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ORIGINAL CONTRIBUTIONS

Application of Topographical Methods to Clinical Esophageal Manometry

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OBJECTIVE: Topographical manometric methods have improved the understanding of esophageal peristalsis in research applications but require a large number of recording sensors. Commonly used methods limited to four sensors were compared to topographical methods to determine whether the latter also had significant clinical utility.

METHODS: Two hundred twelve patients referred for esophageal manometry were studied with a data acquisition system having 21 intraluminal recording sites, and the findings were analyzed independently using both limited (pull-through plus four recording sites) and topographical approaches (all sites). Discrepant results were clarified using supportive clinical data.

RESULTS: The two methods were in diagnostic agreement in 187 cases (88.2%). Topographical methods correctly identified all 26 patients with achalasia within the group with aperistalsis ($n = 36$). The limited methods could not confidently identify six achalasia patients and were significantly less effective in segregating aperistaltic disorders ($p < 0.05$ across methods). Topographical methods alone detected evidence of incomplete lower esophageal sphincter relaxation in 12 additional patients, eight of whom had clinical data supporting the findings. Topographical methods identified the upper margin of the lower sphincter in all but three subjects (1.4%); limited methods could not identify this location in these and five additional subjects (3.8%) and differed from the topographical measurement by ≥2 cm in 11.9% of cases.

CONCLUSIONS: Topographical methods are more accurate than commonly used methods in diagnosing the type of severe motor dysfunction and provide additional information important in the clinical practice of esophageal manometry. (Am J Gastroenterol 2000;95:2720–2730. © 2000 by Am. Coll. of Gastroenterology)

INTRODUCTION

Esophageal manometry retains several important roles in clinical practice (1, 2). The test can establish the diagnosis of achalasia that, after investigation with barium radiographs or endoscopy, may remain undiagnosed or unsuspected in as many as 33% of patients with compatible symptoms (3). Manometry has some value in determining causes of unexplained chest pain and is ideal for locating landmarks needed for positioning other intraluminal devices, *e.g.*, lower esophageal sphincter (LES) location preceding pH probe placement (1). Despite these important uses, little technical advancement has occurred in the past two decades (4, 5).

Topographical manometric methods take advantage of an increased number of recording sites to examine spatial as well as temporal relationships of pressure data (6–8). Three-dimensional plots originally designed for geographical mapping integrate data in the axial direction and offer a simplified method for displaying large data sets (9). These methods demonstrate that peristalsis is comprised of three sequential pressure segments in the esophageal body merging with a fourth segment at the level of the LES (6, 7). Besides providing previously unrecognized information on the segmental nature to peristalsis, topographical methods show that certain motor disturbances, such as the "nutcracker esophagus," are localized to specific peristaltic segments, as are the pharmacological effects of cisapride (7, 10).

Whether topographical methods would have important uses in clinical practice, beyond these research applications, remains unproven. Because topographical approaches use more recording sites as well as interpolation of data between sites, their ability to improve on usual methods in establishing the nature of motor dysfunction, in identifying motor abnormalities potentially responsible for symptoms, and in locating the LES for pH probe placement seems plausible. At present, the most commonly used manometric systems involve a very limited number of recording sites in the esophageal body and LES, because it remains unproven that additional manometric information is necessary for clinical diagnosis (1, 11). In this investigation we compared the diagnostic accuracy of commonly used manometric techniques using four pressure sensors with topographical methods to determine whether the latter had a potential role in clinical practice.

Presented in preliminary form at the Annual Meeting of the American Gastroenterological Association, Washington, D.C., May 1997.

MATERIALS AND METHODS

Subjects

Consecutive patients referred to the Digestive Disease Clinical Center of Barnes-Jewish Hospital for esophageal manometric studies between November 1996, and December 1997, inclusive, were invited to participate in this investigation. Subjects who could not provide informed consent or for whom informed consent could not be obtained from a parent or legal guardian were excluded; there were no other specific exclusionary criteria. Subjects referred from July 1996, to November 1996, were also asked to participate in a preliminary study of the clinical feasibility of topographical methods. Results from these subjects were not used in the comparative study. Investigation of topographical analysis methods was approved by the Human Studies Committee (Institutional Review Board) of Washington University School of Medicine.

Manometric Methods

All subjects were studied after an overnight fast using a system described previously for developing three-dimensional topographical plots from individual swallows (9). A 21-lumen extruded silicone catheter of 4.0-mm outer diameter having recording sideholes spaced helically at 1-cm intervals (Dentsleeve Pty, Bowden, South Australia) was passed transnasally until all recording locations were positioned in the stomach. Each lumen (0.5 mm inner diameter) was attached to an extracorporeal pressure transducer perfused by a pneumohydraulic perfusion device (Mui Systems, Mississauga, Ontario, Canada). A perfusion rate of 0.28 ml/min/lumen allowed measurement of pressure upstrokes $>$300 mm Hg/s with a total perfusion rate of 5.9 ml/min (9). Pressure data were acquired at a rate of 10 Hz using a computerized manometric acquisition, display, and analysis system (Millar-MMS, Houston, TX) (9). The catheter was withdrawn slowly during quiet breathing and suspended swallowing in 1-cm steps allowing several respiratory cycles per station. The process was continued until the most distal recording location reached the level of the LES. The catheter was then repositioned such that up to three distal ports were recording from the stomach, and 10 swallows of 4-ml ambient temperature water spaced by $\geq$20 s were taken. The catheter was repositioned again such that the most proximal recording location rested in the region of the upper sphincter, 10 swallows were repeated, the catheter was withdrawn, and total intubation time was recorded.

