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REVIEW ARTICLE

Structure and motility of the esophagus from a mechanical perspective

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Abstract Esophagus is an important part of the alimentary canal that performs various functions, most important of which is the transfer of bolus from the pharynx to the stomach. This involves active contraction of both the circular and longitudinal esophageal muscles. Esophageal anatomical features are harmonized with the functional and physiological demands of esophagus. However, impairment of esophageal functions may occur resulting in symptoms like dysphagia, gastroesophageal reflux or esophageal pain. This review covers broadly the anatomical and physiological details of esophagus, mechanical function of esophagus and its motility. In particular, the mechanical characteristics of the esophageal tissue and its motile function have been scrutinized. An overlay of the diagnostic technologies tapping these metrics is also covered.

Keywords Esophagus · Bolus · Esophageal motility · Peristalsis

The anatomy and physiology of the esophagus

The esophagus is an expandable, normally closed muscular tube which connects the pharynx to the stomach and measures about 25–30 cm in the adult. As a conduit, its main function is to pass food and fluid, which it propels by means of antegrade peristaltic contractions. It also serves to prevent the reflux of gastric contents from the stomach while allowing regurgitation, vomiting and belching to take place. These functions of the esophagus are supported by the upper and lower esophageal sphincters located at its proximal and distal ends. Any esophageal function impairment can lead to the debilitating symptoms of dysphagia, gastroesophageal reflux or esophageal pain [1].

The esophagus is an expandable muscular tube which is protected by the upper and lower esophageal sphincter at both ends. It begins as a continuation of the pharynx at the lower border of the cricopharyngeus muscle situated at the sixth cervical vertebra [1]. The esophagus covers three anatomic regions by extending from the 6th cervical level (C6) to the 11th thoracic vertebra level (T11). Normal narrowing of the esophageal lumen occurs at the three areas: at the cricoid; at the left main bronchus and the aortic arch, where it is compressed by these structures; and at the diaphragmatic hiatus [2].

Esophagus has a variable luminal diameter and an approximately cylindrical shape. This is surrounded by a wall, composed of four main layers, the mucosa, submucosa, muscularis externa and the adventitia. The mucosal layer is composed of connective tissue with the collagen fibrils in a loose, random arrangement. The passage of food between the stomach and esophagus is regulated by the lower esophageal sphincter. The mechanism of action of this sphincter involves both the smooth muscle of the distal part of esophagus as well as crural diaphragm skeletal muscles. It should be noted that the temporary relaxation of both sphincters is a causative factor in cases of gastroesophageal reflux; as opposed to just diminished pressure of the lower esophageal sphincter. The muscles forming the lower esophageal sphincter are thicker than those of the adjacent parts of the esophagus. The sling fibers (in oblique orientation) of the stomach also form a part of the anti-reflux barrier. These fibers have a C-shaped arrangement,

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the closed C side towards the greater curvature and open C towards the lesser curvature. This arrangement results in a 'flap mechanism'; gastric fundus pressure creates a flap which causes pressure against the lower esophageal end, this ultimately augments the LES (lower esophageal sphincter) pressure [3]. A detail of the investigation of the esophageal sphincter with reference to motility disorders is covered in the latter section.

Mechanical properties of esophageal tissue

The evaluation of esophageal wall mechanics calls for a histological analysis of submucosa. The submucosa actually plays a vital mechanical role in offering strong resistance to the deformation of the wall. Collagen is a key submucosa component, particularly type I and type II collagen. Unlike mucosa which shows very fine collagen fibrils, submucosa has collagen fibrils organized in thick fibers arranged in a crisscross pattern. Two groups of collagen fibers are present; one runs in a clockwise helix down the esophagus and the other is arranged in an anticlockwise helical fashion. The fibers of both the groups do not lie in different planes, but intertwine extensively while crisscrossing each other. The muscularis externa consists of striated and smooth muscles and can be subdivided into two layers in accordance with the main direction of the muscular fibers. The orientation of the musculature in the inner layer is circumferential and in the external layer it is axial. The final and outer layer (adventitia) is a thin layer composed of loose soft connective tissue that has a rich supply of blood and lymph vessels, an abundance of adipose tissue and a simple squamous covering epithelium [4].

