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Axial force measurement for esophageal function testing

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Abstract

The esophagus serves to transport food and fluid from the pharynx to the stomach. Manometry has been the "golden standard" for the diagnosis of esophageal motility diseases for many decades. Hence, esophageal function is normally evaluated by means of manometry even though it reflects the squeeze force (force in radial direction) whereas the bolus moves along the length of esophagus in a distal direction. Force measurements in the longitudinal (axial) direction provide a more direct measure of esophageal transport function. The technique used to record axial force has developed from external force transducers over in-vivo strain gauges of various sizes to electrical impedance based measurements. The amplitude and duration of the axial force has been shown to be as reliable as manometry. Normal, as well as abnormal, manometric recordings occur with normal bolus transit, which have been documented using imaging modalities such as radiography and scintigraphy. This inconsistency using manometry has also been documented by axial force recordings. This underlines the lack of information when diagnostics are based on manometry alone. Increasing the volume of a bag mounted on a probe with combined axial force and manometry recordings showed that axial force amplitude increased by 130% in contrast to an increase of 30% using manometry. Using axial force in combination with manometry provides a more complete picture of esophageal motility, and the current paper outlines the advantages of using this method.

INTRODUCTION

The primary function of the esophagus is to transport ingested material to the stomach. Some of the most prevalent diseases in the esophagus relate to malfunction of transport e.g. reflux of stomach contents and motility disorders. The regulation of the normal function of the esophagus is complex, and requires fine coordination of the longitudinal muscles and circular muscles^[1]. Manometry is the gold standard for the diagnosis of motility diseases in the esophagus^[2]. It has been used for many decades, and provides an indirect picture of the motility patterns because it only gives information about muscle contraction or radial squeeze^[3]. However, any contraction - strong or weak - will only be measured by manometry if it occludes the measuring catheter. Using data from computer models, it has been argued that shortening of the longitudinal muscle plays an important role in the mechanisms of peristalsis and that pressure amplitude per se does not give any indication of the force required to drive the bolus forward^[4]. Hence manometric recordings alone are insufficient to describe and quantify esophageal motility. To improve this, and gain more knowledge, modalities such as fluoroscopy^[5,6] and ultrasound^[7] have been used in combination with manometry. These modalities have confirmed that parameters recorded by manometry only partly describe the peristaltic wave, but these imaging modalities do not provide quantitative information on force in either radial or axial directions^[8]. Furthermore, in the clinic, these extra modalities in combination with manometry are inconvenient because multiple examinations are needed.

A more physiologically related measure that gives direct information about the motility is to record the force that pushes or propels the bolus in an axial direction towards the stomach. This method of quantifying peristalsis is referred to as propulsive force^[6,9-13], traction force^[6,14-17] and peristaltic force^[11,18]. We refer to these concepts as axial force as this is the direction of the force in contrast to manometry, which records the radial force.

AXIAL FORCE RECORDING TECHNIQUES

The number of publications in relation to axial force is limited to less than ten, with Winship *et al*^[12] being the first to publish a method that recorded the axial force of the human esophagus in 1967. They used an external force transducer connected to a plastic sphere placed in the esophagus. This enabled assessments of the esophagus' ability to propel the plastic sphere against a known resistance. Pope *et al*^[11] and Schoen *et al*^[18] used a mercury-in-silastic strain gauge which was placed together with a plastic sphere in the esophagus. The next development by Russell *et al*^[13] was similar to previous editions though the mercury in the strain gauge was replaced by saline to reduce the effect of temperature dependence. The use of a plastic sphere did not allow a change of volume *in vivo*, hence in studies with varying bag sizes, the probe had to be redrawn, the sphere replaced and swallowed again. This could introduce some errors in terms of positioning as well as irritation and secondary contractions. Williams *et al*^[14] and Poudroux *et al*^[6] and co-workers used a strain gauge, but did not describe any technical details. The next series of publications were based on the use of a miniature strain gauge, and published in the period from 1992 to 1997^[6,14-17]. A new technique, based on impedance planimetry, was introduced recently (2008) by our group^[19]. The principle of impedance planimetry is to create an electric field between two excitation electrodes placed in a bag with conductive fluid. Two detection electrodes placed close to each other, and midway between the excitation electrodes, measure the cross-sectional area. This is possible as the impedance between the electrodes is proportional to the distance between the detection electrodes, and inversely proportional to the conductivity of the fluid and the cross-sectional area^[20]. The only variable left is the cross-sectional area, as the other parameters are constants implemented in the calibration^[12]. We took advantage of our experience with impedance planimetry, and redesigned the probe to have a constant cross-sectional area, but allowed the distance between the detection electrodes to vary (Figure 1). Thus, the potential between the electrodes would be linearly related to the axial force. This design enabled easier probe construction and less technical pitfalls compared to the strain gauge design.