Data Analysis and Interpretation

The manometric methods allowed for both common, clinical analysis (limited analysis methods), selectively censoring data as if a four-lumen recording catheter had been used, and topographical analysis methods, using data from all recording sites. LES resting pressure measurements (average end-expiratory over 10 channels) were extracted from the same pull-through performed at the beginning of the manometric study and were not used in the subsequent comparisons of analysis methods. Limited and topographical analyses were performed independently by separate investigators, and diagnoses were established without knowledge of clinical information, including current symptoms, previous diagnoses, or test results. For the preliminary study preceding this investigation, 70 additional subjects were studied with the same manometric protocol. Clinical data and results from limited analysis were available at the time of topographical analysis during this learning period to establish a baseline expertise in interpreting topographical plots.

For limited methods, pressure data from the initial 10 swallows were examined, and the recording location most representative of the LES was identified. This tracing and tracings from 3, 8, and 13 cm above the LES were retained on the screen for visual and analytical evaluation. The resultant study mimicked the appearance of a four-channel system configured in the same fashion. From the pull-through and 10 swallows, four characteristics of esophageal motility were determined: 1) peristaltic performance (progressive or nonprogressive wave forms), 2) contraction wave characteristics (amplitude, duration, multipeaked configuration), 3) LES basal pressure, and 4) LES relaxation (12). Peristaltic performance was determined from the recording locations 3 and 13 cm above the LES; contraction wave parameters were calculated from the tracings at 3 and 8 cm above the LES. Normal values were extracted from the literature and our previous reports (Appendix). The determined characteristics were used to establish a single manometric diagnosis (Fig. 1) (13). Because the same pull-through was used for each analysis method, LES resting pressure characteristics were not used in reaching a final diagnosis. For example, if hypotension or hypertension of the lower sphincter was the sole abnormality, the tracing was classified as normal for this investigation. Swallows taken in the proximal catheter position were examined using the same four-lumen configuration for their qualitative contribution to diagnosis.

Topographical analysis involved creating three-dimensional plots of pressure data over time along an esophageal segment (6, 9, 14). With these methods, data interpolation provide the sense of continuous pressure measurement over the sampled 20-cm length (Fig. 2). Subject data were analyzed as contour plots, wherein concentric contour rings indicate increasing pressure amplitude. Contour plots of each swallow, created immediately after completion of the manometric study, were simplified visually by coloring amplitude levels according to a legend at the bottom of the screen. The plots are interrogated directly using the mouse to extract *x*, *y*, *z* coordinates at any point, methods that have been described in further detail (9). LES resting pressure from the pull-through was the only analytical result provided at the time of topographical analysis. The 10 swallows from each catheter position were reviewed rapidly, using mouse interrogation for zeroing plots to gastric baseline, confirming specific pressure amplitudes (*e.g.*, for estimating mean wave amplitude) or locating wave onset (*e.g.*, for

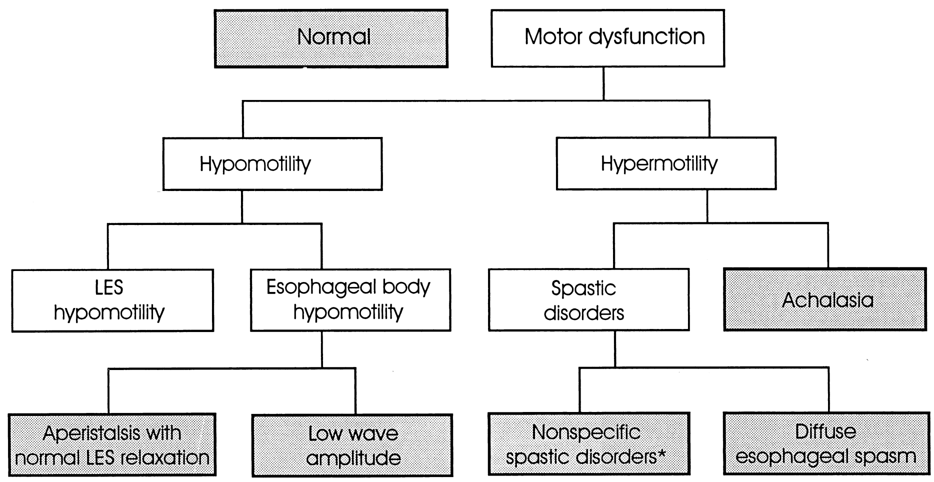

Figure 1. The diagnostic scheme used for classifying manometric patterns by each analysis method. The six shaded end point categories were compared; lower esophageal sphincter (LES) hypomotility was not considered, as the same pull-through was used to establish LES pressure for each analysis method. *Includes vigorous contraction wave abnormalities (*i.e.*, increased distal wave amplitude, prolonged wave duration, abnormal occurrence of double- and triple-peaked waves), incomplete LES relaxation (without other evidence of achalasia), and resting LES hypertension, although LES resting pressures were not considered when comparing analysis methods. Adapted from Alrakawi A, Clouse RE. Changing trends in the clinical use of esophageal manometry. Am J Gastroenterol 1998;93:2359–62.

determining propagation velocity), as required. Each study was then classified with the same parameter guidelines (Appendix) and classification scheme (Fig. 1) used for conventional analysis.

Limited and topographical methods were also compared for their ability to determine the proximal margin of the LES. Limited methods involved averaging the upper margins determined from the pull-through measurements using data from the four selected recording channels. The 10 swallows with the catheter in the distal position were used in topographical methods, the sphincter location determined from its characteristic appearance on topographical plots. The upper margin was taken as the proximal edge of the first contour line (5 mm Hg above gastric baseline), averaging the value around respiratory variation. These measurements were extracted as distantly as possible from swallows to avoid effects resulting from axial esophageal movement (15, 16).