The esophageal body is normally relaxed in the fasting state and the upper and lower esophageal sphincters are contracted to avert gastroesophageal reflux and aspiration. In the cervical esophagus, the intraluminal pressure is atmospheric; it becomes negative distally and comes closer to intrapleural pressure (Lamb and Griffin 2006). The information from histological studies suggests that from a mechanical standpoint, the esophageal wall may be analyzed as a multilayered anisotropic composite. Due to the specific orientation of reinforcing fibers, each layer of the esophageal wall is characterized by anisotropic behavior. Additionally, experimental data showed that esophageal tissues can undergo a great degree of strain and displacement and can be characterized by largely non-linear mechanical behavior [4]. The availability of literature on structural and mechanical analysis of esophageal tissues is limited. To investigate the multiaxial behavior of esophageal tissues, the underlying microstructure has been investigated, and uniaxial, biaxial and extension–inflation tests have been performed. These studies were conducted on ovine esophagus samples. It was found that the various tissue layers demonstrated different mechanical behaviors and overall, the behavior was anisotropic and heterogenous. Cyclic inflation tests performed on esophageal tissue showed a softening in the circumferential direction. The mucosa–submucosa demonstrated a higher degree of rupture strength as compared to the muscularis layer [5].

Some degree of residual strain (stress) has been observed at the no-load state. A vital physical feature of the esophagus is the buckling of mucosa during the active muscle contraction. Additionally, for the propagation of food bolus along with the requirement for intra-luminal pressure, the active contraction force of muscle cells is also needed to compress the inner mucosal layer and to occlude the lumen of the esophagus [6]. During esophageal wall peristaltic activity, wall tension and cross-sectional area of the esophagus increase dramatically [7]. The in vivo peristaltic behavior can be studied in terms of mechanical energy outputs as well, as detailed in a recent study [8]. It was seen that peristaltic waves consisted of pressure–cross-sectional area (P-CSA) phases of contraction and relaxation. Increase in distension pressures led to increase in work values from 1311 ± 198 to 16330 ± 1845 μJ. The propulsive tension increased from 18.7 ± 1.9 to 88.7 ± 5.5 N m^{-1}.

Mechanical characteristics of esophagus modeled as an isotropic layer

Studies analyzing the destructive strain and the maximum stress borne by the human esophagus (in which the esophagus has been taken as a homogenous layer) have been conducted using a tensiometer. Results depict a maximum stress of 1.2 MPa and a destructive strain of 140 % [9].

Experimental data exist in which the esophagus has been mechanically modeled as a continuous, isotropic layer which is incompressible. In one such study, data have been collected from pigs with a robotic indentor along with a force transducer. Material modeling has been carried out using a quasi-linear viscoelasticity framework proposed by Fung. Characterization was performed by comparing experimental force values and the FEM data, with estimated parameters and experimental forces for the selected experiments of the lower esophagus. Through FEM modeling, the Young's modulus was estimated to be 5.222 kPa. The force values of the hyperelastic model (ABACUS) matched experimental data [10]. In this study, the esophagus was modeled as one continuous tube (60 mm) with an internal pressure of 30 mmHg.

Stress–strain responses of the distinct esophageal layers

Mutiaxial tensile testing was carried out on the mucosa/submucosa and muscle layers. It was found that in uniaxial testing, both layers (mucosa/submucosa) and the

muscularis layer, showed stiff behavior. A distinct stiff response was seen in the axial direction as compared to the circumferential direction (for both mucosal and muscular layers). The esophageal layers show a non-linear behavior under uniaxial stress, which may be advantageous to the physiological function. This means that the esophagus shows compliant behavior under low stretches, but at higher stretches, the resistance of the mucosa–submucosa increases, preventing it from over-dilatation. Uniaxial testing showed very pronounced anisotropic behavior. However, biaxial testing showed very minor anisotropic differences. The main advantage of multiaxial testing over uniaxial tests was a closer simulation of physiological deformation behavior. (Sommer, Andreas 2013). In some studies it has been postulated that the mucosa contributes negligibly in the strength of the esophagus that is, until the outer diameter is almost doubled, showing that small intraluminal pressures are held by the muscle layer alone [11]. According to this finding, it is apparent that the diameter of the esophagus does not change because of any pathological modifications in the mucosa alone. If muscle is involved though, as in scleroderma, the diameter of the esophagus may change significantly. However, the growth and surface folding or mucosa may be clinically relevant in a better understanding of many pathologies. Mucosal growth can create residual stresses that affect its mechanical properties. Abnormal growth of mucosa (such as in the case of lymphoma, edema and inflammation can affect residual stress fields which can affect surface patterns (wrinkling) of the mucosa. Tissue re-modeling and many biological functions are affected by residual stresses. These have been studied by biomechanical models (Bo, Li 2011) which might be ideal for understanding these patterns in vivo, as opposed to cutting tissue and making observing changes in its shape [12].

