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3D-High Resolution Manometry of the Esophagogastric Junction

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Abstract

BACKGROUND—The esophagogastric junction (EGJ) is a complex structure that challenges accurate manometric recording. This study aimed to define EGJ pressure morphology relative to the squamocolumnar junction (SCJ) during respiration with 3D high-resolution manometry (3D-HRM).

METHODS—A 7.5 cm long 3D-HRM array with 96 independent solid-state pressure sensors (axial spacing 0.75 cm, radial spacing 45°) was used to record EGJ pressure in 15 normal subjects. Concurrent videofluoroscopy was used to localize the SCJ marked with an endoclip. Ex-vivo experiments were done on the effect of bending the probe to match that seen fluoroscopically.

RESULTS—3D-HRM EGJ pressure recordings were dominated by an asymmetric pressure peak superimposed on the lower esophageal sphincter (LES) attributable to the crural diaphragm (CD). Median peak CD pressure at expiration and inspiration (51 and 119 mmHg respectively) was much greater in 3D-HRM than evident in HRM with circumferential pressure averaging. EGJ length, defined as the zone of circumferential pressure exceeding that of adjacent esophagus or stomach was also substantially shorter (2.4 cm) than evident in conventional HRM. No consistent circumferential EGJ pressure was evident distal to the SCJ in 3D-HRM recordings and ex-vivo experiments suggested that the intragastric pressure peak seen contralateral to the CD related to bending the assembly rather than the sphincter per se.

CONCLUSION—3D-HRM demonstrated a profoundly asymmetric and vigorous CD component to EGJ pressure superimposed on the LES. EGJ length was shorter than evident with conventional HRM and the distal margin of the EGJ sphincteric zone closely correlated with the SCJ.

Keywords

crural diaphragm; esophagogastric junction; lower esophageal sphincter; esophageal pressure topography; squamocolumnar junction; esophageal manometry

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DISCLOSURES

No relevant competing financial and other interests exist for Monika A. Kwiatek, John E. Pandolfino or Peter J. Kahrilas.

Monika A. Kwiatek contributed to the conception and study design, study supervision, data collection, analysis and interpretation, statistical analysis, manuscript drafting, editing, critical revision and final approval. John E. Pandolfino contributed to the conception and study design, obtained funding, data interpretation, manuscript drafting, editing, critical revision and final approval. Peter J. Kahrilas contributed to the conception and study design, obtained funding, data interpretation, manuscript drafting, editing, critical revision and final approval.

INTRODUCTION

The esophagogastric junction (EGJ) is a complex valvular structure controlling bolus entry into the stomach and gastric reflux into the esophagus. Among the contributors to EGJ function, the most established are the specialized muscle of the lower esophageal sphincter (LES), the surrounding crural diaphragm (CD), and the integrity of the phrenoesophageal attachments (1–5). Recently proposed as additional sphincteric components are the opposing gastric sling and clasp fibers, a middle layer of the gastric muscularis propria just distal to the squamocolumnar junction (SCJ) and LES with unique pharmacological properties (6–8).

Intraluminal manometry has facilitated understanding key aspects of EGJ physiology including the very existence of the LES (9), the CD contribution (10–12), radial asymmetry of LES pressure (2, 13–15), transient LES relaxation (16), esophageal shortening during LES relaxation (17–20), and even transient conformational change of the EGJ into and out of sliding hiatus hernia configuration (21). However, somewhat paradoxically, characterizing the normal EGJ has proven quite challenging. Devices optimized to detect EGJ relaxation (notably the sleeve sensor) often do so at the expense of axial and/or radial pressure resolution and techniques optimized to define spatial conformation (notably pull-through techniques) do so at the expense of accounting for respiratory dynamics. Consequently, depending on methodology, the views on what constitutes a normal EGJ pressure profile diverge.