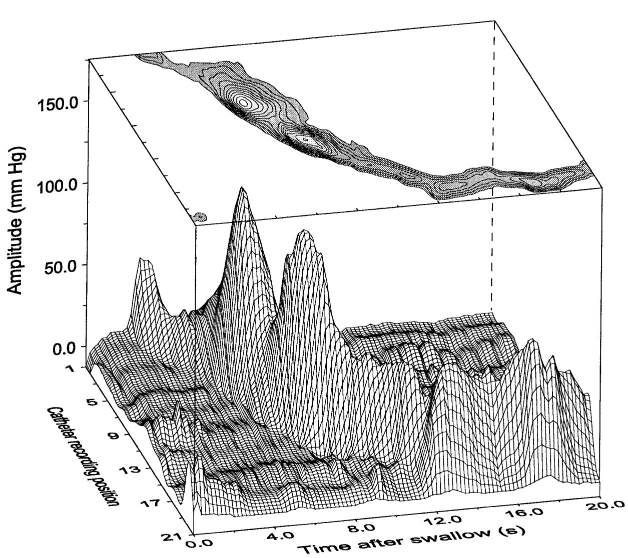

Figure 2. Examples of three-dimensional topographical plots. The lower surface plot shows the LES in the foreground. The peristaltic pressure wave in this normal subject proceeds from the proximal esophagus in the background until it merges with the LES after-contraction. Data are interpolated between recording sites positioned at 1-cm intervals over the 20-cm catheter length. The contour plot of the same swallow superimposed at the top of the figure demonstrates how three-dimensional data are represented using concentric rings at 10 mm Hg intervals to indicate increasing amplitudes.

Subjects completed clinical questionnaires at the time of manometry indicating nature of symptoms, diagnoses, and previous treatments. Discrepancies between diagnostic methods were clarified using this information and also by reviewing radiological and endoscopical reports, contacting referring physicians for additional historical data and test results, and learning the outcome of therapeutic interventions.

Statistical Methods

Data are reported as mean ± SD throughout. Values across groups were compared using Student's *t* test (two-tailed), χ^2 analysis, or Fisher's exact test, as appropriate. Correlations are reported as Pearson's *r*. In all instances, $p < 0.05$ was required for statistical significance.

RESULTS

A total of 224 subjects was referred for manometric evaluation during the study. No patient, parent, or guardian refused to give consent for participation. Fluoroscopy or en-

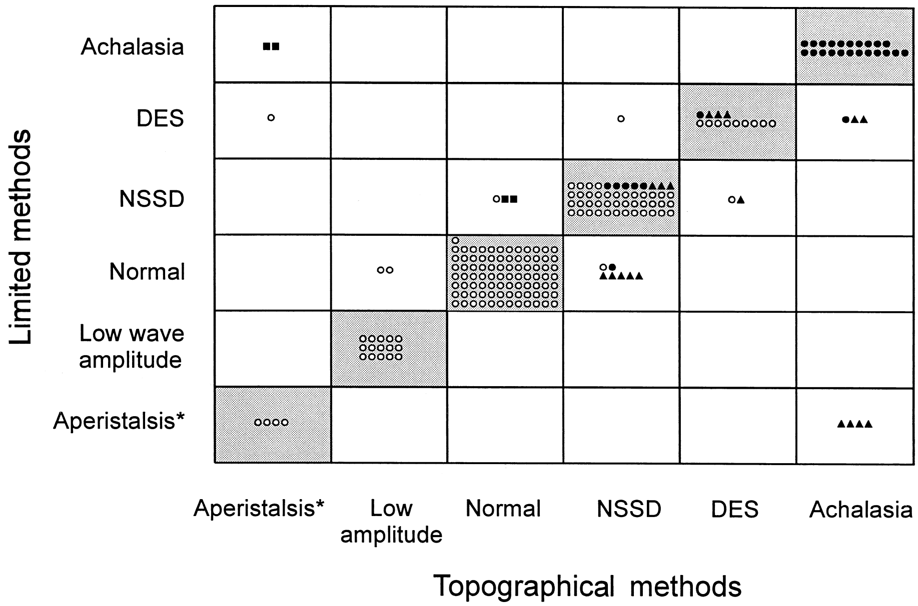

Figure 3. Comparison of diagnoses established by limited and topographical analysis methods. Each symbol represents one subject, and those in the shaded boxes indicate diagnostic agreement. Lower esophageal sphincter (LES) relaxation was normal in subjects represented by open circles (○), whereas filled symbols indicate incomplete LES relaxation determined by both analysis methods (●), by limited methods alone (■), or by topographical methods alone (▲). NSSD = nonspecific spastic disorder; DES = diffuse esophageal spasm. *with normal LES relaxation.

doscopy was used to assist with catheter placement in nine patients. In seven patients, the study could not be completed because of patient intolerance or inability to pass the catheter; in five the tracings were technically inadequate for comparative analyses (excessive artifact or inadequate number of swallows, three patients; inability to cross the LES, two patients). The resultant 212 patients serve as the subjects for this study (aged 49.7 ± 15.4 yr; range, 13–85 yr; 125 women [59.0%], 87 men [41.0%]). Esophageal complaints included heartburn in 117 patients (55.2%), regurgitation in 111 patients (52.4%), chest pain in 93 patients (43.9%), dysphagia for solid foods in 89 patients (42.0%), and dysphagia for liquids in 70 patients (33.0%), reflecting a recent trend toward evaluating more gastroesophageal reflux patients and fewer chest pain patients (13). The duration of the manometric study declined during the preliminary investigation from 28.6 ± 5.4 min for the first 10 subjects to 19.8 ± 3.9 min for the fourth 10 subjects and remained near that value throughout the preliminary and comparative investigations (18.3 ± 3.8 min for the final 10 subjects).

Comparison of Manometric Diagnoses

With LES resting pressure excluded from consideration, both analysis methods diagnosed a normal manometric pattern with the greatest frequency (limited methods, 93 patients [43.9%]; topographic analysis, 88 patients [41.5%]; Fig. 3). Hypermotility disorders were diagnosed more often than hypomotility disorders by both methods, and spastic disorders (nonspecific spastic disorders and diffuse esophageal spasm) were the most common types of abnormality detected. Across all patterns, the two analysis methods were in good agreement ($\chi^2 = 1.22$, df = 5, $p = 0.88$), but there were 25 instances (11.8%) of disagreement in diagnosis between analysis methods (Fig. 3).

