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The contractile deceleration point: an important physiologic landmark on oesophageal pressure topography

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Abstract

Background—This study aimed to correlate oesophageal bolus transit with features of oesophageal pressure topography (OPT) plots and establish OPT metrics for accurately measuring peristaltic velocity.

Methods—About 18 subjects underwent concurrent OPT and fluoroscopy studies. The deglutitive Contractile Front Velocity (CFV) in OPT plots was subdivided into an initial fast phase (CFV_{fast}) and subsequent slow phase (CFV_{slow}) separated by a user-defined deceleration point (CDP). Fluoroscopy studies were analyzed for the transition from the initial rapidly propagated luminal closure associated with peristalsis to slow bolus clearance characteristic of phrenic ampullary emptying and to identify the pressure sensors at the closure front and at the hiatus. Oesophageal pressure topography measures were correlated with fluoroscopic milestones of bolus transit. Oesophageal pressure topography studies from another 68 volunteers were utilized to develop normative ranges for CFV_{fast} and CFV_{slow}.

Key Results—A distinct change in velocity could be determined in all 36 barium swallows with the fast and slow contractile segments having a median velocity of 4.2 cm s⁻¹ and 1.0 cm s⁻¹, respectively. The CDP noted on OPT correlated closely with formation of the phrenic ampulla making CFV_{fast} (mean 5.1 cm s⁻¹) correspond closely to peristaltic propagation and CFV_{slow} (mean 1.7 cm s⁻¹) to ampullary emptying.

Conclusions & Inferences—The deceleration point in the CFV on OPT plots accurately demarcated the early region in which the CFV reflects peristaltic velocity (CFV_{fast}) from the later region where it reflects the progression of ampullary emptying (CFV_{slow}). These distinctions should help objectify definitions of disordered peristalsis, especially spasm, and improve understanding of impaired bolus transit across the oesophagogastric junction.

Keywords

manometry; oesophageal pressure topography; peristalsis; phrenic ampulla

INTRODUCTION

Oesophageal pressure topography (OPT) is a derivative of high-resolution manometry data that dynamically displays intraluminal pressure as a continuum along the length of the oesophagus. In the initial description of OPT, Clouse and Staino proposed that peristalsis occurred as a sequence of segmental contractions, denoted S1 to S4.1 The first segment (S1)

extends from the upper oesophageal sphincter (UOS) to the first pressure trough in the region of the aortic arch, functionally corresponding to the striated muscle oesophagus. Distal to the transition zone, the smooth muscle oesophagus is composed of two overlapping neuromuscular segments, S2 and S3. Conceptually, S2 is dominantly controlled by excitatory (cholinergic) myenteric plexus neurons while S3 is more strongly controlled by inhibitory (nitric oxide) myenteric plexus neurons.^{2,3} The fourth contractile segment (S4) encompasses the lower oesophageal sphincter (LOS). However, in addition to imaging the contractility of these lumen-obliterating contractions, OPT also dynamically monitors the intraluminal pressure leading the propagated contraction, indicative of intrabolus pressure (IBP). Consequently, the potential exists to characterize conditions conducive to either successful or impaired bolus transit.

Studies combining fluoroscopy and OPT have provided insight into mechanisms of impaired bolus transit through the UOS,⁴ oesophageal body⁵ and oesophagogastric junction (OGJ).⁶ However, minimal data exist on the direct correlation between an independent measure of bolus transit (fluoroscopy or intraluminal impedance recording) and OPT plots akin to studies using conventional manometry or impedance recording in the tubular oesophagus^{7,8} or phrenic ampulla.⁹ Of particular interest are the concurrent high resolution manometry/fluoroscopy studies by Lin *et al.* proposing that the termination of bolus emptying into the stomach is a postperistaltic event. Peristalsis terminates within the LOS after which emptying is completed by the combination of a sustained hydrostatic pressure gradient across the hiatal canal and re-elongation of the oesophagus attributable to longitudinal muscle relaxation and elastic recoil of the phrenoesophageal membrane. These features cannot be appreciated with conventional manometry but might be discernible on OPT plots, given their enhanced spatial resolution and ability to image oesophageal shortening.¹⁰