Axial force still needs to prove its utility in relation to high resolution manometry. It has not yet been documented how high resolution manometry and axial force correlate. We believe that despite the extra

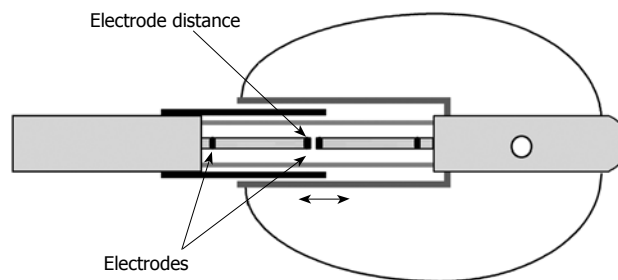


Figure 1 The redesign of impedance planimetry has enabled measurements of axial force instead of changed in cross-sectional area. The variable in the redesign is the distance between the detecting electrodes. This distance can be related to axial force by means of calibration. Any axial force applied to the bag will increase the distance between the electrodes. The thick black and dark gray lines represents rigid plastic cylinders that ensures that the construction will not bend. The design also enables the bag to be inflated *in vivo*.

information high resolution manometry can provide, it still does not record the actual function of the esophagus and any attempt to interpret the bolus transport can be flawed. An undetected transport of the bolus can still occur with manometry because it mainly quantifies the circular muscles' contractions.

Axial force, based on strain gauge or impedance, has some limitations. Despite anchoring the probe to the nose or cheek, some movement will occur. This will affect the axial force recordings but in manometry would merely relocate the recording site. This movement will primarily influence the amplitude of the axial force recordings.

Future development of axial force recordings may include multiple recordings on the same probe. Recordings at different sites would provide a more complete picture of esophageal transport function and axial forces.

AXIAL FORCE RECORDINGS IN HEALTHY SUBJECTS

The axial force can be divided into two main components; the "grip" effect, and the ability to push in the axial direction against an intra luminal object^[13]. The "grip" effect is primarily determined by manometry as the squeeze effect. A better grip will decrease the chances for the peristaltic wave to slip over a given intraluminal object and, thereby, create a basis for a strong axial force. The grip effect is also determined by frictional force. Any amount and type of fluid will change the frictional forces between the probe/bag and the esophageal wall and, thereby, change the grip effect. It has been shown that a swallow of 10 mL of salad oil decreased the amplitude by more than 50% in subsequent swallows^[11]. The influence of frictional forces is an issue that needs further investigation before a statement about their influence in real-life situations can be made.

The information gained from axial force recordings has differed depending on the design of the studies. As with manometry, the absolute axial force values in control subjects vary markedly^[11]. The coefficient of variation has been reported to be in the same range