The esophageal tube is unique as a biomechanical model because it can be separated into two distinct layers (the mucosa/submucosa and the muscularis layer) without damage to either layer. The mucosa/submucosa layers have been analyzed in several experiments on guinea pigs and rabbits. It has been found that this layer has larger opening angles and greater residual strain values as compared to the muscle layer [13, 14]. It is incumbent to point out the discrepancies obtained in results when the esophageal mechanical properties of two different species are compared. This might be due to different methods of decapitating the two layers mentioned above. In some studies, the layers have been cut radially, and then circumferentially separated from each other [13, 14]. In other studies, the layers have been separated from each other first and then cut radially. The former experimental technique claims to cause less damage [15].

In the same study, the submucosal layer has also been found to be the stiffest layer in comparison with the muscular layers; that is, it becomes stiffer at larger loads. This might be due to the fact—that the layer is rich in collagen. Collagen fibrils tend to be crimped up at lower loads; when the fibrils un-crimp, they lead to lower stiffness values, and then straighten up at higher loads. The study mentioned covers only uniaxial data and assumes that the esophageal tube is incompressible. It also assumes that the two muscle layers are homogenous, although distinct circular and longitudinal divisions are present.

The behavior of smooth muscle cells under different two-dimensional mechanical strains was studied. This study was carried out with the help of a bioreactor specially designed for the purpose. The polyurethane sheets with oxygen plasma treatment were used for cell seeding and the cells were stimulated mechanically at 420 cycles per day, for 3 days. Cell alignment was studied by phase contrast microscopy. Smooth muscle cells showed alignment under various biaxial strains, but it was found that cell proliferation also changes over a period of mechanical stimulation [16].

The properties of longitudinal muscle behavior have been scrutinized independently of other esophageal layers as well. One research outlines the use of concurrent manometry and ultrasonography methods to study longitudinal muscle shortening. Larger values of muscle shortening could be correlated to larger values of maximum intraluminal pressure. A higher magnitude of closure force, the force near the bolus tail, was accompanied by a greater degree of longitudinal muscle shortening. The magnitude of the closure force of the lumen was changed by the degree of longitudinal muscle shortening and also by the proximity of coordination (temporally) between the circular and longitudinal muscle contractions [17].

Esophageal peristaltic mechanism

Peristaltic wave moves down the esophagus when the food bolus is passed through the upper esophageal sphincter. Esophageal movement during peristalsis engages active contraction of the circular and longitudinal esophageal muscles. During bolus transport both the longitudinal and circular musculature act collectively. Sequential circular muscle contraction helps in the transport of bolus by pushing the bolus toward the stomach [18]. Longitudinal peristaltic contraction causes the esophagus to engulf the bolus and to shorten; this results in the bolus being pulled towards the stomach and contributes to the lower esophageal sphincter opening mechanism [19]. The Bayeless and Starling law of ascending contraction and descending relaxation apply to both longitudinal and circular layers

of the esophagus. There is also a correlation between the amplitudes of both types of muscular contractions.

The relaxation of upper esophageal sphincter depends on the subsequent tongue base; contraction of the posterior pharyngeal wall, as well as pharyngeal wall contraction which allows the bolus transfer and clearance into the esophagus [20]. The peristaltic wave initiated by swallowing is referred to as Primary peristalsis. The esophagus shortens initially by the contraction of the longitudinal muscle layer. This is the point where progressive lumen occluding circular muscle contraction proceeds distally through the muscles (both striated and smooth) of the esophageal wall, preceded by a wave of inhibition. The lower esophageal sphincter subsequently relaxes and then closes after the bolus, with a prolonged contraction [2].

Secondary peristalsis results from the stimulation of sensory receptors in the esophageal body because of food not completely cleared by the primary peristaltic waves, or by gastroesophageal reflux [21]. These events may also trigger swallowing-induced primary peristalsis in an attempt to clear the esophagus [2]. It may be pertinent to mention here that patients with Long-Segment Barrets Esophagus (LSBE) have shorter secondary peristalsis lag times as compared to healthy patients. (Kobayashi G et al. 2014). Tertiary contractions are the localized non-propagating events of the esophagus without any link to the swallowing or distension of the esophagus [2].

