Biomechanical and sensory parameters of the human esophagus at four levels

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Patel, Rig S., and Satish S. C. Rao. Biomechanical and sensory parameters of the human esophagus at four levels. Am. J. Physiol. 275 (Gastrointest. Liver Physiol. 38): G187–G191, 1998.—The biomechanical and sensory characteristics of the lower esophageal sphincter (LES) and those of the striated and smooth muscle portions of the esophagus have not been compared in humans. Our aim was to determine sensory perception, cross-sectional area (CSA), and biomechanical parameters at different levels of the esophagus. We studied 11 healthy volunteers, using impedance planimetry. Intermittent balloon distensions (5–60 cmH₂O) were performed at four sites: 1) the LES, 2) 5 cm above LES (distal), 3) 10 cm above LES (mid), and 4) 5 cm below the upper esophageal sphincter (proximal). During these distensions, CSAs, biomechanical parameters, and sensory responses were measured. The mid-esophagus had a higher (P < 0.05) CSA than the distal esophagus. The LES had the smallest CSA (P < 0.05). The LES and the proximal esophagus had greater (P < 0.05) wall tension and were less (P < 0.05) deformable than the mid- or distal esophagus. Sensory thresholds were lower (P < 0.05) in the proximal compared with the mid- or distal esophagus. Biomechanical and sensory parameters are not uniform along the length of the esophagus. The striated muscle portion is more sensitive and less compliant than the smooth muscle portion. These differences could affect the results of balloon distension tests of the esophagus.

impedance planimetry

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The esophagus is not a simple or uniform conduit. Anatomically, it has distinct areas: the upper esophageal sphincter, the proximal striated muscle portion, the intermediate zone of transition to smooth muscle, the distal smooth muscle portion, and the lower esophageal sphincter (LES). The biomechanical and sensory parameters of the human esophagus should vary among these morphologically distinct zones. Such variation might account for the discrepancies in the results of balloon distension tests that have been used to assess patients with noncardiac chest pain. Balloon volumes ranging from 8 to 30 ml have been reported to induce chest pain (2, 4, 5). The location of the distending balloon in the esophagus, the type and the size of the balloon, and the use of fixed balloon volumes are all variables that might account for some of the discrepancies (8, 12).

We have perfected a new technique, impedance planimetry (6, 12, 13), that permits the assessment of cross-sectional area (CSA), biomechanical characteristics, and sensory responses of the esophagus during balloon distension with graded increments of intraluminal pressure. The aim of this investigation was to examine and compare the biomechanical and sensory parameters at different levels along the length of the esophagus in healthy volunteers, using impedance planimetry.

METHODS

Subjects. We studied 11 healthy volunteers (5 men and 6 women), with a mean age of 31 yr (range 22–39 yr). All subjects gave written informed consent. The study was approved by the Human Ethics Research Committee of the University of Iowa College of Medicine (no. 90–12585).

Impedance probe and measuring system. The probe, the planimetry system, and the methodology have been described in detail previously (12, 13). The probe (6 mm in diam) had two infusion channels and four ring electrodes: two outer (excitation) electrodes that were connected to a generator that provided a constant alternating current of 100 A at 5 kHz and two inner (detection) electrodes that were connected to the impedance measuring system. A latex balloon, 4.5 cm long, was tied around the catheter enclosing the ring electrodes. This balloon was inflated by the infusion of an electrically conducting fluid (0.018% NaCl solution) that was stored in a leveling container. The container was connected to external transducers (Gould, Essex, UK) for measuring intraluminal pressures.

Study protocol. After an overnight fast, we sprayed the volunteers' throats with dicyclomine HCl (Dyclone, Astra, Westborough, MA) to attain oropharyngeal anesthesia. With the subject sitting in the upright position, the lubricated probe was passed perorally until the tip was ∼55 cm from the incisors. The subject was then placed in the supine position with the head end of the bed elevated by 30°. After an adjustment period of 15–20 min, the probe was pulled back in 1-cm steps while the manometric pressure recordings on the monitor were observed. The lower and upper esophageal sphincters were identified as high-pressure zones that relaxed in response to wet swallows, and their locations in relation to the incisors were noted.