Recent technological advances have led to the increased utilization of high resolution manometry (HRM) and esophageal pressure topography (EPT) both in research and clinical settings. Certainly, these methods have enhanced our understanding of the segmental architecture of esophageal peristalsis and of the interaction between peristalsis and the EGJ in facilitating bolus transit (22–27). However, despite these strengths, the ability of HRM to assess the EGJ pressure morphology is still limited. The available devices utilize either circumferentially sensitive transducers or point sensors, neither of which faithfully records radial pressure characteristics. This consideration led to the development of the 3D-HRM device utilized in this study. By combining closely spaced HRM sensors, which also provide radial pressure resolution, 3D-HRM should facilitate high fidelity dynamic recordings of EGJ pressure morphology in a way not possible thus far (28). Hence, the aim of this study was to resolve the pressure morphology of the EGJ during respiration in 3D-HRM, correlating the location of pressure constituents with the respiratory cycle and with the position of the SCJ by means of an endoclip and concurrent fluoroscopy.

MATERIALS AND METHODS

Subjects

Fifteen normal subjects were studied. None of the subjects had a history of prior gastrointestinal surgery, significant medical disease, or using medications for upper gastrointestinal symptoms. All subjects provided written consent. The study protocol was approved by the Northwestern University Institutional Review Board.

3D High Resolution Manometry (3D-HRM)

Manometry studies were done using a novel solid-state manometry assembly (Figure 1, ManoScan™ 3D, Given Imaging, Los Angeles, CA, U.S.A.). This hybrid assembly (4.2 mm outer diameter) incorporated an array of twelve 3D high resolution sensors spaced 7.5 mm apart and situated between segments of 28 proximal and 4 distal “conventional” circumferential sensors spaced at 1-cm intervals. The novelty of the 3D array was of slightly increased axial pressure resolution and completely preserved radial pressure resolution. With respect to axial pressure resolution, both the 3D array and the conventional array utilized

individual sensing elements that were 2.5 mm in length, but these were spaced 7.5 mm apart on center in 3D array compared to 10 mm apart on center in the conventional segment. With respect to radial pressure sensitivity, each axial level within the 3D array consisted of 8 sensors dispersed 45° apart circumferentially with each functioning as an independent pressure sensor. On the other hand, each circumferentially sensitive sensor within “conventional” segments of the hybrid catheter averaged the pressure signals from 12 circumferential sensors into a single recorded pressure. Consequently, an 8 cm segment of “conventional” HRM yielded 8 averaged pressure readings compared to 96 in the 7.5 cm 3D-HRM segment. Each sensing element, whether in the conventional or 3D array, recorded pressure transients in excess of 6000 mmHg/s with an accuracy of ± 1 mmHg after thermal compensation. The data acquisition frequency was 35 Hz.

Manometric data were displayed as pressure topography plots using both the proprietary ManoView™ software (Given Imaging, Los Angeles, CA, U.S.A.) and MATLAB™ (The MathWorks Inc., Natick, MA, U.S.A.). MATLAB™ was used to depict the HRM and 3D-HRM EPTs, because of its greater flexibility. All pressure measurements were referenced to atmospheric pressure.

Study Protocol

Studies were done after at least a 6-hour fast. After a brief interview and examination, participants completed questionnaires assessing symptoms of dysphagia and gastroesophageal reflux (see *Symptom Questionnaires*). Subjects then underwent esophagogastroduodenoscopy (EGD) using moderate sedation with 5–10 mg midazolam and 75–200 µg fentanyl as necessary. During endoscopy, an endoclip was placed at the SCJ (Resolution® Clip, Boston Scientific, Natick, MA, U.S.A.). Although the radial orientation of the clip on the SCJ could not be precisely controlled, this naturally oriented toward the lesser curvature of the stomach.

