹ The Eckardt score (range 0 – 12) was generated by the sum of scores for dysphagia, chest pain, and regurgitation based on the frequency of each symptom (0: never, 1: occasional, 2: daily, 3: with each meal) plus a score based on the degree of weight loss since the last therapeutic intervention (0: none, 1: < 10 lbs, 2: 10-20 lbs, 3: > 20 lbs). Patients reporting an Eckardt score ≤ 3 were considered as a good PRO; those with Eckardt score > 3, a poor PRO.

The BEDQ is a validated questionnaire consists of eight 6-point Likert scale questions (scored 0-5) that assesses frequency and severity of dysphagia and odynophagia and two open-ended questions regarding frequency of food impactions and related emergency room visits.¹² Scores range from 0 (asymptomatic) – 50; a BEDQ score threshold of 10 was previously reported as an optimal score to diagnose major esophageal motor dysfunction and thus a BEDQ < 10 was considered as a good PRO; a BEDQ ≥ 10 was considered a poor PRO.

Timed barium esophagram protocol and analysis

Timed barium esophagrams were performed in the upright position with x-ray images of the esophagus obtained at one, two and five minutes after ingestion of 200-ml of low-density (45% weight to volume) barium sulfate. The height of the barium column (cm) at 5 minutes was measured vertically from the esophagogastric junction (EGJ).

HRIM protocol and analysis

After a minimum 6-hour fast, HRIM studies were completed using a 4.2-mm outer diameter solid-state assembly with 36 circumferential pressure sensors at 1-cm intervals and 18 impedance segments at 2-cm intervals placed transnasal to span from the hypopharynx to stomach (Medtronic Inc, Shoreview, MN). After a 2-minute baseline recording, the HRIM protocol using a 0.45% saline solution included ten 5-ml swallows in a supine position and five 5-ml swallows in the upright position.

Manometry studies were analyzed using ManoView version 3.0 analysis software (Medtronic) according to the Chicago Classification.^{1, 13} Esophageal motility diagnoses were designated from the supine swallows in accordance with the Chicago Classification v3.0, using a median integrated relaxation pressure of > 15 mmHg as the upper-limit of normal.¹ Although the Chicago Classification was designed and intended for patients without previous surgery, we utilized the classification scheme in our post-treatment cohort to describe the motility patterns observed on follow-up. Based on our previous findings that assessing upright liquid swallows provided better symptom-association over supine swallows, we used the 5-upright swallows for further testing.⁹

The HRIM plots of upright liquid swallows were analyzed with placement of impedance channels at 5, 10, 15, and 20-cm proximal to the EGJ to emulate a previous method to characterize dichotomized bolus clearance.^{6, 7} Dichotomized bolus clearance was assessed by an investigator (DC) blinded to other clinical details. Complete bolus clearance was considered if bolus entry (i.e. 50% decrease in impedance from baseline to nadir) occurred at the 20-cm channel and bolus exit (i.e. return to 50% impedance point) occurred at the 15-cm, 10-cm, and 5-cm channels. Incomplete bolus clearance was considered if bolus exit was not identified at any one of the three distal impedance measurement sites. Based on previously utilized thresholds,^{6, 7} normal bolus transit was defined as complete bolus clearance in > 70% of swallows; abnormal bolus transit was defined as complete bolus clearance in ≤ 30% of swallows.

To calculate the EII ratio, HRIM data of the upright 5-ml swallows for each subject were exported to MATLAB™ (The MathWorks Inc., Natick, MA, U.S.A.) into a customized program. The EII ratio was calculated as previously described by an investigator (ZL) that was blinded to other clinical details.^{8, 9} The measurement region of interest including the swallow to the completion of peristalsis (or 12 seconds if peristalsis was absent) was divided into two impedance domains: swallow (Z1) and post-swallow (Z2); Figure 1. The amount of bolus present within each domain was quantified by measuring the impedance-pixel density (impedance value × time × axial length), i.e. the EII. Finally, the EII ratio was calculated as the ratio of residual bolus volume (EII-Z2) relative to the intra-esophageal bolus volume immediately following the swallow, but before the deglutitive contraction (EII-Z1): $EII\ ratio = (EII-Z2) / (EII-Z1)$. A greater EII ratio indicated a greater degree of bolus retention.⁸ Excellent inter-rater agreement [intra-class correlation coefficient (95% confidence interval) of 0.905 (0.875 – 0.928)] of EII-ratio calculation was recently demonstrated between two raters analyzing 200 swallows from patients with and without achalasia.¹⁴