Next, the center of the balloon was positioned randomly at four different levels along the length of the esophagus: 1) the LES, 2) 5 cm above the LES (distal esophagus), 3) 10 cm above the LES (mid-esophagus), and 4) 5 cm below the upper esophageal sphincter (proximal esophagus). After the balloon was positioned at a particular level, we anchored the probe at the angle of the mouth, the cheek, and the neck by adhesive plaster. After a rest period of 10 min, we zeroed the intraluminal balloon pressure with respect to atmospheric pressure by adjusting the height of the leveling container. The balloon pressure was then increased in steps from 0 to 10, 20, 30, 40, 50, and 60 cmH₂O by raising the leveling container and infusing the 0.018% NaCl solution at 37°C. In the proximal esophagus, the balloon pressures were increased in smaller increments from 0 to 5, 10, 15, 20, 25, 30, 35, 40, and 45 cmH₂O.
because pilot studies suggested that the proximal esophagus was less distensible and more sensitive.

Each distension was maintained for 3 to 5 min or until the measured CSA reached a steady state. During balloon distension, the subjects were asked to lie still, to make no attempt to speak, and to refrain from swallowing. After each inflation, the CSA as well as sensations were noted. Subjects were asked to grade their sensation on a scale of 0–4, where 0 equals no sensation, 1 equals perception of distension, 2 equals mild fullness, 3 equals moderate discomfort/mild pain, and 4 equals severe pain. Subjects were unaware of the level of distension because the leveling container was hidden behind a screen. If the subject reported severe pain, the balloon was immediately deflated and no further distensions were performed at that level of the esophagus. The balloon was calibrated before and immediately after the study, by placing it inside polyvinyl chloride cylindrical chambers with diameters ranging from 9 to 30 mm (13).

Data analysis. The steady-state CSA was measured at each level of balloon distension with the help of computer software (12, 13). The pressure elastic modulus (PEM), a measure of wall stiffness, was calculated as follows: PEM = \( \frac{r \cdot dP}{d \cdot \cdot CSA} \), where \( r \) is the radius of the balloon (i.e., \( CSA/\pi \)), \( dP \) is the change in pressure, and \( d \) is the change in radius between two consecutive balloon distensions.

The circumferential wall tension (T) was calculated as \( T = r \cdot dP \), where \( dP \) is the transmural pressure difference. The strain (\( e \)) is a ratio that expresses the deformability of the esophageal wall during distension. It was calculated as \( e = (r_x - r_0) r_0^{-1} \), where \( r_x \) was the balloon radius at a given pressure and \( r_0 \) was the radius at zero pressure.

By measuring the impedance of the conducting fluid within the balloon, we were able to calculate the balloon CSA according to the field gradient principle. When a current (I) is induced in a uniform cylinder by the two outer electrodes, the voltage difference (V) between the two inner electrodes can be expressed according to Ohm’s law: \( V = Iz \), where \( Z \) is the electrical impedance of the conducting fluid. The impedance can be expressed as the product of the distance (d) between the inner electrodes, the inverse of the conductivity (\( \delta \)) of the fluid, and the inverse of the CSA of the cylinder: \( R = \delta^{-1} \cdot CSA^{-1} \). Thus \( V = l \cdot \delta^{-1} \cdot CSA \), and as \( l \), \( \delta \), and \( CSA \) are known constants, \( V \) is inversely proportional to the CSA. The computer software provided a display of voltage difference that was directly proportional to the CSA. Data for intraluminal pressures and CSA were then converted into a digital format and either displayed on-line on a monitor or stored on disks for later analysis.

Reactivity. Balloon distension induced reactive esophageal contractions that produced a transient decrease in the CSA. During each distension, reactivity was measured as the difference in height between the steady-state CSA and the minimum CSA that was observed during reactive contraction.

Statistics. The results are expressed as means ± 95% confidence interval. The differences in the biomechanical and sensory data at different stations along the esophagus were analyzed and compared by using multifactorial ANOVA.