The act of swallowing initiates the primary peristalsis, which is the basic coordinated esophageal motor pattern. A rapidly progressing pharyngeal contraction transfers the bolus through a relaxed upper esophageal sphincter into the esophagus. When the upper esophageal sphincter closes, a progressive circular contraction begins in the upper esophagus and proceeds distally along the striated and smooth muscle portions of the esophageal body to propel the bolus through a relaxed lower esophageal sphincter. The lower esophageal sphincter then closes with a prolonged contraction [22]. In the resting state, the esophageal body has no motor activity. A contraction is initiated in the upper esophagus when food passes through the upper esophageal sphincter, which progresses distally toward the stomach. Esophageal peristaltic waves travel at 3–4 cm/s, last between 3 and 4.5 s, and reach peak amplitude of 60–140 mmHg in the lower esophagus [2].

The circular smooth muscle is first inhibited as bolus enters the esophagus, this is followed by a series of local contractions. The temporal delay of these contractions increases with the distance (axially) along the length of the esophagus. The temporo-spatial inhibition pattern, followed by circular muscle contraction, is what causes the transport of the bolus along the esophagus. In the middle region of the esophagus, the longitudinal muscle contraction precedes contraction of the circular muscle by approximately 1 s; the longitudinal muscle contraction takes place for roughly 1.25 s. Through these investigations it can be concluded that the esophagus is prepared for circular muscle contraction by the preceding longitudinal muscle contraction. This is probably because the circular muscle fibers get concentrated in the contraction zone [18]. Based on a study of the mechanical advantages of local longitudinal shortening (LLS), it has been concluded that the shear stress and local pressure in the contraction zone are reduced to a great extent because of LLS. The contractile pressure is reduced by two-thirds when peak LLS is aligned with the peak contractile pressure. It may be concluded that local longitudinal shortening provides an enhanced mechanical advantage by reducing the circular muscle tone in peristalsis [23].

The esophagus may have the capacity to change its propulsive force in response to bolus size and neurohumoral agents. The lower esophageal sphincter can change its strength in response to humoral stimuli and alterations in intra-abdominal pressure [24].

It has been observed that the viscosity of the bolus also affects how much axial force is exerted by the esophagus. This study was carried out using a probe that could record impedance-based axial force measurements when boluses of different viscosities were swallowed. In comparison with manometry techniques (that measure radial pressure), it was hypothesized that a measurement of axial force would be more significant in a study of esophageal contraction, since the swallowed boluses travel in an axial direction. It was found that there was a marginal increase in axial force with the bolus size, however, viscosity did not affect the pressure readings [25].

Investigation of esophageal motility

Symptom-based information in esophageal diseases might not be enough for clinical investigation and management. To fill the gaps, technologies providing an insight into esophageal motility can be relied upon. Manometry is a well-recognized method for investigating esophageal motility. There have been many advances in high-resolution manometry (HRM), coupled with esophageal pressure topography (EPT), and HRM with impedance. These techniques provide the basic pathophysiological causes for symptomatic representations of disease [26]. 350 studies have been investigated from patients with abnormalities ranging from achalasia, scleroderma, nutcracker esophagus and distal esophageal spasm. The mode of investigation was through a combination of multichannel intraluminal impedance and esophageal manometry (MII-EM). A basic insight from this investigation was that esophageal symptoms were not caused by dismotility alone, unless this phenomenon was accompanied by reflux or bolus retention [27].

The esophagogastric junction (ECG) has been studied using the "Functional Lumen Imaging Probe" or "FLIP". The study was conducted on eight normal subjects and two achalasia patients. The location of the EGJ was identified by manometry. Cross-sectional areas were measured through FLIP. A geometric reconstruction of EGJ in a three-dimensional animation was obtained. It was found that the CSA increased to 38 mm^2 after a pressure of 37 cm H2O. In an achalasia patient, the pressure did not rise above a minimum measurable value. It was concluded that the FLIP could be used as a technique for dynamic evaluation of EJG dysfunction cases [28].