With the experience of analyzing more than 3000 OPT studies, we have observed that peristaltic propagation slows in the distal oesophagus with a deceleration point in contractile front velocity localized in the distal oesophagus (Fig. 1). We hypothesized that this deceleration point is related to formation of the phrenic ampulla during the latter stages of oesophageal emptying. Thus, the goal of this study was to establish the pressure topography correlates of bolus transit using concurrent OPT/fluoroscopy and to test the hypothesis that the deceleration point in contractile front velocity represented a transition from peristaltic transport to ampullary emptying. Special emphasis was given to validating methodology for localization of the deceleration point in contractile front velocity.

METHODS

Patients

Eighteen asymptomatic volunteers (seven male, ages 20 to 45) were recruited by advertisement or word of mouth for concurrent OPT/fluoroscopy studies. An additional group of 68 OPT studies done without concurrent fluoroscopy on another group of asymptomatic volunteers (35 male, ages 19 to 48) was utilized to develop normative ranges for OPT measures. The Northwestern University Institutional Review Board approved the study protocol and informed consent was obtained from each subject.

Oesophageal pressure topography protocol

A solid-state manometric assembly with 36 circumferential sensors spaced at 1 cm intervals (outer diameter 4.2 mm) was used for all OPT studies (Sierra Scientific Instruments Inc., Los Angeles, CA, USA), as previously described.¹¹ Prior to recording, the transducers were calibrated at 0 and 100 mmHg using externally applied pressure.

Subjects underwent transnasal placement of the manometric assembly and were studied in a supine position after at least a 4-h fast. The manometric assembly was positioned to record from the hypopharynx to the stomach with at least three intragastric sensors and fixed in place by taping it to the nose. The manometric protocol included a 5-min period of baseline recording and ten 5 mL water swallows in a supine position. The same sequence was then repeated in an upright sitting position.

The 18 subjects undergoing the combined OPT/fluoroscopy studies were subsequently placed in a supine position under a C-arm fluoroscope (Easy Diagnostics; Phillips Medical Systems, Shelton, CT, USA) and shielded with a lead apron below the umbilicus and a lead collar for thyroid protection. Fluoroscopic images were recorded using a DVD recorder (LG RC797T) and a video timer (model VC 436; Thalner Electronics Laboratories, Ann Arbor, MI, USA) that encoded time in hundredths of a second on each video frame. Fluoroscopy was synchronized with OPT by simultaneously resetting the video timer and pressing the event marker on the Manoscan recorder immediately prior to each swallow. Two 5 cc barium swallows were recorded with the potential for a third swallow if either of the first was technically inadequate. Oesophageal pressure topography data were subsequently analyzed using ManoView™ analysis software, version 2.0 (Sierra Scientific Instruments Inc., Los Angeles, CA, USA).

Correlating bolus transit with oesophageal pressure topography

The concurrent OPT/fluoroscopy swallows were analyzed in a blinded manner to identify five fluoroscopic events: T1, when the leading edge of the bolus first entered the distal oesophagus; T2, when the bolus was first compartmentalized in the oesophagus between the contractile front and the closed OGJ; T3, when the compartmentalized bolus began transitioning from a sharpened pencil shape to a globular form; T4, when barium emptying through the OGJ began; and T5, when barium emptying through the OGJ was completed (or ended). Thereafter, the time and corresponding distal limit of oesophageal luminal closure was localized and marked on the concurrent OPT plot for T1–T5 using the radio-opaque manometric sensors as reference points (Fig. 2).

Measures of closure/contractile front velocity on fluoroscopy and OPT plots

Contractile Front Velocity (CFV) is the speed at which the propagated contraction progresses along the oesophagus, demarcating the intrabolus domain ahead from the domain of luminal closure behind. Consequently, CFV needs to be measured at an isobaric contour pressure that exceeds intrabolus pressure. By convention this is done at a default value of 30 mmHg (Fig. 1). When imaged fluoroscopically, the closure front velocity slows markedly in the distal oesophagus with the shift from peristaltic transport through the tubular oesophagus to phrenic ampullary emptying.⁹ We calculated mean values for peristaltic transport and ampullary emptying from the combined OPT/fluoroscopy swallows as the slopes of the lines between T2 and T3 and between T3 and T5 respectively (Fig. 2).