Following complete recovery from sedation (at least 2 hours after the EGD), patients underwent trans-nasal placement of the manometry assembly. The pressure transducers were calibrated at 0 and 300 mmHg using externally applied pressure prior to the intubation. The 3D-HRM array was positioned within the EGJ, ensuring that the distal end was well within the stomach and the assembly was then fixed in place by taping it to the nose. The study protocol included a baseline swallow-free recording for at least three consecutive respiratory cycles. During the recording, the subjects were supine on a fluoroscopic table (Phillips Medical Systems, Shelton, CT, U.S.A.) and shielded below the umbilicus with a lead apron, along with a lead collar for thyroid protection. Real-time fluoroscopic images were recorded through a video module (ManoScanV™, Given Imaging, Los Angeles, CA, U.S.A.) on the computer and synchronized with concurrent 3D-HRM manometry recordings (Figure 2).

Ex-vivo testing

Figure 2 illustrates the typical conformation of the manometric assembly during a recording with the less-flexible 3D-HRM array straddling and bent at the EGJ. Experiments were done ex-vivo to ascertain the effect of this bend on pressure recordings. This was done in two ways. With the first method, the assembly was anchored on a bench top with pushpins against a cardboard backing to recreate the degree and localization of the bend observed fluoroscopically. However, the pushpins were positioned such that they contacted only the housing and not any pressure sensor, simulating the effect of passive bending of the sensor housing on the recording. The second set of experiments similarly stabilized the assembly on a flat surface, but now reproduced the angulation with two rubber bands placed around the assembly in a sling-like fashion such that they directly contacted two of the sensors on the 3D-HRM sensors spaced 1.5 cm apart. Traction was applied to the lower rubber band to

bend the manometric assembly while simultaneously preventing it from moving sideways with traction to the proximal rubber band. This model was devised to simulate the CD (proximal rubber band) and gastric wall (lower rubber band). A spectrum of angles were tested, selected so as to bracket the degree of angulation observed in the fluoroscopic studies.

Symptoms Questionnaires

Dysphagia symptoms were assessed using the Hospital Odynophagia Dysphagia Questionnaire (HODQ, maximal score: 50; 5th–95th percentile cut-offs, controls: 2). Reflux symptoms were measured using the Reflux Disease Questionnaire (RDQ, maximal score for heartburn or regurgitation: 20; normative cut-off: < 8).

Statistical Analysis

Pressure data from the studies performed in subjects were summarized as median (5th–95th percentile) and compared using nonparametric statistical tests. A $p < 0.05$ was considered significant.

RESULTS

Subject demographics

All 15 subjects (9F:6M, 21–52 yr) completed the study. Fourteen had a normal HODQ score (≤ 2) and one had a borderline abnormal score of 9. All 15 subjects had normal RDQ scores of 2 or less. One subject had Los Angeles grade A esophagitis with a single erosion at the SCJ; the remainder had a normal endoscopy. None of the subjects had a hiatal hernia.

3D-HRM EGJ pressure morphology

Figure 3 graphically exemplifies the conversion from HRM mode to 3D-HRM of the EGJ recording. In Figure 3A, pressure data from the 12 axial pressure locations of the 3D array are illustrated as an EPT plot utilizing the average pressure detected at each axial location by the 8 radially dispersed sensors. This is akin to the circumferential averaging done with conventional HRM pressure sensors, which do not resolve radial pressure information. The data depicted in Figure 3A spans an 8-s interval with the black dotted lines indicating instants of peak inspiration and mid-expiration and the magenta dots indicating the location of the SCJ as derived from the concomitant fluoroscopic images. The corresponding 3D-HRM data for the instants of peak inspiration and mid-expiration, with preserved 8-sector radial pressure resolution, are shown in Figure 3B. The magenta dots indicating the position of the SCJ are arbitrarily placed at the 12 o'clock orientation (lesser curvature side).