Studies conducted on gastroesophageal reflux disease (GERD) patients have revealed that the opening of the EJG is altered in certain disease states. This study included seven healthy individuals, nine patients with GERD (without hiatus hernia, and seven with hiatus hernia). A technique used was low pressure distension through the use of a renograffin bag that straddled the EJG and was filled to the optimal pressure. Swallowing was imaged through fluoroscopy. In hiatus hernia patients, opening of the EGJ was observed even at pressures below 0 mmHg, thus explaining the fact that reflux occurs during deglutitive relaxation. At higher pressures, there were increases in the CSA of EGJ for both NHH and HH patients, whereas this was significantly less in NL patients. This study concludes that EGJ compliance should be focused upon when treating patients with certain pathologies related to the esophagus [29].

As opposed to measurements made from barostatic type devices, esophageal distension has recently been measured using a new technology termed as 'EndoFLIP', an endoscopic luminal functional imaging probe. Twenty GERD and twenty case control patients were in involved in this study. The EndoFLIP probe was placed across the EJG cross section where 16 distended diameters (corresponding to changing pressures) were measured. Greater degree of distensibility was usually observed at the hiatus, while GERD patients showed higher EJG distensibility. Data recorded with the help of this novel device correlated closely with previously recorded barometric measurements in other studies. However, when characterizing pathological conditions, it would be pertinent to stratify patients, so that heterogeneity does not interfere with the measurements. The upper esophageal tract (UES) distensibility has been studied using EndoFLIP in several healthy subjects. The results of such studies may be validated by correlation with already available physiological data. Data through EndoFLIP may be obtained without the need for contrast material, radiation or fluoroscopy [30].

Videoflouroscopy and scintigraphy are established techniques and bolus transit can be visualized through these methods. Multiple intraluminal electrical impedancometry is a high-resolution novel technique that has been introduced to aid investigation of the mechanism of bolus transport [31]. However, both these techniques only give a visual representation of esophageal motility. Esophageal screening has been used to identify patients with abnormalities that would have been missed otherwise. This technique is simple as far as procedural considerations are implied but can be used to decrease the overall time needed for esophageal fluoroscopy. It is incumbent to highlight that the technique itself is not very sensitive, and in case of high clinical suspicion, esophagrams should be considered.

In several studies, it has been observed that the bolus head portion is propelled forward much faster as compared to the tail or the body of the bolus. The transit of the pharyngeal bolus has been found to be faster as compared to the transit of the esophageal bolus. Propulsion velocity of the bolus decreases gradually in the esophagus. In the experimental conditions under which this investigation was conducted, air was swallowed along with the bolus and was propelled ahead of the bolus. The velocity with which the head of the bolus was injected from the pharynx region into the esophagus was approximately 37 cm/s. The velocity at which the bolus transverses the pharynx was 9.6 cm/s (mean velocity). The 'chamber pump function' in addition to the high velocity of the ejection of bolus from the pharynx into the esophagus is largely responsible for bolus transport through the pharynx [31]. Impedance monitoring has been used to study the transit of a food bolus through impedance monitoring. Intraluminal impedance can provide us with a large number of observations as it assesses bolus transit without the use of radiation [25].

Propulsion of the esophageal bolus, on the other hand, is far more complex. The bolus propulsion in the esophagus is a series of peristaltic movements that clear out the bolus tail. The propulsion of the bolus is faster in the proximal region because of high-velocity pharyngeal propulsion, and it becomes slower in the distal end because of increased abdominal pressure. The proximal esophageal region mainly consists of striated muscular layer and the distal esophagus is mainly of smooth muscle. A combination of both muscular types occurs in the middle third. These muscle types show different behaviors related to different responses: vagal simulation, innervations configuration, neurotransmitters for contraction, along with the mechanisms of peristalsis [31].

Previously conducted manometric studies for fluid bolus transport in the esophagus have ignored the hydrodynamic differences between intra-bolus pressure and the pressure that exists inside the contracted esophageal segment that has an occluded lumen. Studies conducted in normal volunteers have used intra-luminal manometric recordings along with esophageal videofluoroscopic techniques. Different volumes and viscosities of boluses have been used. The results have shown that intra-bolus pressure was elevated

with bolus viscosity, abdominal compression and volume. The esophageal diameter increases with an increase in larger bolus volumes, and the increase can been correlated with an increase in intra-bolus pressure. The intra-bolus pressure is highest in the bolus tail. Intra-luminal pressures of >20 mmHg above basal intra-bolus pressure are almost always associated with effective peristalsis. However, values of this pressure differential <20 mmHg correspond with retrograde bolus escape and ineffective paralysis. Intra-bolus pressure can serve as an indicator of the forces resisting peristaltic transport and it can also indicate the occurrence of ineffective bolus transport [32].