Statistical analysis

Descriptive statistics for all continuous and ordinal measures were presented as median and IQR, unless otherwise stated. Correlations were assessed using Spearman's rho. Outcome groups were compared using the Mann-Whitney U test for continuous variables and χ^2 for dichotomous and categorical variables. Receiver operating characteristic (ROC) curves were generated by plotting the sensitivity by false positive rate (1 – specificity) to predict good PRO for incremental value increases of each HRIM and TBE metric. The optimal threshold value for each metric was chosen as the closest value to 100% sensitivity and 0% false positive rate (the 0,1 point on the graph). Analyses assumed a 5% level of statistical significance.

Results

Study subjects

70 patients with achalasia, mean age 51 years (range 20 – 81 years), 30 (43%) females, were included (Table 1). The median (range) follow-up interval was 12 (3 – 183) months after previous intervention with pneumatic dilation (n = 10, 14%), laparoscopic Heller's myotomy (n = 25, 36%), or POEM (n = 35, 50%); two patients had received esophageal botulinum toxin injection since a previous intervention which occurred six months and two years prior to follow-up testing. Nine patients had received more than one previous intervention. The majority of patients, 58 (83%), were treated at Northwestern; the remaining 12 (17%) patients received their previous intervention at an external facility (2 with pneumatic dilation, 10 with laparoscopic Heller's myotomy).

Among all patients, the median (IQR) Eckardt score was 2 (1-4). Forty-six (66%) patients had a good PRO and 24 (34%) had a poor PRO. Two patients did not complete the BEDQ. Among the remaining 68 patients, the median (IQR) BEDQ was 5 (1 – 11). By the BEDQ, 45 (66%) patients had a good PRO and 23 (34%) had a poor PRO. The percent agreement on PRO between the ES and BEDQ was 87% ($\kappa = 0.701$). Characteristics by PRO are displayed in Table 1.

Measures of esophageal clearance

Among all patients, the median (IQRs) TBE-column height was 3.2 (0 – 7.2) cm, and EII ratio was 0.36 (0.24 – 0.5). The correlation between TBE-column height and EII ratio was 0.20.

Nineteen patients (27%) had complete bolus transit and the remaining 51 (73%) had incomplete bolus transit. TBE-column height was 0 cm (0 – 2.3) among patients with complete bolus transit and 4 cm (1 – 10) among patients with incomplete bolus transit ($p < 0.001$). EII ratio was 0.28 (0.18 – 0.35) among patients with complete bolus transit and 0.39 (0.25 – 0.55) among patients with incomplete bolus transit ($p = 0.002$).

Relationships with HRIM parameters and TBE-column height, EII ratio, and bolus transit are presented in the supplementary table.

Associations of esophageal clearance metrics with patient-reported outcome

The correlation between Eckardt score and TBE-column height was 0.437 and between Eckardt score and EII ratio was 0.496. The correlation between BEDQ score and TBE-column height was 0.304 and between BEDQ score and EII ratio was 0.366 (all statistically significant). PRO groups differed in TBE-column height (Eckardt score: $p < 0.001$; BEDQ $p = 0.042$) and EII ratio (Eckardt score: $p < 0.001$; BEDQ $p = 0.02$), as displayed in Figure 2, with greater column height and greater EII ratio associated with poor PRO. Of the 19 patients with complete bolus transit, 13 (68%) had a good PRO (defined both by Eckardt score and BEDQ) while 33/51 (65%) and 32/49 (65%) of patients with incomplete bolus transit also had a good PRO, as defined by Eckardt score and BEDQ, respectively (p -values 0.999 for both PROs); Figure 2.