RESULTS

Cross-sectional area. At all stations in the esophagus, the stepwise increments in balloon pressure were associated with a stepwise increase in the CSA. Figure 1 shows a typical planimetry recording from one subject. As can be seen, for example, at a balloon pressure of 20 cmH\(_{2}O\), the CSA was 175 mm\(^2\) at the LES, 196 mm\(^2\) at the distal esophagus, 256 mm\(^2\) at the mid-esophagus, and 274 mm\(^2\) at the proximal esophagus. The mean changes of the CSA of the esophagus at all four stations are shown in Fig. 2. The CSA of the proximal esophagus was similar to that of the mid-esophagus up to 25 cmH\(_{2}O\) but thereafter there was a less linear increase (Fig. 2). In the proximal esophagus, the balloon could not be distended above 40 cmH\(_{2}O\) because most subjects could not tolerate further inflation. The CSA of the mid-esophagus was higher than that of the distal esophagus (P < 0.05). The LES had the lowest CSA (P < 0.05). In all of our subjects the balloon stayed in position across the LES up to a pressure of 30 cmH\(_{2}O\). Above this pressure the balloon slipped out of the high-pressure zone into the stomach, as illustrated by the large CSA in Fig. 1.

Pressure elastic modulus. The PEM showed significant differences along the length of the esophagus. At balloon pressures of <15 cmH\(_{2}O\), the PEM was higher (P < 0.05) in the LES (100 ± 60 cmH\(_{2}O\)) than in the proximal (25 ± 14 cmH\(_{2}O\)) or the mid-esophagus (41 ± 27 cmH\(_{2}O\)). At balloon inflation pressures of 20 or 30 cmH\(_{2}O\), the PEM was higher (P < 0.05) in the proximal (138 ± 46 cmH\(_{2}O\)) than in the distal (50 ± 16 cmH\(_{2}O\)) or mid-esophagus (80 ± 32 cmH\(_{2}O\)). There was no significant difference between the mid- and the distal esophagus.
Circumferential wall tension and tension-strain relationship. At all stations, the wall tension showed a linear relationship with balloon pressure, i.e., stepwise increments in balloon pressure were associated with higher wall tension. However, the association between the changes in wall tension and the changes in strain were dissimilar along the length of the esophagus (Fig. 3). The curve describing the changes at the LES was shifted to the left, suggesting that this was the least deformable segment. Compared with the mid-esophagus, the curves describing the changes in the proximal and the distal esophagus were significantly \( (P < 0.05) \) shifted to the left, suggesting that these segments were less deformable than the mid-esophagus. However, no differences were seen between the proximal and distal esophagus.

Reactivity. The reactivity to balloon distension was similar and was significantly higher \( (P < 0.02) \) in the mid- and distal esophagus than in the proximal esophagus or LES (Fig. 4). In contrast, the proximal esophagus and the LES zone showed very little reactivity.

Sensation. The mean scores for the intensity of esophageal sensation during balloon distension are shown in Fig. 5. The proximal esophagus was more sensitive than the mid-esophagus \( (P < 0.02) \), and the latter was more sensitive than the distal esophagus \( (P < 0.02) \). At the LES level, all subjects perceived balloon distension but none of them reported either discomfort or pain.

Correlation of wall tension and sensation. Although at each level there was a good correlation between wall tension and sensory responses, there was a significant variation between different points along the esophagus. When subjects described their first perception, the mean (95% confidence interval) wall tensions at the distal, mid-, and proximal esophagus were \( 246 \pm 12 \), \( 160 \pm 8 \), and \( 74 \pm 7 \) mm·cmH\(_2\)O, respectively. For a first sensation, the wall tension was significantly \( (P < 0.02) \) lower in the proximal esophagus than in the distal or mid-esophagus. Similarly, when the subjects described a sensation of discomfort or pain, the wall tensions at the distal, mid-, and proximal esophagus were \( 780 \pm 42 \), \( 732 \pm 90 \), and \( 281 \pm 100 \) mm·cmH\(_2\)O, respectively. Again, for moderate discomfort the wall tension was significantly \( (P < 0.02) \) lower in the proximal esophagus than at the other two levels.

Correlation of strain and sensation. The proximal esophagus exhibited higher sensory scores at significantly \( (P < 0.05) \) lower levels of strain compared with the other three segments (Fig. 6). This confirms that the proximal esophagus is more sensitive and less deformable than the rest of the esophagus.

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**Fig. 2.** Changes in esophageal CSA during stepwise increments in balloon pressure at 4 levels.

**Fig. 3.** Relationship between wall tension and strain at 4 levels in esophagus in response to graded balloon distension.

**Fig. 4.** Changes in reactivity of esophageal wall during graded balloon distension of esophagus.
DISCUSSION

We examined the sensory and biomechanical characteristics of the esophagus at three different levels and at the LES. Our investigation shows that there are distinct differences in the biomechanical and sensory parameters along the length of the human esophagus.