The manometric measurement of esophageal motility usually focuses on the peristaltic pressure waveforms that are a result of the series of esophageal muscular relaxations and contractions. Quantifiable features of the waveform for example amplitude, velocity and duration have been affected changes in certain physical bolus parameters, such as viscosity and volume, as well as by the stoppage of esophageal outflow. An analysis of the relationship between manometric readings and peristaltic transport of a fluid bolus through the esophagus has indicated the significance of considering two different pressure domains that are recorded by the manometry technique. One pressure domain is within the fluid bolus and the other one is within the esophageal segment where the esophageal segment is contracted and the lumen is occluded (the fluid bolus is absent).

There is a difference between pressure values within these two domains. Also, these pressures are not transmitted between the two domains when the lumen is sealed by the oncoming wave. The relationship between intra-bolus pressure to the peak intra-luminal pressure allows a prediction of effective peristalsis and it can also indicate the presence of ineffective peristalsis [32]. Automated impedance manometry pressure flow analysis (AIM) has been used to assess intra-rater and inter-rater reproducibility of AIM metrics [33]. Generally, patients who present with NOD (non-obstructive dysphagia) present with symptoms that cannot be traced back to abnormal motility patterns. High-flow resistance has been hypothesized to be an indicator that can be related to bolus hold-up. This has been characterized by esophageal pressure impedance recordings. It was found that NOD patients had higher pressure flow index (PFI); this indicated the presence of an esophageal motility disorders [34].

A decrease in pressure wave amplitude posteriorly (below pharyngoesophageal junction), and an increase in the wave amplitude distally, has been documented. Contractile duration also increases along the length of the esophagus. It has been established that a liquid bolus as compared with a dry swallow causes longer and slower, more forceful contractions, particularly in the distal esophagus. The durations, amplitudes and propagation times of esophageal contractions are greater with wet swallows than with dry swallows. Esophageal peristalsis is significantly altered by body position as well, because peristaltic amplitudes have been found to be greater in the supine position, as compared to the upright position [35]. Also, with a wet swallows the incidence of peristalsis was greater than with a dry swallow [36].

At the point of contraction, a longitudinal muscle brings together the rings of circular muscle fibers and increases the thickness of circular muscle layers which, in turn, increases the force generated by circular muscle. Additionally, the increase in muscle thickness caused by longitudinal muscle contraction reduces the stress on the wall of the esophagus at the site of contraction in accordance with Laplace's law [37]. According to the recent high-resolution manometry studies, it was seen that esophageal peristalsis actually comprises two distinct contractile waves, corresponding to the distinct muscle types and neural control mechanisms of the proximal and distal esophagus. There is a state called transition zone (TZ) which represents the region of spatiotemporal merger between these two contractile waves. To affect uninterrupted bolus transport across the TZ, the proximal and distal contractile waves normally exhibit smooth spatiotemporal coordination [38]. When all bolus material is cleared into the stomach, peristalsis is considered successful, and when all or some of the bolus material is not cleared into the stomach, peristalsis is believed to be dysfunctional. The peristaltic contraction maintains luminal closure behind the bolus as it traverses the esophagus, affecting clearance against downstream resistance [39].

The possible association between TZ defects and the occurrence of dysphagia has been studied through high-resolution manometry (HRM) in a cohort of 178 dysphagia patients with 175 control patients. The main findings of this research were that TZ abnormalities occur in approximately 6 % patients and such abnormalities might be responsible for dysphagia in half of this population. The quantification of TZ dimensions (spatiotemporal measures) has been achieved. Through this large patient study it was concluded that an association can be drawn between TZ abnormalities (greater than 1 s in duration 2 cm in length) and the unexplained occurrence of dysphagia. Defects in TZ should be taken as motility disorders that might form a part of evaluation of dysphagia [39].