We then analyzed the accuracy with which the fast and slow CFV could be estimated independent of fluoroscopic localization based on a user-defined deceleration point of the CFV in the distal oesophageal contraction on the OPT plot (Fig. 1). The contractile deceleration point (CDP) was identified as the point along the 30 mmHg isobaric contour at which an abrupt reduction in velocity occurred. Although this point was usually easy to identify by visual inspection, it could also be localized objectively by fitting two tangential lines to the initial and terminal portions of the 30 mmHg isobaric contour and noting the intersection of the lines. The first tangent skirts the 30 mmHg isobaric contour distal to the transition zone without intersecting it. The second tangent originates from the termination point at which the oesophageal contraction intersects the postswallow OGJ (be that the native position of the LOS

or OGJ depending on the individual's anatomy) and skirts the 30 mmHg isobaric contour in the retrograde direction without intersecting it. A horizontal line is then drawn through the intersection of these tangents to the 30 mmHg isobaric contour to localize the CDP. The fast contractile front velocity (CFV_{fast}) applies to the segment of oesophagus distal to the transition zone and ending at the CDP. The slow contractile front velocity (CFV_{slow}) is the slope of the line connecting CDP to the leading edge of the postswallow OGJ.

All measurements of CFV and CDP were made on the 30 mmHg isobaric contour as a default with the caveats that lower or higher pressures were used for hypotensive peristalsis and elevated intrabolus pressure respectively (Fig. 1). In cases of peristaltic hypotension, the isobaric contour threshold is lowered to the magnitude at which a continuous contractile front is identified and the deceleration point can then be localized similarly to with the standard 30 mmHg isobaric contour (Fig. 1B). In cases that no intact isobaric contour exists, measurement of CDP is not valid as these patients have failed or absent peristalsis. In instances in which there is elevated IBP and compartmentalization of pressure between the OGJ and the propagating contraction, the isobaric contour is set to a magnitude greater than IBP to differentiate contraction from pressurization (Fig. 1C). Values of CFV_{fast} and CFV_{slow} were then compared to measures of the early and late closure velocity derived from fluoroscopy images.

The reproducibility and accuracy of localizing CDP was assessed using three experienced oesophagologists and three gastroenterology trainees. The concept of CFV was explained to each participant as the velocity with which the onset of the distal oesophageal contraction progressed along the oesophagus. The participants were then asked to localize the deceleration point on the 30 mmHg isobaric contours of 10 normal and 10 abnormal OPT plots where the CFV markedly slowed. Accuracy for identifying CDP to within a range of ± 0.5 s on these 20 plots was calculated as a simple dichotomous outcome of correct/incorrect based on a predetermined measurement made by three independent blinded observers.

Normal values for OPT measures of contractile front velocity

After having validated OPT measures of CFV_{fast} and CFV_{slow} on the combined OPT/fluoroscopy studies, these measures were made on the OPT studies done without concurrent fluoroscopy on 68 normal volunteers. The measures were made by the same three independent blinded observers as had been trained with the combined OPT/fluoroscopy studies. In instances of major discrepancies among the three, these were first reconciled by consensus prior to reporting the final value.

Statistical analysis

Manometric parameters were summarized using mean, median, inter-quartile range (IQR) and standard deviation (SD). For the development of normative ranges, CFV measures were summarized as the overall mean among the ten test swallows for each subject to preserve the independence of the variable. Comparisons of measurements among subjects were performed using paired non-parametric analysis. The analysis of accuracy for defining CDP for the three experienced oesophagologists and three gastroenterology trainees was performed by calculating the number of correct answers (CDP within 0.5 s) and presenting them as a percentage. Agreement was summarized as a mean value with a standard deviation.