Although software can be used to rotate the pressure cylinders in Figure 3B on a computer monitor to reveal the hidden side (1–5 o'clock of the clock face) of the EGJ pressure morphology, this is not possible on a piece of paper. Alternatively, to fully display all 360° of the EGJ pressure morphology depicted in Figure 3B in a single image, the cylinders are cut open lengthwise along either the 12 o'clock or 6 o'clock radian and laid flat, resulting in landscape plots of instantaneous 3D-HRM EGJ pressure at peak inspiration and mid-expiration (Figures 4A and B). Again, the position of the SCJ is indicated by the magenta dots, derived from the corresponding fluoroscopic images and placed at the 12 o'clock location of the lesser curvature.

Respiratory and crural diaphragm effects on EGJ pressure

The most striking feature of the 3D-HRM plots in Figure 4 was the maximal EGJ pressure centered at the 6 o'clock orientation and localized 1.3 cm (range –0.7 to 2.1 cm) proximal to

the SCJ. This pressure signature varied among individuals, but was always identifiable by its respiratory oscillation typified in Figure 4B, consistent with the inspiratory contraction of the CD. The magnitude of the CD contraction detected by 3D-HRM (130 mmHg during inspiration in Figure 4B) was compared to what would be recorded in conventional HRM, emulated by averaging the eight radial sector signals at that instant. Evident in Table 1, the median pressure augmentation associated with CD contraction in 3D-HRM greatly exceeded that evident with circumferential averaging (63 mmHg vs 22 mmHg, $p < 0.01$). Similar large differences were evident in maximal EGJ pressure (3D-HRM 119 mmHg vs conventional HRM emulation 55 mmHg, $p < 0.01$). Interestingly, even at expiration significant radial pressure asymmetry persisted with the CD side (6 o'clock) still exhibiting significantly greater pressure than the opposing side (51 mmHg vs 20 mmHg, $p < 0.01$). Conversely, the corresponding minimum sector pressures (12 o'clock) were considerably less than evident with HRM emulation at both inspiration (3D-HRM 29 mmHg vs HRM emulation 55 mmHg, $p < 0.01$) and expiration (3D-HRM 20 mmHg vs HRM emulation 36 mmHg, $p < 0.01$). Being in opposition to the CD pressure signature and centered at 12 o'clock, the minimal sector pressure was located on the lesser curvature.

EGJ length

3D-HRM EGJ pressure morphology was also analyzed for sphincter length and intrasphincteric position of the SCJ. In calculating EGJ length, the proximal and distal limits were defined as the axial locations first detecting a 360° circumferential pressure increase relative to the adjacent esophagus and stomach, respectively. The rationale for this was that, without meeting this criterion, the lumen would not be sealed relative to the esophagus or stomach. Figure 4 exemplifies the definition of the distal margin of the EGJ high pressure zone (arrow) based on the most proximal extent of the intra-gastric pressure (IGP). The same methodology was applied to the HRM data depicted in Figure 3A without radial pressure resolution (dotted yellow line). The EGJ length, reported as the minimal distance separating the intra-esophageal and intra-gastric pressure environments was significantly less when measured in the 3D-HRM mode than with HRM at both peak inspiration (2.3 vs 5.0 cm, $p < 0.05$) and expiration (2.4 vs 5.0 cm, $p < 0.05$) (Table 2). Contrasting Figures 3A and Figure 4, it becomes evident that most of the EGJ “shortening” when measured with 3D-HRM was due to the upward shift in the limit of IGP at the 12 o'clock position in Figure 4, extending proximal to the lesser curve pressure peak best illustrated in the right hand panel of Figure 4A. The “shortening” of the EGJ at the 12 o'clock sector also effectively altered the relative position of the SCJ to the distal margin of the EGJ high-pressure zone. Whereas the HRM emulation, on average, positioned the distal limit of the EGJ 1.6 and 2.9 cm distal to the SCJ at expiration and inspiration respectively, these values were 0.3 and 0.4 cm respectively in 3D-HRM (Table 2). The change in location of the proximal EGJ margin was subject to a similar averaging effect, but was less pronounced in magnitude with intra-esophageal pressure extended more distally by 0.9 (0.2–2.2) cm at expiration and 0.6 (0.1–1.4) cm at inspiration on 3D-HRM compared to emulated HRM.