Receiver operating characteristic curves (Figure 3) of metrics related to good PRO defined by Eckardt score yielded areas-under-the-curve (95% confidence intervals) of 0.752 (0.631 – 0.873) for TBE-column height and 0.789 (0.666 – 0.911) for EII ratio. Receiver operating characteristic curves of metrics related to a good PRO defined by BEDQ yielded areas-under-the-curve (95% confidence intervals) of 0.648 (0.504 – 0.792) for TBE-column height and 0.731 (0.585 – 0.878) for EII ratio. Use of 5-cm as the cut-point for TBE-column height yielded a sensitivity of 78% (Eckardt score) and 76% (BEDQ) and specificity of 54% (Eckardt score) and 43% (BEDQ) to detect a good PRO.^{4,5} Achieving complete esophageal emptying at 5-minutes (TBE-column height of 0 cm) yielded a sensitivity of 46% (Eckardt score) and 40% (BEDQ) and a specificity of 88% (Eckardt score) and 74% (BEDQ) to detect good PRO.¹⁵ The ideal cut-points to identify a good PRO identified via the ROC curves was 3-cm for TBE-column height and 0.41 for EII ratio; associated sensitivities and specificities to predict good PROs are displayed in Table 2.

Combined use of TBE and HRIM metrics to predict PRO

Plotting the TBE-column height with EII ratio or bolus transit demonstrated the effects of complementary use of TBE with HRIM evaluation to detect PRO. When determining PRO by the Eckardt score (Figure 4), 23/25 (92%) patients with both a favorable TBE-column height *and* favorable EII ratio had a good PRO, while 14/17 (82%) patients with a poor TBE-column height *and* poor EII ratio had a poor PRO. 20/28 (71%) of patients with mixed TBE-EII ratio results (i.e. favorable TBE, poor EII ratio or vice versa) had a good PRO. In terms of dichotomous bolus transit, 12/16 (75%) patients with a favorable TBE-column height *and* complete bolus transit had a good PRO, while 16/32 patients (50%) with poor TBE and incomplete bolus transit had a poor PRO. 18/22 (82%) patients with mixed TBE-bolus transit results had a good PRO, though 17 of these 18 patients (94%) had a favorable TBE column height with incomplete bolus transit. Similar results were observed when the BEDQ was used to determine PRO (not displayed).

Discussion

We evaluated the relationships of PROs (Eckardt score and BEDQ) with radiographic (TBE) and HRIM measures of esophageal retention among achalasia patients during follow-up after pneumatic dilation or myotomy and found that the novel HRIM metric, the EII ratio

carried a similar to enhanced association with PRO as TBE-column height. Further, complementary use of TBE-column height and the EII ratio led to an improvement in PRO association.

Previous work demonstrated the benefit for quantifying esophageal retention via the change in TBE column height. Although short-term (1-month follow-up) symptomatic improvement after pneumatic dilation was generally associated with reduced esophageal retention, a subset of patients with symptomatic improvement had persistent esophageal retention.¹⁵ Further study demonstrated that this symptom-discordant esophageal retention was a strong predictor for therapeutic failure and need for re-intervention within one year.³ Although baseline TBE studies were not uniformly available in the current study to all for a similar assessment, we did observe discordance between PRO and measures of esophageal retention at follow-up evaluation, supporting the use of objective esophageal function data, including TBE and manometry, in addition to a PRO in the outcome assessment in achalasia.

When applied to patients with ineffective esophageal motility, assessing dichotomous esophageal bolus clearance with intraluminal impedance aided characterized the functional consequence of the peristaltic abnormalities.^{6, 16} Moreover, there was a good correlation between bolus transit and retention on TBE timed barium esophagram in patients with achalasia following intervention.¹⁷ Distinct from the *qualitative* assessment provided by the conventional impedance-manometry approach, the EII ratio provides a *quantitative* assessment of impaired bolus transit and associated bolus retention.⁶⁻⁹ Additionally, EII ratio can be used irrespective of the initial baseline impedance values, which is otherwise a limitation of HRIM assessment in patients with achalasia. Furthermore, the EII ratio can be calculated regardless of the integrity of peristalsis, which is fundamental for calculation of other HRIM pressure-flow metrics.¹⁸ In this study, EII demonstrates a significant association with achalasia symptoms, which was not consistently observed using the dichotomized bolus transit assessment.