RESULTS

Correlation between OPT and bolus transit on fluoroscopy

All 36 combined OPT/fluoroscopy swallows had normal peristalsis. Fig. 3 depicts a typical swallow in three manometric formats: conventional low resolution line tracings (Fig. 3A), high-

resolution OPT (Fig. 3B), and as a high resolution landscape plot (Fig. 3C). In each case the locations of the five bolus transit milestones (T1–T5) and the position of luminal closure at the tail end of the bolus derived from the concurrent fluoroscopy images are indicated.

Focusing on the OPT plot, bolus entry into the distal oesophagus was uniformly noted to occur during the time period encompassing the proximal segment (S1) contraction.

Compartmentalized pressurization of the bolus, evident by an increase in IBP to greater than 10 mmHg, first occurred during the early S2/S3 domain in 78% of the swallows while the remaining 22% of the swallows did not exhibit this until late in S3. Compartmentalized pressurization could be appreciated as a ramp up in pressure on the line tracings, as a colour shift on the OPT plots, and as a ridge between the contractile front and the OGJ on the landscape plots (Fig. 3).

Transformation of the bolus from a sharpened pencil appearance to a more globular form (T3) on fluoroscopy was associated with a median increase in oesophageal radial diameter of approximately 15.0% (IQR, 8.3–36%) and a reduction in contraction front velocity. The median closure front velocity (Fig. 2) determined fluoroscopically for peristaltic transport prior to T3 was significantly greater than the closure front velocity during the latter stages of emptying (closure front velocity prior to T3, 4.4 cm s^{-1} (IQR, $3.5\text{--}5.2 \text{ cm s}^{-1}$; closure front velocity after T3, 1.25 cm s^{-1} (IQR, $1.1\text{--}1.6 \text{ cm s}^{-1}$, $P < 0.001$). The globular shaped phrenic ampulla was gradually established before emptying began in the majority of swallows (78%) and emptying was not complete until the S4 segment had reestablished its native position.

Measures of contractile front velocity on OPT plots

The CDP on OPT plots uniformly occurred within the third topographic segment (S3). The CDP occurred in close proximity to T3 on fluoroscopy, the time that the bolus began transitioning from a sharpened pencil shape to a globular form. The median time interval between CDP on the OPT plot and T3 on fluoroscopy was 0.2 s (IQR, -0.14 to 0.6 cm s^{-1}). The corresponding velocities for CFV_{fast} and CFV_{slow} calculated were 4.1 cm s^{-1} (IQR, $3.5\text{--}5.7 \text{ cm s}^{-1}$) and 1.2 cm s^{-1} (IQR, $0.8\text{--}1.5 \text{ cm s}^{-1}$) respectively ($P < 0.001$). The median difference between the CFV_{fast} measured on OPT plots and the closure front velocity determined fluoroscopically for peristaltic transport prior to T3 was 0.1 cm s^{-1} (IQR, -0.7 to 0.3 s). Similarly, the median difference between CFV_{slow} and the closure front velocity during the latter stages of emptying on fluoroscopy was 0.05 cm s^{-1} (IQR, -0.4 to 0.25 cm s^{-1}).

Comparing the three plotting formats in Fig. 3, all three permit reasonable assessment of CFV within the oesophagus, but only the high resolution plots (Figs 3B,C) permit a valid identification of the CDP and a confident assessment of CFV associated with ampullary emptying. The accuracy of defining CDP with OPT plots to within $\pm 0.5 \text{ s}$ was 86% (SD, 7.1%) and there was no significant difference in accuracy between trainees (83%) and experienced oesophagologists (89%).

Normative OPT values for CFV

The normal values for the CFV_{fast} and CFV_{slow} for the 68 normal subjects, each assessed during ten 5 mL water swallows are presented in Table 1. Values for both variables were significantly greater in the upright position compared to the supine position.

DISCUSSION

The aims of this study were to relate OPT to bolus transit and to establish the significance of CDP in accurately measuring peristaltic velocity. Concurrent fluoroscopy and HRM was used to correlate OPT patterns with localization of the swallowed bolus and fluoroscopically defined

milestones of bolus transit. Our findings demonstrate that advance of the contractile front through the distal oesophageal segment is associated with two distinct domains with significantly different velocities. The observed shift in velocity did not occur at the pressure trough previously described between segments 2 and 3.¹² Rather, the CDP occurred within S3 and correlated closely with the transition from peristaltic clearance to phrenic ampullary emptying. The importance of defining these phases of bolus emptying is that they occur by distinct mechanisms and, hence, are subject to distinct pathologies.