Estimation of esophageal peristalsis

Peristaltic propulsive forces in the esophagus were measured [40] using a force transducer. The transducer was constructed by a strain gauge (mercury-in-Silastic gauge) that was attached with a plastic sphere (Fig. 1). This Silastic tubing contained mercury columns that attained different

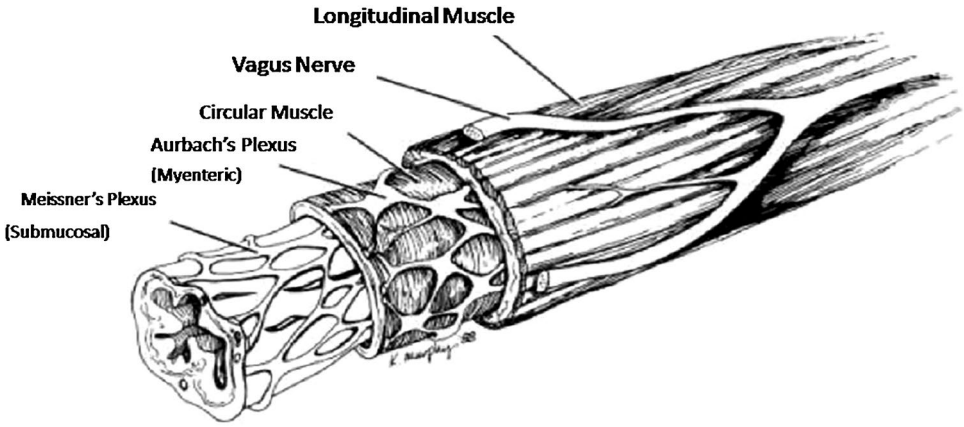

Fig. 1 A schematic showing the layered structure of the esophagus [17]

heights when propulsive force of the esophagus was exerted on the plastic sphere. The elongation produced an increase in electrical resistance values which were recorded and then converted to force values. When propulsive force stopped the elastic extension of the Silastic tubing, the columns of mercury were returned to their original length.

For this study, two groups of subjects were taken for esophageal force measurements, the 'control group' which was symptom free and the 'dysphagia group' with intermittent dysphagia. Each subject was asked to swallow the assembly into the stomach, where it was electronically balanced. The assembly was then withdrawn until the sphere had gone past the point of the lower esophageal sphincter. The force values were then obtained by five dry swallows at each 2 cm level, from lower esophageal sphincter to upper esophageal sphincter. Deglutitions that produced significant evidence of peristalsis were considered. Simultaneous contraction caused by the esophagus on gauge caused no output, force values were calculated only when peristaltic contractions occurred. It was assumed that the esophageal length from the lower to upper sphincter was 100 %. This was so that comparison between the subjects could be facilitated [40].

When the transducer assembly was inside the gastric fundus of the stomach, no output was recorded. When the sphere came in contact with the lower edge of the gastroesophageal sphincter, an increase in force values was observed. Variation in output was recorded when the transducer was placed at a constant level and the subject was asked to make repeated swallowing actions. Some other factors were identified which influenced transducer output. If the size of the sphere was increased from 6.9 to 10.6 mm, this increased the output to more than double. When the sphere was pulled from one esophageal end to the other, the regional differences became obvious. In the lower third of the esophagus, values of force obtained were the largest. In the middle third of the esophagus the force values declined, and lowest force values were recorded in the upper one-third [40].

In another study by [41], the peristaltic force in human esophagus was evaluated and factors which altered peristaltic force values were identified using an intraluminal strain gauge. The study was performed in only healthy subjects. Peristaltic force values were measured using a mercury-in-Silastic strain gauge represented schematically in Fig. 1. The strain gauge apparatus was used to simultaneously measure intra-luminal pressure and peristaltic force. Peristaltic force varied directly with sphere size at each level of the esophagus, and as sphere size was increased, the rise in peristaltic force was directly proportional. The basis for this observation is not clear, but a number of possibilities maybe considered, such as the bolus (sphere) may offer different surface areas for impingement of the peristaltic wave, or the bolus may cause changes in the muscles mechanical during contraction [41].

It is clear from the above graph that peristaltic force directly increased with the size of the sphere and was highest at the distal esophageal level. Peristaltic variation in force at different levels of the esophagus might be explained through differences in the mechanical characteristics or the muscle mass of the esophagus. The muscularis mucosa is not present in the proximal esophagus and normally gains thickness distally. Therefore, increase in muscle mass may fairly explain the increase (distally) in esophageal peristaltic activity [42] (Figs. 2, 3).