Important discrepancies involved classification of the aperistaltic disorders at the extremes of dysmotility. Limited analysis methods identified 32 patients with aperistalsis (independent of LES relaxation); topographical analysis identified 36 patients. Disagreement in final diagnosis occurred in 10 patients (27.8% of this subset) (Fig. 3). In four subjects, limited methods indicated normal LES relaxation, whereas topographical analysis determined the presence of achalasia. In each instance, the topographical plots demonstrated proximal movement of the high pressure zone after swallows and maintenance of isobaric elevations in esophageal pressure proximal to the poorly relaxing LES, features that typify achalasia (Fig. 4*A*) (17). LES relaxation appeared normal by limited analysis methods, and clinical correlation was recommended in only two of the four subjects because of intermittent isobaric phenomena noted in the esophageal body. Aperistaltic disorders were diagnosed in four additional subjects by topographical methods, whereas limited methods indicated the diagnosis of diffuse esophageal spasm, with LES dysfunction (one subject) or normal LES relaxation (three subjects), or aperistalsis with normal LES relaxation (one subject; Fig. 3). In the three subjects diagnosed with diffuse esophageal spasm by limited methods because of intermittently normal-appearing peristaltic se-

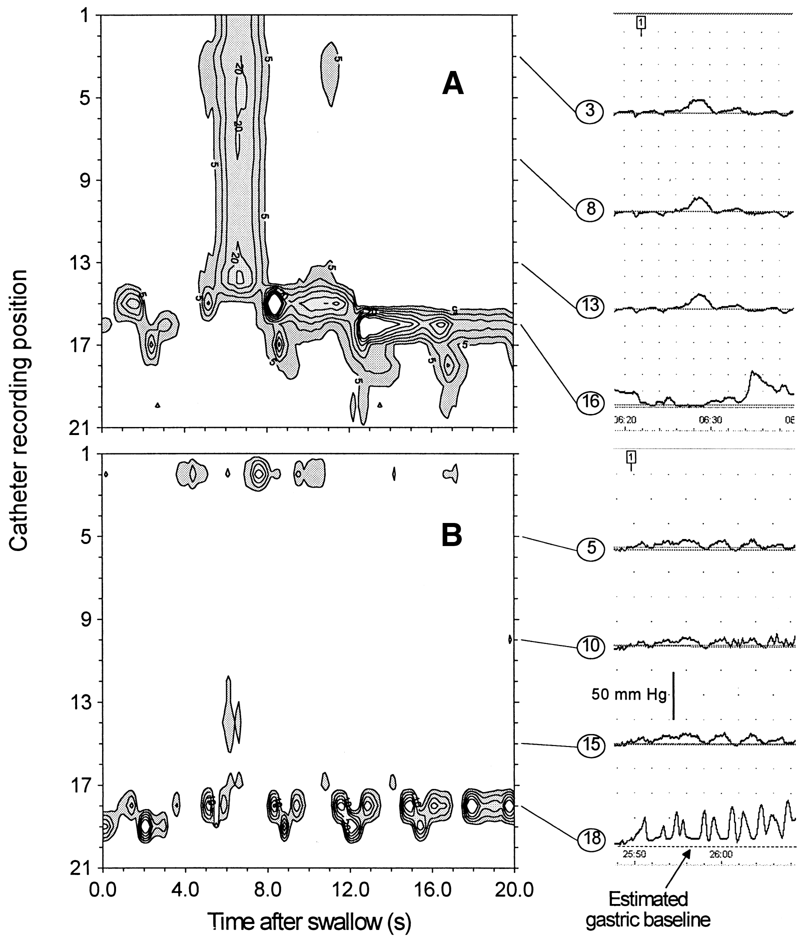

Figure 4. Discrepant findings in two subjects with aperistalsis. (*A*) A gradient persists across the LES region in this patient with confirmed achalasia with isobaric pressure increment in the esophageal body where normal peristalsis should be seen. These topographical features indicate achalasia, but LES relaxation appears normal in the conventional tracing. (*B*) The gastric baseline was incorrectly estimated by limited methods, and achalasia was suspected in this patient who was ultimately diagnosed with severe reflux disease and a hypomotil esophagus. The topographical plots, when intragastric pressure was correctly zeroed for each swallow, indicated normal LES relaxation amid a prominent diaphragmatic pinch, no reversal of the esophagogastric pressure gradient, and no evidence for achalasia. Resting LES pressure had been calculated as 12 mm Hg, a value within the normal range. Catheter recording positions for the conventional wave forms are indicated in the circles adjacent to each tracing and represent the LES and esophageal body at 3, 8, and 13 cm above the LES.

quences, topographical methods revealed that these "peristalses" were artifactual (from isobaric segments, repetitive contractions, and sporadic nonprogressive pressure events covering short distances) and not representative of progressive contraction sequences. On subsequent review, the same errors were made using the limited number of waves for the decision-making process. Two subjects thought to have achalasia by limited methods did not have this diagnosis by topography. In both instances, LES relaxation appeared incomplete, because of both diaphragmatic artifact and incorrect estimation of the gastric baseline from the pressures preceding the pull-through (Fig. 4*B*). Gastric pressure changed during the study, but the limited methods, having no intragastric pressure monitor, were unable to make this determination.