Ex-vivo testing

A consistent aspect of 3D-HRM EGJ pressure morphology was the asymmetric pressure peak distal to the SCJ at the 12 o'clock radial orientation of the lesser curvature. As suggested in the top panel of Figure 4A, the amplitude of this distal peak varied in direct proportion to the inspiratory increase in CD pressure at 6 o'clock and this distal peak was on the opposing wall, consistent with being on the lesser curvature of the stomach. One possibility was that this was an electronic artifact consequent from a passive bend imposed on the stiff 3D HRM array as it traversed the EGJ (Figure 2). That possibility was excluded by reproducing the identical deformation of the 3D-HRM array on a cardboard backing using pushpins carefully positioned so as not to contact any pressure sensing elements. The

resulting experiment yielded no measured pressure signal. An alternative hypothesis was that the lesser curvature pressure signal was the result of the probe being deflected off of the gastric wall as the probe was bent by contraction of the CD. This possibility was modeled with the dual rubber band experiment illustrated in Figure 5A. Applying sufficient traction with the opposed rubber bands to achieve the magnitude of assembly bend observed fluoroscopically during recordings resulted in the 3D-HRM pressure morphology exemplified in Figure 5B and C, paralleling that observed in vivo and suggesting this to be the explanation for the distal pressure peak along the lesser curvature in Figure 4. The maximal pressures recorded at the contact points of the rubber bands were directly proportional to the degree of angulation imposed and essentially equal to each other in magnitude (Figure 6).

DISCUSSION

This investigation used 3D-HRM, a novel solid-state 7.5 cm long manometry device with 96 independent pressure sensors, to characterize EGJ pressure morphology during respiration. The major findings were that: 1) the magnitude of radial pressure asymmetry contributed by the CD and centered 1.3 cm proximal to the SCJ was significantly greater than previously reported, 2) the length of the EGJ, distinguished as the region of increased pressure relative to the adjacent esophagus or stomach, was significantly shorter than when measured with circumferentially averaging sensors, and 3) the SCJ demarcated the boundary between the distal margin of the EGJ and intragastric pressure.

A prominent feature of the 3D-HRM plots exemplified in Figure 4 was the focal, highly asymmetrical pressure signature of the CD. The CD locus on the 3D-HRM plots was identifiable throughout the respiratory cycle, nearly doubling in magnitude with inspiration, but persisting at the 6 o'clock radian throughout. This pressure signature is strongly supportive of the extrinsic "pinchcock" action of the CD as originally proposed by Allison (29) and consistent with its anatomy. Although often illustrated as an extrinsic ring surrounding the hiatus, the shape of the hiatus is more accurately likened to a teardrop formed by the elements of the right diaphragmatic crus, emanating from the anterolateral aspect of the lumbar vertebrae and forming a sling around the esophagus within the angle of His (30, 31). The 6 o'clock pressure signature in 3D-HRM corresponds to the apex of that teardrop. A secondary consequence of this "pinchcock" action was angulation of the manometric assembly as it traverses the EGJ. However, for that bend to occur, the force exerted by the CD must be opposed by deflection off the contralateral wall. That point of contact on the lesser curvature was evident as a pressure peak distal to the SCJ (Figure 4). Ex-vivo modeling experiments support this interpretation and suggest that the magnitude of the distal pressure peak is proportional to the degree to which the assembly is bent (Figure 6).