The present study represents the first application of the EII ratio to achalasia. The EII ratio appeared to be a useful HRIM metric among patients with non-obstructive dysphagia as it demonstrated the strongest correlation with dysphagia among various HRIM metrics among patients without a major esophageal motility disorder.⁹ We recently reported that a novel HRIM measure of trans-esophagogastric junction (EGJ) flow, the bolus flow time (BFT), provided an improved evaluation of EGJ function related to clinical outcomes in achalasia over conventional manometric measures of EGJ pressure (including the integrated relaxation pressure, which was elevated, i.e. > 15 mmHg, in 19/70, 27% of the present cohort).¹⁰ Whereas the BFT provides an evaluation of esophageal emptying, the EII ratio addresses the consequence of impaired esophageal emptying, specifically *bolus retention*. While the EII ratio carried a stronger symptom association than the BFT among patients without major motility disorders, the sensitivity and specificity to detect a good PRO with the BFT (using a cut-point of 0 seconds) among this achalasia cohort evaluated during follow-up after treatment was 78% and 77%, respectively.^{9, 10} These are similar values to those observed with the EII ratio in this study. However, the agreement of BFT and EII ratio among this cohort was only moderate (kappa 0.491).

While both TBE and EII ratio assess esophageal retention, TBE assesses retention of a larger volume over time while the EII ratio reflects the amount of esophageal retention associated with small volume swallows. Further, TBE provides important anatomical information. These differences may account for the low correlation between the two measures, but may also account for their beneficial complementary nature. Having both a favorable TBE column height and EII ratio provided an improved association with good PRO than either metric alone. This is not observed with the dichotomized measure of bolus transit. Although additional prospective studies are needed to validate the use of EII ratio to aid management decisions, these results are promising.

Limitations of our study include the utilization of the Eckardt score, which is a non-validated, albeit commonly used, PRO with its own inherent limitations. We attempted to offset this limitation by also including a validated dysphagia-chest pain PRO, the BEDQ.¹² Further, while our aim was to assess metrics based on small-volume, liquid swallows and liquid barium retention to generalized symptom scores, this does not completely address symptom generation in achalasia, which would require swallow-based perception assessment during the HRIM or TBE study, possibly including viscous or solid boluses. Additionally, because calculation of the EII ratio requires use of both HRM with impedance and a customized MATLAB program, it is quite technical and not yet widely available limiting the generalizability of this study to use in general practice. However, future integration of this metric into commercially-available HRIM-analysis software could expand its clinical use to potentially aid outcome evaluation in achalasia. Lastly, although the association of clinical factors, such as achalasia subtype or treatment modality, with treatment outcome could be inferred from our results (as in Table 1), our study did not intend to assess these associations that are subject to selection and referral biases.

In conclusion, the goals of achalasia treatment are both improving patient symptoms and reducing esophageal retention. Our evaluation of objective measures of esophageal retention demonstrates the value of the EII ratio as an outcome assessment tool in achalasia, both independently and as a complementary measure to TBE-column height. Although further prospective studies are necessary, use of novel HRIM metrics complemented by TBE may improve the outcome assessment of achalasia treatments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

BEDQ	Brief Esophageal Dysphagia Questionnaire
BFT	bolus flow time
EGJ	esophagogastric junction
EII	esophageal impedance integral

HRIM	high-resolution impedance manometry
IQR	interquartile range
POEM	per-oral endoscopic myotomy
PRO	patient-reported outcome
ROC	receiver operating characteristic
TBE	timed barium esophagram

Figure 1. The esophageal impedance integral (EII) ratio

The high-resolution impedance-pressure topography plots (left) and MATLAB output for calculation of the EII ratio (right) are displayed from two patients (**A** and **B**). A failed swallow with pan-esophageal pressurization is displayed in **A** and a weak swallow is displayed in **B**. The region of interest for the EII ratio is designated with the red-dashed box (right panels). The diagonal dashed line represents the *expected* (**A**) or *actual* (**B**) peristaltic wave. After accounting for the baseline impedance, the areas of bolus presence were determined (enclosed within the white lines) and the bolus volumes within each domain were measured from the impedance pixel-density within areas of bolus presence. The displayed swallows yielded EII-ratios of 0.28 (**A**) and 0.33 (**B**). Figure used with permission from the Esophageal Center at Northwestern.