Clinical information was used to clarify discrepant diagnoses in the aperistaltic disorders. Sufficient data were available to secure a confident impression in each case, and topographical analysis appeared correct in 9 of the 10 discrepancies (Table 1). The esophagus was markedly dilated by barium evaluation or endoscopy in three of the six subjects correctly identified as achalasia by topographical methods, and two of the six had been treated previously with pneumatic dilation or myotomy. These subjects had very low amplitude pressure excursions in the esophageal body during manometry or low basal LES pressures, factors that appeared to interfere with conventional diagnosis. One subject diagnosed as having diffuse esophageal spasm and poor LES relaxation by limited methods but achalasia by topographical analysis lacked supporting evidence for achalasia, although the only progressive pressure sequences appeared artifactual on review of the contour plots. Taken together, topographical methods correctly diagnosed 35 (97.2%) of the 36 patients with aperistalsis by either method and was superior to limited methods (28 of 36 [77.8%]; $p = 0.028$).

Table 1. Clarification of Discrepant Diagnoses by the Two Analysis Methods in Patients With Suspected Aperistalsis

Sex/Age (yr)	Limited Methods	Topographical Methods	Clinical Information: Pertinent Historical Features	Clinical Information: Esophageal Contrast Studies	Clinical Information: Other Investigations	Final Clinical Diagnosis
M/54	Achalasia	Aperistalsis with normal LES relaxation	Systemic scleroderma. Good symptomatic response to antireflux treatment	Loss of primary peristalsis; free gastroesophageal reflux	None	Aperistalsis with normal LES relaxation (scleroderma esophagus)
F/49	Achalasia	Aperistalsis with normal LES relaxation	Heartburn and dysphagia that responded to antireflux treatment	Break-up of peristalsis; no esophageal dilatation; no hang-up of a 12.5-mm pill	Erosive esophagitis at endoscopy	Aperistalsis with normal LES relaxation
M/39	DES	Aperistalsis with normal LES relaxation	Cerebral palsy; severe gastroesophageal reflux symptoms	Spontaneous gastroesophageal reflux to thoracic inlet; large hiatal hernia	Erosive esophagitis at endoscopy	Aperistalsis with normal LES relaxation
F/37	DES	Achalasia	Nonspecific chest pain; partial response to nifedipine before meals	Break-up of persistalsis with barium retention in the distal esophagus; no inducible reflux; achalasia suspected	Normal endoscopy and 24-h pH study; typical achalasia on subsequent manometry	Achalasia
F/64	DES	Achalasia	Dysphagia and chest pain that responded well to antireflux treatment	Break-up of peristalsis and tertiary contractions; no esophageal dilatation; intermittent hang up of barium at the esophagogastric junction	Small hiatal hernia at endoscopy	DES
M/78	DES	Achalasia	Dysphagia for liquids and solid foods; previous pneumatic dilation and botulinum toxin injection for diagnosed achalasia	Loss of primary peristalsis; esophageal dilatation; barium retention at a beak-like esophagogastric junction	Dilated esophagus and closed esophagogastric junction at endoscopy	Achalasia
F/45	Aperistalsis with normal LES relaxation	Achalasia	Myotomy for achalasia 20 yr previously	Loss of primary peristalsis; marked esophageal dilatation and barium retention in upright position	Dilated esophagus and closed esophagogastric junction at endoscopy	Achalasia
M/76	Aperistalsis with normal LES relaxation	Achalasia	Dysphagia that did not respond to antisecretory treatment	Loss of primary peristalsis and tertiary contractions; narrowed esophagogastric junction and delayed barium transit; achalasia suspected	Closed esophagogastric junction with no stricture at endoscopy	Achalasia
F/66	Aperistalsis with normal LES relaxation	Achalasia	Progressive dysphagia for liquids and solid food. Subsequent response to botulinum toxin injection	Loss of primary peristalsis; esophageal dilatation; beak-like esophagogastric junction	Dilated, fluid-filled esophagus with closed esophagogastric junction at endoscopy	Achalasia
M/67	Aperistalsis with normal LES relaxation	Achalasia	Progressive dysphagia for liquids and solid food. Subsequent response to pneumatic dilation.	Loss of primary peristalsis; marked esophageal dilatation; minimal barium passage through esophagogastric junction	Markedly dilated esophagus with closed esophagogastric junction at endoscopy	Achalasia

DES = diffuse esophageal spasm; LES = lower esophageal sphincter.