Rapid peristaltic propagation is a defining criterion for distal oesophageal spasm in conventional manometric classification.^{13,14} However, no convention exists on how or where to quantify peristaltic propagation. This study demonstrates that when assessed in OPT terms, CFV is not uniform and, in fact, in its later phase, has little to do with peristalsis. Rather, the measure defined as CFV_{fast} (Figs 1 and 3) is most reflective of the neuromuscular transduction of peristalsis as in this region there are minimal confounding influences of IBP or oesophageal shortening. A consequence of this, evident in Table 1, is that the normative range for CFV_{fast} extend beyond the upper limit of normal for peristaltic velocity reported in conventional manometry studies (2 to 8 cm s⁻¹)^{13,14} to 9.1 cm s⁻¹ (supine swallows) or 12.7 cm s⁻¹ (upright swallows). Although the specifics remain to be defined, this will necessarily impact on the definition and identification of distal oesophageal spasm in OPT terms.

Peristalsis consists of both longitudinal and circular muscle contraction and as peristalsis reaches the distal contractile segments (S3 and S4), luminal closure is achieved with the oesophagus still in a shortened state as a consequence of longitudinal muscle contraction.⁹ Fluoroscopically, the termination of peristalsis in the distal oesophagus is associated with transformation of the bolus cavity from the appearance of a pencil point to the globular form of the phrenic ampulla (see images of T3 and T4 in Fig. 2). Emptying of the ampulla occurs with reduction of what amounts to physiological herniation, dependent upon sustained closure of the lumen above and the elastic recoil of the phrenoesophageal ligament restoring the LOS (S4) to its native position within the hiatus. The velocity at which this occurs, defined as CFV_{slow} is significantly less than peristaltic propagation (Table 1). This difference in clearance velocity between the oesophagus and phrenic ampulla was previously reported in an investigation that utilized concurrent manometry and fluoroscopy.⁹ However, the current investigation represents the first validation of a manometric algorithm to differentiate the two based solely on OPT characteristics. Variability in CFV_{slow} among individuals is likely dependent upon either an abnormally sustained peristaltic contraction or anatomical factors such as OGJ obstruction, laxity of the phrenoesophageal membrane or early hiatus hernia. With a well-defined, persistent hiatal hernia it may not be possible to measure CFV_{slow} as trans-hiatal emptying would be incomplete.

In summary, we utilized concurrent OPT/fluoroscopy studies to validate OPT paradigms for quantifying peristaltic velocity and the progression of phrenic ampullary emptying. A major observation was that the deceleration point in the CFV, occurring during the contraction of the distal smooth muscle oesophagus, was indicative of the transition from peristaltic clearance to formation and emptying of the phrenic ampulla. Additionally, this anatomic landmark can be easily identified using either a simple visual assessment or a more objective technique utilizing intersecting tangent lines along the CFV_{fast} and CFV_{slow} (Fig. 1). The description of these OPT landmarks will likely facilitate a furthering of our understanding of disorders of peristalsis, especially distal oesophageal spasm. We suspect that restricting the CFV measurement to the domain that is reflective of peristaltic clearance will alter the definition of distal oesophageal spasm as normal values of CFV_{fast} can be greater than 10 cm s⁻¹ in the upright posture. Furthermore, identification of the CFV_{slow} domain as a correlate of phrenic ampullary emptying may prove helpful in understanding abnormal mechanics and bolus transit in the context of OGJ abnormalities.

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Figure 1.