Figure 2. Comparison of metrics of esophageal clearance among patient-reported outcome (PRO)

A good PRO was considered as an **A)** Eckardt Score ≤ 3 and **B)** Brief Esophageal Dysphagia Questionnaire score < 10 . ○= outlier; *=extreme outlier.

Figure 3. Receiver operating characteristic (ROC) curves for metrics to predict good patient-reported outcomes (PRO)

A good PRO was considered as an **A**) Eckardt Score ≤ 3 and **B**) Brief Esophageal Dysphagia Questionnaire score < 10 TBE -timed barium esophagram. EII - esophageal impedance integral.

Figure 4. Complementary use of timed barium esophagram (TBE) and high-resolution impedance manometry (HRIM) to detect patient-reported outcome (PRO)

A good PRO was considered as an Eckardt Score ≤ 3 . Outliers are identified by arrows. TBE – timed barium esophagram. EII – esophageal impedance integral.

Table 1

Patient characteristics

Values are displayed as median (interquartile range) unless otherwise specified.

	All patients	Eckardt score outcome		BEDQ outcome	
		Good	Poor	Good	Poor
N, n	70	46	24	45	23
Age, years, mean +/- SD	51 +/- 17	53 +/- 17	46 +/- 16	52 (38 – 68)	49 (39 – 62)
Gender, female/male	30/40	15/31	15/9 ¹	14/31	15/8 ²
Body mass index, kg/m²	27 (24 – 30)	28 (25 – 31)	25 (24 – 30)	28 (25 – 30)	26 (24 – 30)
Intervention, n (%)^{1,2}					
Pneumatic dilation	10 (14)	6 (13)	4 (17)	6 (13)	4 (17)
Laparoscopic Heller's myotomy	25 (36)	9 (20)	16 (67)	8 (18)	15 (65)
POEM	35 (50)	31 (67)	4 (17)	31 (69)	4 (17)
Follow-up interval, months	12 (8 – 34)	11 (7 – 16)	39 (12 – 114) ¹	11 (7 – 18)	30 (10 – 82) ²
Pre-treatment motility diagnosis[*], n (%)^{1,2}					
Type I achalasia	19 (27)	13 (28)	6 (25)	15 (33)	4 (17)
Type II achalasia	28 (40)	25 (54)	3 (13)	24 (53)	4 (17)
Type III achalasia	7 (10)	6 (13)	1 (4)	4 (9)	3 (13)
Unknown[†]	16 (23)	2 (4)	14 (58)	2 (4)	12 (52)
Motility diagnosis at follow-up[*], n (%)^{1,2}					
Type I achalasia	9 (13)	5 (11)	4 (17)	4 (9)	4 (17)
Type II achalasia	5 (7)	1 (2)	4 (17)	1 (2)	4 (17)
Type III achalasia	2 (3)	1 (2)	1 (4)	0	2 (9)
EGJ outflow obstruction	3 (4)	2 (4)	1 (4)	3 (7)	0
Absent contractility	28 (40)	16 (35)	12 (50)	17 (38)	10 (44)
Distal esophageal spasm	6 (9)	4 (9)	2 (8)	3 (7)	3 (13)
Ineffective esophageal motility	17 (24)	17 (37)	0	17 (38)	0

^{*} Based on ten supine swallows per the Chicago Classification, v3.0.¹

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Patients without available pre-treatment high-resolution manometry, which was related to remote and/or external previous intervention.
p-value < 0.05 compared with good Eckardt score outcome.
p-value < 0.05 compared with good Brief Esophageal Dysphagia Questionnaire (BEDQ) outcome. POEM – per-oral endoscopic myotomy.

Table 2

Test characteristics of metrics of bolus retention

Sensitivities and specificities reflect detection of good patient-reported outcomes, i.e. Eckardt score (ES) 3 or Brief Esophageal Dysphagia Questionnaire (BEDQ) < 10. TBE – timed barium esophagram. EII – esophageal impedance integral.

Metric	Ideal cut-point	Sensitivity -ES (%)	Specificity -ES (%)	Sensitivity -BEDQ (%)	Specificity -BEDQ (%)
TBE-column height	3 cm	63	75	60	65
EII ratio	0.41	83	75	82	70
Bolus transit	Complete	28	75	29	74