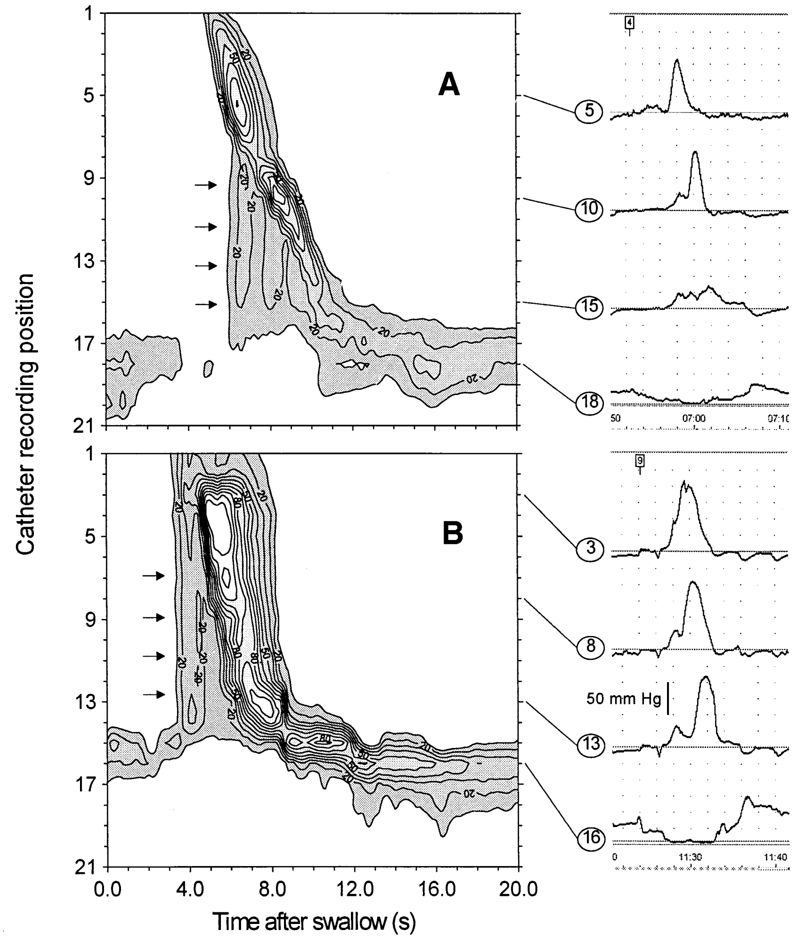

Figure 5. Lower esophageal sphincter (LES) dysfunction in two subjects that was recognized by topographical analysis but not determined by limited methods. (*A*) A gradient exceeding 20 mm Hg above gastric baseline with stripe-like isobars is found leading distal peristalsis (otherwise normal) as it approaches the LES region (arrows). Conventional wave forms in the LES region and esophageal body suggest normal LES function. This patient had undergone fundoplication previously. (*B*) Stripe-like isobars of pressure exceeding 20 mm Hg over gastric baseline (arrows) are again seen to precede peristalsis in this subject with rapid peristalsis, evidence of a nonspecific spastic disorder (broad wave duration), and clinical history supporting the findings. The gradient moved cephalad during swallowing and LES dysfunction was not detected by limited methods.

Discrepancies in the categories near normal were in part related to errors in estimating contraction amplitude by topographical methods (too high, three patients; too low, three patients). Two patients were classified as having diffuse esophageal spasm by topography, but propagation velocity of one swallow in each instance was too slow to qualify as a simultaneous sequence by limited analyses methods. The most conspicuous difference in techniques related to the diagnostic sensitivity for LES dysfunction (Fig. 3). The limited approach identified poor LES relaxation in 34 (16.0%) of the 212 subjects; topographical methods identified this abnormality in 48 (22.6%; $p < 0.01$). In two subjects with otherwise normal manometry, limited methods suggested poor LES relaxation, whereas topography appeared normal. One of these subjects had had a prior gastroplasty, and review of the topographical plots indicated that the gastroplasty itself had been misinterpreted as the area of the LES during analysis by limited methods. In the other subject, the gastric baseline from the pull-through had been misinterpreted (an error that was reproduced when the study was reviewed a second time); topographical contour plots, when correctly zeroed, showed no residual gradient at the LES. Clinical data did not support significant LES dysfunction in that patient.

More commonly, topographical analysis found LES dysfunction in patients with peristalsis that had been overlooked by limited methods (Fig. 3). In these cases, the recording location chosen for LES evaluation by limited methods appeared appropriate, demonstrating typical relaxation and aftercontraction with swallows. Topography indicated that, in most instances, the high pressure zone was maintained proximal to the recording site, producing isobaric increments in intrabolus pressure leading the peristaltic wave (Fig. 5). As for the aperistaltic disorders, clinical information was obtained for clarification and indicated that the topographical observation was probably correct and

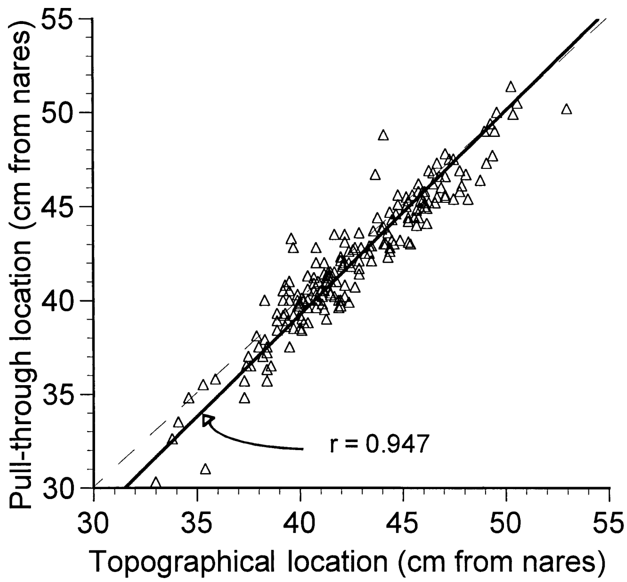

Figure 6. Location of the proximal margin of the LES by pull-through and topographical methods. The dashed line is the line of unity.

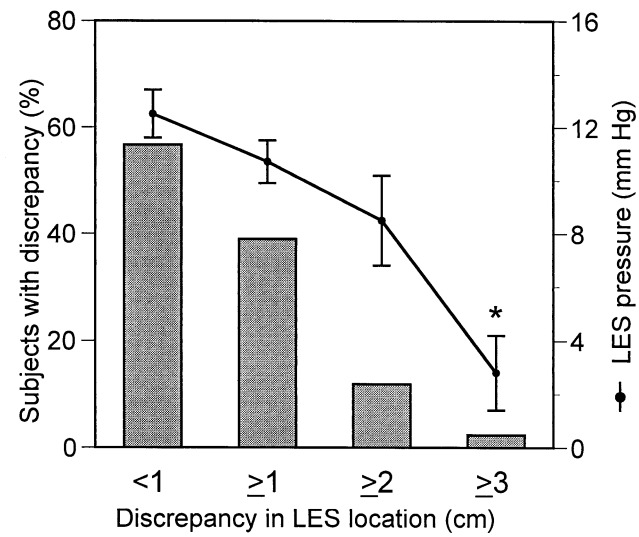

Figure 7. Absolute discrepancy in lower esophageal sphincter (LES) location between pull-through and topographical measurements. LES pressures were lower in the most discrepant cases. Extensions indicate SE; *$p < 0.05$ compared with nondiscrepant cases (<1 cm).

clinically relevant in at least 8 of these 12 discrepant cases. In two patients, Nissen fundoplications had been performed previously producing the poor relaxation effect. In four other patients, historical data or test results were supportive (recurrent distal food bolus impactions, two patients; hang-up of liquid barium or radiopaque pill at the LES region, two patients). Suggestive evidence was found in an additional two patients who had symptoms of solid food dysphagia but no radiographic evidence of delayed clearance. "Puckering" was noted at the LES during endoscopy without evidence of distinct stricture in one of these patients; achalasia was suspected in the diagnostic impression. In the other patient, dysphagia for solid foods was the principal symptom, and the patient responded to bougienage. Although supportive clinical data were absent, LES dysfunction was found in conjunction with diffuse esophageal spasm in three other subjects, disorders known to cooccur frequently (12, 18).