A second major finding from the 3D-HRM data pertains to EGJ sphincteric length. Herein lies a key advantage of 3D-HRM. Rather than selecting among technological compromises that either limit pressure measurement to a single radial orientation, circumferentially average pressure, selectively record only the greatest pressure across the EGJ, or necessitate that measurements be made by motorized pull-through sphincter during suspended respiration (13, 32–34), 3D-HRM can be record EGJ pressure in high radial and axial resolution throughout a natural respiratory cycle. Hence the effects of respiration are not exaggerated by breath holding, axial movement that occurs with respiration can be tracked, and radial pressure asymmetry quantified. The net effect of these considerations is substantial shortening of measured EGJ sphincter length compared to that evident using circumferentially sensitive pressure sensors because the upward limit of intragastric pressure and the downward limit of intra-esophageal pressure are more accurately defined (Table 2).

Of note, the HRM estimates of EGJ length in Table 2 were based on 7.5 mm sensor spacing, likely making them slightly shorter than what would be obtained with conventional 10 mm sensor spacing.

Finally, fluoroscopic imaging of the endoclip marking the position of the EGJ in relation to the pressure sensor housings determined that the intrasphincteric position of the SCJ was, on average, 0.3 to 0.4 cm, from the distal limit of the sphincter. Although an isolated pressure peak was recorded distal to the SCJ, this was not circumferential (Figure 4), its radial position exactly opposed the CD peak, and its magnitude varied in synchrony with respiration. These consideration, along with the, ex-vivo modeling of the force balance required to recreate a bend in the manometric assembly (Figure 5) all argue that this distal peak is attributable to counter-force imparted by the gastric wall at the lesser gastric curvature opposing the action of the CD. This conclusion suggest that, although the gastric sling and clasp fibers in the cardia distal to the SCJ may well be working to maintain the shape of the stomach and the angle of His (1, 3, 32, 35, 36), they do not generate a circumferential intraluminal pressure distal to the SCJ.

In conclusion, 3D-HRM monitoring of EGJ pressure, highly resolved in both the axial and radial planes, was possible during normal respiration using a novel 128-channel solid state prototype device. Recordings demonstrated a profoundly asymmetric and vigorous CD component to EGJ pressure that was spatially superimposed on the LES. As determined with an endoclip marker, the distal margin of the EGJ sphincteric zone was shown to closely correlate with the locus of the SCJ. Accurate measurements of these features of EGJ pressure topography likely reflect sphincter integrity in both a physiological and anatomical sense. A pilot experiment with an earlier prototype device also demonstrated the feasibility of 3D-HRM for defining aberrations associated with hiatus hernia (10). The major potential clinical application of this technology pertains to quantifying the indications for, and objectives of, antireflux surgery. Achieving that objective, however, will require further experiments to explore potential pathophysiological relationships between atypical features of EGJ pressure morphology and gastroesophageal reflux disease.

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ABBREVIATIONS

CD	crural diaphragm
EGJ	esophagogastric junction
EPT	esophageal pressure topography
IGP	intra-gastric pressure
SCJ	squamocolumnar junction

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Figure 1.

The 3D-HRM manometry assembly. This assembly incorporates both circumferentially sensitive sensors and a 3D-HRM segment making for a total of 128 independent pressure signals. Each circumferentially sensitive sensor averages the signal of 12 radially dispersed sensing elements with the circumferential sensors being spaced 10 mm apart. The 3D-HRM segment consisted of 12 sensing loci, housed as six pairs. However, regardless of whether within the same housing or in the adjacent housing the sensors were 7.5mm apart. Each axial 3D-HRM locus contained 8 independent pressure sensors radially dispersed 45° apart. (Assembly drawing courtesy of Given Imaging, Los Angeles, CA).

Figure 2. Videofluoroscopic imaging of the manometric assembly during recording with an endoclip demarcating the position of the SCJ (E, expiration; I, inspiration).

Figure 3.