Representative examples of oesophageal pressure topography (OPT) plots of normal (A), hypotensive peristalsis (B) and elevated intrabolus pressure (IBP) and hypertensive peristalsis (C) illustrating the localization of regions of fast and slow Contraction Front Velocity (CFV) separated by a user-defined deceleration point (pink circle). Note that measurements are made at the default isobaric contour pressure (black outline) of 30 mmHg in the normal contraction while a lesser pressure is used with the hypotensive contraction (20 mmHg) and a greater pressure (50 mmHg) with the increased intrabolus pressure evident in panel C and outlined with the dashed white line. Although the deceleration point (pink circle) can usually be identified visually by noting the location of the sharpest deceleration in CFV, a more objective alternative method is to fit two tangential lines to the initial and terminal portions of the 30 mmHg isobaric contour and note the intersection of the lines. The first tangent skirts the 30 mmHg isobaric contour distal to the transition zone without intersecting it. The second tangent originates from the termination point at which the oesophageal contraction intersects the postswallow oesophagogastric junction (OGJ) (be that the native position of the lower oesophageal sphincter (LOS) or OGJ depending on the individual's anatomy) and skirts the 30 mmHg isobaric contour in the retrograde direction without intersecting it. A horizontal line is then drawn through the intersection of these tangents to the 30 mmHg isobaric contour to localize the contractile deceleration point (CDP) (white line arrow). This technique closely estimates the CDP that was determined using visual inspection.

Figure 2.

Methodology for measuring closure front velocity for the early and late phases of bolus transit. Times T1–T5 were the times at which five milestones of bolus transit occurred, identified by analysis of fluoroscopic swallow sequences (see text). Thereafter, the corresponding time and pressure at which luminal closure occurred was localized on the oesophageal pressure topography (OPT) plots based on the encoded time on the fluoroscopy images and radio-opacity of the manometric sensors. The position of the hiatal canal is indicated on the fluoroscopic images by the black arrow and on the OPT plots by the black line at the 30 cm sensor. The white arrow (images) or dots (OPT plots) indicates the location at which intrabolus pressure (IBP) was measured. Note that a dominant determinant of bolus transit from T3–T5 is descent of S4 back to its native position within the hiatus, which occurs as the oesophageal shortening associated with peristalsis is reversed.

Figure 3.

Panels A, B and C illustrate low resolution conventional manometric tracing (five pressure sensors and a 4 cm sleeve), oesophageal pressure topography (OPT), and a landscape plotting of the same normal swallow. In each panel, the corresponding times of the key milestones of bolus transit (T1–T5) are localized from the corresponding fluoroscopic images. Although not possible in panel A, the positions to the pressure troughs between contractile segments are localized by the translucent circles and contractile deceleration point (CDP) by the pink dot on both the (B) OPT plot and (C) 3-dimensional landscape plot. The domain of the oesophagogastric junction (OGJ) is defined by the dashed red lines and the solid red line defines the sensor centred in the hiatal canal. In this swallow, T1 (bolus present) occurs immediately

after the swallow during S1 and T2 (compartmentalized pressurization) occurs during CFV_{fast} . Globular transformation (T3) occurs just after the CDP. All emptying is associated with the phrenic ampulla and emptying finally ends as the oesophagus elongates and the lower oesophageal sphincter (LOS) is returned back to its baseline position after the CDP. The same events are depicted on the manometric tracing in panel A to highlight deficiencies in describing the terminal events of the swallow and the pressure changes associated with flow through the OGJ. Note the inability to discern the fast and slow segments of the contraction wave with only three 5 cm spaced sensors. In addition, most of emptying occurs during the period where the manometric sleeve is recording resolution of LOS relaxation. Panel C depicts a 3-dimensional landscape plot that further delineates the location of the various bolus transit events and the topographic contractile segments. The deceleration point (pink circle) is located between the 2nd and 3rd pressure trough (3-dimensional landscape plot software courtesy of Menne Biomed, Tübingen, Germany).

Table 1

Normal values for OPT variables

	CFV-fast (cm s ⁻¹)	CFV-slow (cm s ⁻¹)
Supine		
Mean (SD)	5.1 (2.3)	1.7 (0.6)
Median (5th–95th, %)	4.6 (2.8–9.1)	1.6 (0.9–2.7)
Upright		
Mean (SD)	6.2 (4.6)*	1.9 (1.3)
Median (5th–95th, %)	5.0 (3.0–12.7)	1.6 (0.8–3.4)

CFV, contraction front velocity; OPT, oesophageal pressure topography.

* $P < 0.001$, supine versus upright.