LES Location Determination

Topographical methods identified the upper margin of the LES in all but three subjects (1.4%); pull-through methods could not identify this location in these and five additional subjects (3.8%). In the remainder, site of the proximal margin was similar using pull-through or topographical methods ($r = 0.946$, $p < 0.001$; Fig. 6). A bias occurred toward more proximal location by the pull-through technique, possibly because of tension on the catheter during measurement. Discrepancy of ≥2 cm, however, was found in 11.9% of patients and ≥3 cm in 2.4% (Fig. 7). In nearly all of the latter cases, topographical determination of the LES was proximal to that of conventional pull-through analysis. As also shown in Figure 7, discrepancies were more likely associated with decreased resting LES pressure.

Cases with discrepancy ≥2 cm were reevaluated using the available manometric data, as no external standard was used. In most instances, the station pull-through location appeared influenced by diaphragmatic activity and change in baseline pressure from intraabdominal to intrathoracic location. Because swallowing was suspended during the pull-through maneuver, cues from peristalsis were not available. In contrast, topographical methods relied on visualization of sphincter activity in its relationship to the normal topographical appearance of peristalsis (Fig. 8). After review of both pull-through and topographical data, topographical assessment of LES location appeared most likely correct in all the highly discrepant cases.

DISCUSSION

Topographical methods involve two separate augmentations of conventional manometry, each of which offers potential technical advantages. One is the increased number of recording sites, now feasible because of improvements in extruded catheters that maintain a comfortable outside diameter—not dissimilar from that of assemblies with many fewer lumens. Despite the very thin webs that separate lumens, there is no evidence of significant pressure cross-communication between channels and recording fidelity is equivalent to previous methods (J Dent, personal communication). This augmentation is largely responsible for detecting subtle pressure troughs separating the peristaltic response into individual segments through the esophageal body and LES (6, 19). The number and proximity of re-

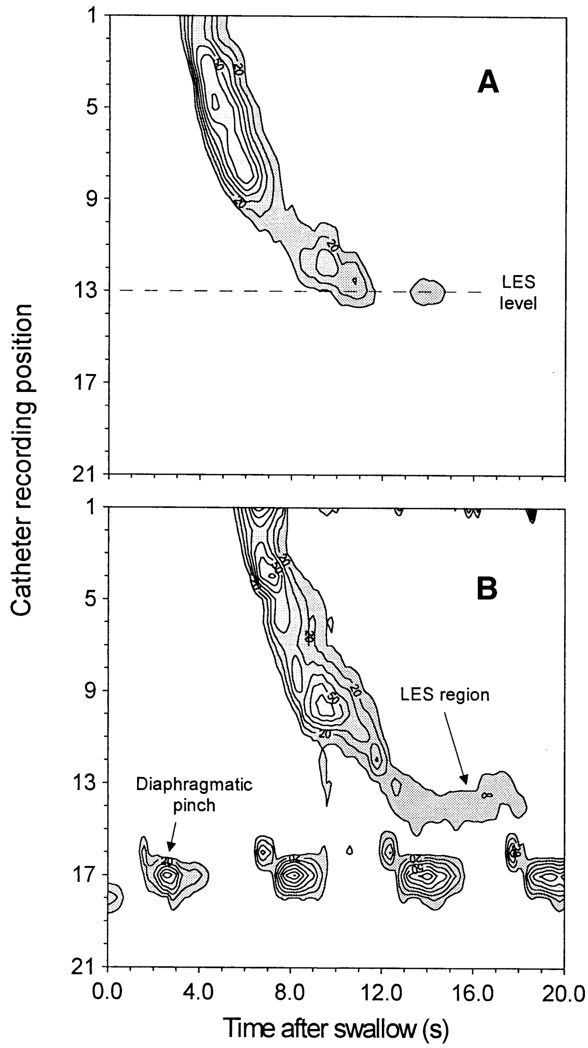

Figure 8. Lower esophageal sphincter (LES) localization using topographical methods. (*A*) The LES was not detected on the pull-through, but the weak sphincter was seen on contour plots from several swallows. (*B*) The pull-through suggested the LES margin was at the level of the diaphragm. Contour plots indicated a more proximal location. In both instances, the discrepancy exceeded 2 cm; resting LES pressure appeared very low in the top subject and measured 3.5 mm Hg in bottom.

cording sites required for best representation of peristalsis in the esophagus are unknown, but site separation in excess of 2 cm begins to alter significantly the axial representation of data (20). At present it remains assumed that the spatial representation of pressures in the axial direction will be important to fully understand the mechanics of bolus transport through the esophagus (8, 21).

The second advancement is in the continuous representation of pressures in both temporal and spatial orientations using data interpolation and three-dimensional plotting. This aspect of topographical analysis is dependent on but not an unnecessary redundancy of the increase in recording sites. Axial interpolation has already proved useful in understanding the correct relationship of pressure data when unusual wave forms occur, for example, multipeaked waves (22). Three-dimensional topographical plots are convenient methods of visually representing the large amount of data provided by the increased number of recording sites. Contour plots can provide vivid images of surface shapes, and recognizable picture representations of data take advantage of specialized hemispheric brain regions not tapped by data presented in other forms (23, 24). Consequently, identifying motor disorders may be simplified for some individuals using these methods. In addition to their amplification of data by integrating across recording sites, contour plots better use screen space than the 21 individual tracings, allow rapid interpretation of swallow performance, and provide new opportunities for computerized pattern recognition not previously considered with conventional manometric methods (9, 19).