(A) Eight second segment of 3D-HRM EPT EGJ recording illustrated in conventional-HRM mode with circumferential pressure averaging. The instants of peak inspiration and mid-expiration are indicated by dotted black lines. The position of the SCJ was determined by the endoclip position relative to the assembly housing on concurrent videofluoroscopy (magenta circles). The dotted yellow line demarcates the *distal margin of the EGJ high pressure zone* from intra-gastric pressure (IGP). (B) Corresponding peak inspiration and mid-expiration EGJ pressure morphology with full radial pressure resolution illustrated as a cylinder with the central axis representing atmospheric pressure. Radial pressure orientation was related to a clock face with 6 o'clock indicative of the CD and 12 o'clock the lesser curve of the stomach.

3D-HRM instantaneous EPT with radial pressure resolution (opened clock face)

A. Centered at 12 o'clock (lesser gastric curvature)

B. Centered at 6 o'clock (crural diaphragm)

Figure 4.

Alternative graphic formatting of the plots in Figure 3B derived by lengthwise “cutting open” and laying flat the cylinder plot at (A) the 12 o'clock radian or (B) the 6 o'clock radian to reveal the entire 360° pressure topography. The minimal and peak sector pressures at the level of the CD are indicated with black triangles. The proximal extent of IGP and hence the distal margin of the EGJ high pressure zone occurs at the 6 o'clock radian indicated by the arrow.

Figure 5.

Ex-vivo simulation of catheter bending by opposing rubber bands positioned so as to model the effects of the CD and contralateral gastric wall. (A) Videofluoroscopic image of the experimental setup. (B) and (C) illustrate the corresponding pressure recording during a degree of bending typical of that seen fluoroscopically. The plots are formatted similarly to Figure 4 to emphasize the similarity in pressure morphology with the CD and intra-gastric pressure peaks.

A. Modeled 3D-HRM array configurations

B. Maximal pressures detected by 3D-HRM array

Figure 6.

Ex vivo model varying the degree of probe angulation (A) along with the corresponding pressure data (B). Models 1–2 typifying array configurations during the interdeglutitive period and models 3–4 show hypothetical, more extreme angulation. The pressure values plotted are the peak values from the sensors on which the rubber bands were centered. The difference between the two peaks (pressure difference) is plotted by red dots indicating that the two pressures nearly exactly offset each other. In vivo, the surface opposing the CD is much more diffuse than modeled by the rubber band.

Table 1

The effect of respiration on basal EGJ pressure at the axial level of the CD with and without circumferential averaging. Radial sectors are expressed in terms of a clock face with 12 o'clock being the lesser curve side and 6 o'clock the center of the CD pressure signal.

	<u>HRM emulation (mmHg)</u>	<u>3D-HRM</u>	
		<u>6 o'clock sector (mmHg)</u>	<u>12 o'clock sector (mmHg)</u>
Expiration(E)	36(23–49)	51(29–95) ^{* †}	20(14–39) [*]
Inspiration(I)	55 (38–92)	119 (51–204) ^{* †}	29(16–45) [*]
Respiratory variation (I-E)	22(2–59)	63(9–143) ^{* †}	7 (–2–21) [*]

Data shown as median (5th–95th percentiles).

* p < 0.01 vs. circumferential mean pressure;

† p < 0.01 vs. 12 o'clock sector pressure.

Table 2

EGJ length and intrasphincteric position of the SCJ in 3D-HRM compared to emulated conventional HRM. The negative values indicate that the SCJ extends into the intra-gastric domain, while positive values indicate a length of EGJ circumferential pressure distal to the SCJ.

	EGJ sphincteric length (cm)		Distance between SCJ and the distal EGJ limit (cm)	
	HRM	3D-HRM	HRM	3D-HRM
Expiration	5.0 (4.5–6.4)	2.4 (1.0–3.3)*	1.6 (2.0 to 2.6)	0.3 (–1.9 to +1.1)*
Inspiration	5.0 (1.7–5.8)	2.3 (1.5–4.8)*	2.9 (1.2 to 3.9)	0.4 (–2.0 to +1.7)*

Data shown as median (5th–95th percentile).

* $p < 0.03$ vs. HRM;

† $p < 0.02$