Conclusion

It is seen that mechanical features of esophageal tissue have been characterized based on data from different species. However, it is mandatory to consider that different responses may be evident from different kinds of tissue samples. More studies on the human esophagus need to be considered before a significant library of baseline data is developed, with which readings from diseased esophagus can be compared. A detailed study of the mechanical

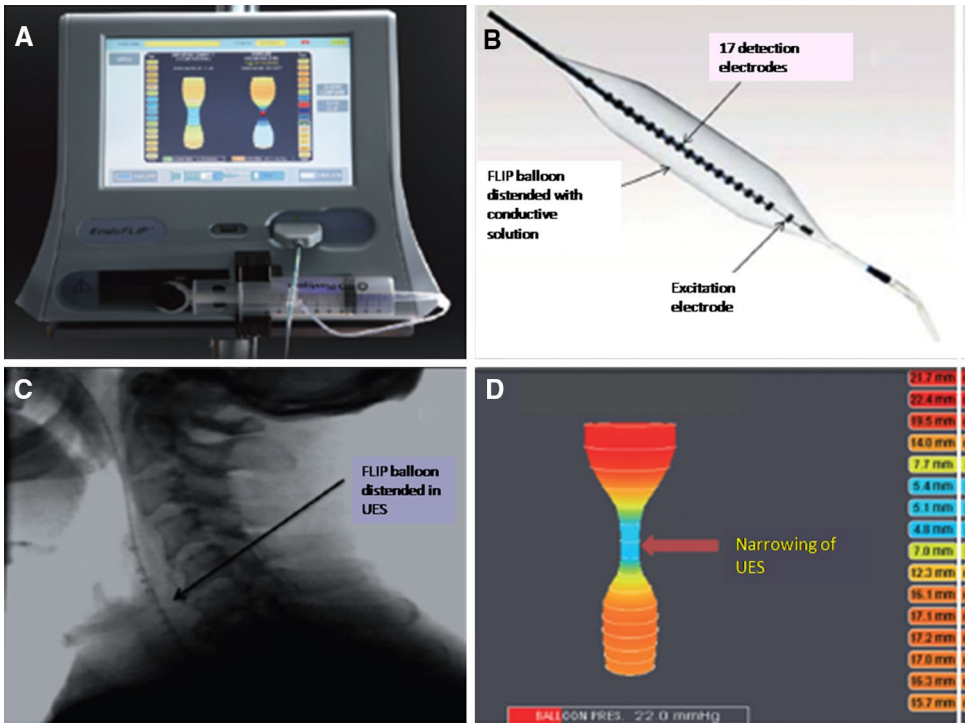

Fig. 2 Showing the EndoFLIP system **a** EndoFLIP, **b** functional luminal imaging probe balloon, **c** distended balloon, **d** the screen on EndoFLIP software [43]

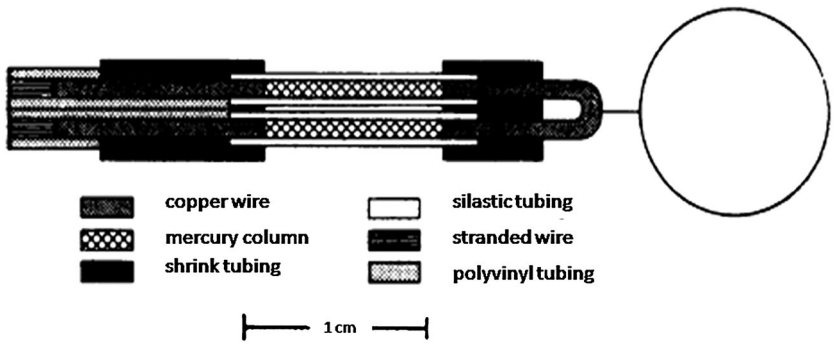

Fig. 3 Schematic representation of force transducer [40]

characteristics of the esophageal tissue is of significance because in case of pathological conditions or patients presenting with dysphagia, an analysis and comparison of the behavior of the pathological tissue with normal tissue is crucial. However, a perusal of literature makes the dearth of baseline data evident. For example, the multiaxial mechanical testing of esophagus is only a relatively recent effort. Direct stress strain readings of the human esophagus still rely largely on videofluoroscopy, which has to be supported by other techniques. It may be concluded that more research in this area is a priority. Esophageal motility and peristalsis are affected in most pathology, and there have been tremendous advances in the technologies that touch upon this aspect. A more holistic approach towards measurement of the pathological metrics of esophageal tissue still needs to be appended to the current technological advances. One advantage would be that the design of implants (for example stents) for patients presenting with serious pathologies may be tailored according to specific data about the mechanical characteristics and esophageal motility of a category of patients (sectored according to demographics, gender or pathology).

Ethical Statement This article does not contain any studies with human or animal subjects performed by any author(s).

Conflict of interest There are no financial or other relations that could lead to a conflict of interest.

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