The threshold for sensory perception at the proximal or the striated muscle portion of the esophagus was lower than that of the distal or the smooth muscle portion of the esophagus. This finding suggests that the proximal esophagus was more sensitive. The muscular transition zone showed intermediate sensitivity, whereas the high-pressure zone at the LES was least sensitive.

The biomechanical parameters of the esophageal wall were also variable along its length. At each level, graded balloon distension was associated with a steady increase in the CSA. However, the CSA decreased along the length of the smooth muscle portion of the esophagus, and the LES exhibited the smallest CSA. At lower balloon pressures, the striated muscle portion and the mid-esophagus showed similar CSAs, but at higher balloon pressures the CSA in the striated muscle portion was lower than in the mid-esophagus. This suggested that the proximal esophagus was less distensible. This finding was further corroborated by the measurements of tension-strain relationship. Compared with the distal esophagus, the curve that described the changes in the proximal esophagus was significantly shifted to the left. This indicated that the proximal esophagus was less deformable (stiffer).

The PEM was also higher in the proximal than in the distal esophagus. This confirms a previous report that suggested that the striated muscle portion was less compliant than the smooth muscle portion (9). These biomechanical differences along the length of the esophagus may reflect a gradual transition in the composition of the muscle wall from skeletal muscle proximally to smooth muscle distally (1, 10), as well as variations in the connective tissue matrix and anatomic differences in the luminal diameter.

Our attempts to characterize the biomechanics of the LES proved suboptimal, because above a threshold pressure of 30 cmH2O, the balloon was spontaneously propelled into the stomach. Nonetheless, the findings of a relatively smaller CSA, a higher PEM, and a shift of the tension-strain curve to the left would confirm the existence of a higher tone at the LES.

The differences in esophageal biomechanics at different levels were also related to the differences in esophageal sensation. Correlations between wall tension and esophageal sensory responses revealed that a first sensation and moderate discomfort were reported at a lower wall tension in the proximal esophagus than in the distal esophagus. Similarly, esophageal sensations were reported at a lower degree of strain in the proximal esophagus than in the other segments of the esophagus. This confirms that the striated muscle portion is the most sensitive zone in the esophagus. Also, at this level, esophageal sensations were perceived at distending pressures that did not significantly deform the esophageal wall. These findings may be due to a greater population of mechanoreceptors in the proximal than in the distal esophagus. However, the prevalence of tension-sensitive mechanoreceptors along the length of the human esophagus has not been characterized, although a higher prevalence of these receptors has been described in the proximal segment of the opossum esophagus (16). It is also possible that the proximal segment is innervated by a greater number of sensory neuronal afferents (15), or there could be nociceptors that have a lower firing threshold. These aspects merit further investigation.

Over the last decade, intraesophageal balloon distension has aroused increasing interest as a diagnostic test for evaluating chest pain. In 1986 Richter and associates (2, 14) reported that balloon distensions with <8 ml of air reproduced symptoms in >80% of patients with noncardiac chest pain, whereas none of the con-
trols had symptoms. Since then, many centers have used similar techniques (air-filled balloons) but have either failed to reproduce this result or have demonstrated a large variability in the balloon distension volumes between normal patients and patients with chest pain (2, 4, 5, 8). This discrepancy may be due to several things: 1) differences in the length of the distending balloon could affect the intraballoon pressure that is induced by a fixed volume of air; 2) the composition of the balloon, e.g., silicone or latex, may affect the results because each type of balloon has different pressure-volume characteristics (4); and 3) the subjects’ height, age, and gender have been shown to influence the results of balloon distension tests (3, 7, 11, 17). More importantly, our study demonstrates that the proximal, mid-, and distal esophagus exhibit distinct differences in both biomechanical characteristics and esophageal sensory receptors. This finding indicates that the level at which a balloon is distended in the esophagus could also contribute to the differences between laboratories.

Our study shows that the biomechanical and sensory parameters vary along the length of the esophagus and underscores the need for standardizing the balloon distension tests. Additionally, the positive correlation between esophageal sensory responses with wall tension suggests that esophageal sensation depends on the force that is generated within the esophageal wall. These findings together with the changes in esophageal CSA at different levels would suggest that an assessment of esophageal sensation using increments in balloon pressure rather than increments in balloon volume and at a fixed level (e.g., 10 cm above LES) may improve the sensitivity and the reproducibility of the balloon distention test.

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