Although it seems only sensible that increasing the number of recording sites alone would enhance the diagnostic capabilities of topographical methods, this is not established. In fact, the few direct comparisons of manometric methods have favored simplified methods (25, 26). Minor abnormalities were occasionally overlooked when stationary methods with four or fewer recording sites were compared with more comprehensive mapping techniques; difficulties in diagnosing severe motor dysfunction were not described (25). Although systems with up to 12 recording sites have long been available, >80% of manometric systems sold in the United States at present allow four or fewer recording sites (L Diederich, Sandhill Scientific; T Bombeck, Medtronics; personal communication). For that reason, the comparison was made with a four-channel system in this study.

We found that topographical methods had several important clinical advantages over the common limited approach. First, they were significantly more accurate in identifying achalasia and segregating the disorder from other forms of severe motor dysfunction. Diagnosing or confirming suspected achalasia remains one of the most important uses of manometry, and accuracy should be maximized in this regard (1, 3). Some difficulty with limited methods in this study related to the use of a single sidehole in the LES, a difficulty partially overcome in practice with a sleeve recording device (1, 5). Identification of achalasia by topography, however, is not dependent solely on measuring LES relaxation but also on alterations in the normal esophagogastric pressure gradient and exaggerated isobaric pressure vacillations in the esophageal body (17). Topography can also determine artifactual, sporadic pressure events that might be interpreted as peristalsis by conventional methods. All of these factors helped improve the accuracy of topography in the important differentiation of aperistaltic processes.

Additional clinical information verified the correct segregation of aperistaltic disorders by topographic methods in >95% of patients. Reasonable support was also gained for the correct diagnosis of nonachalasic LES dysfunction in two-thirds of patients in whom the relaxation error was seen by topography alone. These patients were identified by isobaric stripes leading peristalsis to a gradient across the sphincter. Proximal movement of the high pressure region (presumably with axial esophageal movement during swallowing) interfered with conventional detection of such LES abnormalities (15, 16). Although not proved in this investigation, this second advantage of topography may have practical importance in patient management. Poor LES relaxation accompanying spastic disorders can be managed successfully using pneumatic dilation (27, 28). Bougienage may be beneficial in a subset of patients, and botulinum toxin injection may have diagnostic and therapeutic applications in others (29, 30).

Third, topographical methods may have important advantages in identifying the location of the LES, as is required for pH probe placement. The methods seemed particularly helpful when resting pressure in the sphincter was low or the patient could not fully cooperate during the pull-through maneuver. Because of the low interswallow variability in location of physiological landmarks and because the usual peristaltic "fingerprint" is easily recognized on contour plots, we found this advantage of topography very useful in daily clinical practice (19). Discrepancies of at least 2 cm in localization occurred in >10% of our patients, even when the pull-throughs were interpreted by physicians well-trained in the techniques. Errors of this magnitude probably are unacceptable for sphincter-locating methods when planning pH probe studies (at least in some subject groups) (31). These findings will require more rigorous comparison to an external standard before the advantages of topography suggested in this report can be firmly proven. Topographical findings were satisfactory, however, to explain the confusion on the pull-throughs during reevaluation of highly discrepant cases.

Some of the value of topographical methods demonstrated in the comparison could be attributed to a bias against the limited, conventional approach. For example, errors in establishing gastric baseline or in interpreting intraesophageal pressure events may not have been made by others experienced in manometric technique. However, every effort was taken to avoid this bias, and the difference in accurate differentiation of severe motor dysfunction was not established until *post hoc* analysis of substantiating clinical data was complete. Likewise, cues from peristalsis might have improved localization of the LES using limited methods as they did for topographical methods; we adhered to rigid protocols for this comparison that did not allow such information. Consequently, the value of the latter may be more limited in this regard than described. Also disfavoring an immediate embracing of these techniques is the expense involved in the catheter and data acquisition system and the technical expertise required for their maintenance. The goal, however, is toward diagnostic precision and escalation of the learning curve so that manometry in clinical practice is more uniformly accurate. Topographical methods, by describing a pressure continuum, actually become less dependent on experience and technique and have this potential. Acceptance of these methods should encourage development of simplified nonperfused catheter systems with 20 or more recording sites, as one of the principal driving forces for use of limited, four-channel systems today is their compatibility with available solid-state intraluminal transducer probes (L Diederich, Sandhill Scientific, personal communication).

Topographical methods appeared to complement and improve on a more limited approach in several ways in this first clinical application of the techniques. Besides rapidity in screening for motor dysfunction, accuracy of the methods in defining important disorders was gratifying. There were no conspicuous disadvantages to topographical methods other than expense resulting from implementation and maintenance of additional recording channels and the computerized system. With slight modification of technique, the entire esophagus could be sampled without catheter movement, further reducing intubation time for the patient. However, increased spacing of recording sites must be carefully weighed against the fidelity of three-dimensional pressure representation so that the observed advantages of topographical methods are retained.

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APPENDIX

Normal values used in determining the presence of motor dysfunction:

1. Peristaltic performance: $<$30% simultaneous pressure sequences.*
2. Contraction wave parameters: wave amplitude 37–188 mm Hg; wave duration $<$5.6 s; $<$10% double-peaked waves; no triple-peaked waves.†‡
3. Lower esophageal sphincter (LES) resting pressure: not used in this investigation.
4. LES relaxation: mean post-swallow residual pressure (minimum value within 5 s of swallowing) $<$5 mm Hg.§

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