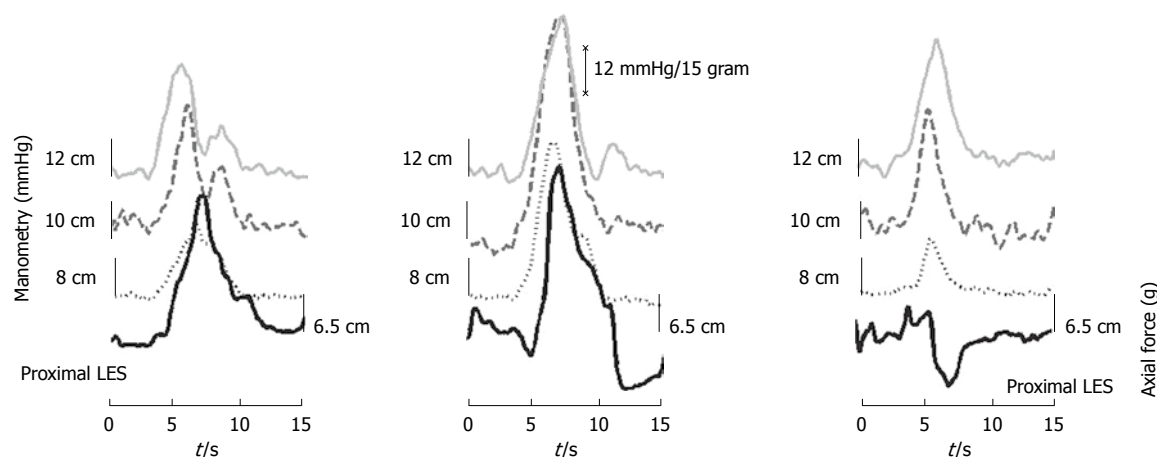


Figure 2 A voluntary dry swallow (time = 0) from three subjects with a bag volume of 2 mL. The solid black tracings are the axial force recorded 6.5 cm proximal to the lower esophageal sphincter, and the three other tracings are the pressure recorded 12 cm, 10 cm and 8 cm proximal to the lower esophageal sphincter. Using the manometric tracings, the first swallow (left) showed a normal propagating peristaltic wave and the resulting axial force response was as expected. The swallow of the second subject (middle tracings) shows a rather powerful pressure amplitude; but, it is not propagating (peak amplitudes are similar in time). In contrast, the axial force response is comparable in amplitude to that in the first subject (left tracings) although it is followed by axial force in the oral direction (negative value). In this case, the interpretation of the manometric recording would be flawed if the axial force had not been recorded simultaneously. The third person (right tracings) had lower manometric amplitudes during swallowing, without any propagation. The axial force response is different from the swallowing in the second person (middle tracings), as there is a weak reflux (oral axial force). The data shown is taken from a study in our group where the data is still being analyzed.

for manometry^[22] and axial force^[23]. These findings are similar to data collected in our laboratory. In assessing whether or not multiple manometric tracings along the esophagus are propagating, axial force recordings have shown to be inconsistent with the interpretation gained from manometric recordings^[11]. This has also been documented using other modalities such as radiographic or scintigraphic imaging^[21,24,25]. As an example from our laboratory, Figure 2 shows three dry swallows from three healthy subjects with a bag containing 2 mL saline. Three manometric tracings (12 cm, 10 cm and 8 cm proximal to the lower esophageal sphincter), and one axial force (6.5 cm proximal to the lower esophageal sphincter) tracings were recorded. These three examples show how the recordings can be very difficult to interpret when the bolus transit is deduced solely from manometry tracings.

Our probe design enables axial force recordings with various bag sizes to provide a challenge test for the esophagus (e.g. greater force with larger bag size). The effect of the bag size during force recordings was studied to some extent by Winship *et al.*^[12] who inflated a bag with 10 mL after which a swallow was initiated. The axial force applied to the bag from the peristaltic wave persisted until the bag was deflated. A comparable experiment was done by Poudroux and co-workers using bag diameters of 15 mm to 20 mm^[6]. During a study in our group a persisting axial force was occasionally generated at even smaller bag volumes (6 mL). However the data analysis for this study is not complete. Swallowing studies recording axial force have previously been performed with a balloon in the esophagus inflated with either air^[11,12,14] or fluid^[19]. Increased bag volume increased the axial force amplitude^[11,14,15]. This could be due to an improved grip effect. These studies extracted parameters from axial force and manometric recordings and found little or weak correlation^[6,11,13,14]. Thus, additional information is

likely to be gained by recording axial force. Using clips attached to the esophageal mucosa, the shortening/elongation of the esophagus was measured in a study by Poudroux and co-workers^[6]. They combined shortening information with axial force and manometry recordings. A good correlation was found between axial force and (1) shortening of the distal esophagus, (2) the maximal contraction of the distal esophageal segment, and (3) the extent of aboral movement during the period of axial force recordings. These factors are all involved in the longitudinal muscle contraction. Hence, axial force recordings may show defects in this area where manometry provides poor information. Unpublished data from our laboratory on pressure and axial force recorded simultaneously have shown that the amplitude of manometry increases only slightly proximal to the bag (approximately 30%) when the volume is increased whereas axial force increased to a major degree (approximately 130%) (Figure 3). Somewhat similar findings were obtained in a previous study^[11]. Axial force was also present with an empty bag. This could be due to the size of the probe (5 mm in diameter) as the grip effect is sufficient to generate an axial force. The amplitude for axial force, and manometry increased when dry and wet swallows were compared.

Using area-under-curve for manometry tracings as a parameter to predict the axial force response has also failed as there was very little correlation between this parameter and the area-under-curve for the axial force tracings^[21].

The clinical standard procedure with manometry during swallow tests does not include a bag being inflated, as this only affects the manometric recordings to a minor degree^[26,27]. On the other hand, increasing the bag volume would present a challenge test to the esophagus similar to an electrocardiogram recorded during exercise. During exercise, the electrocardiogram

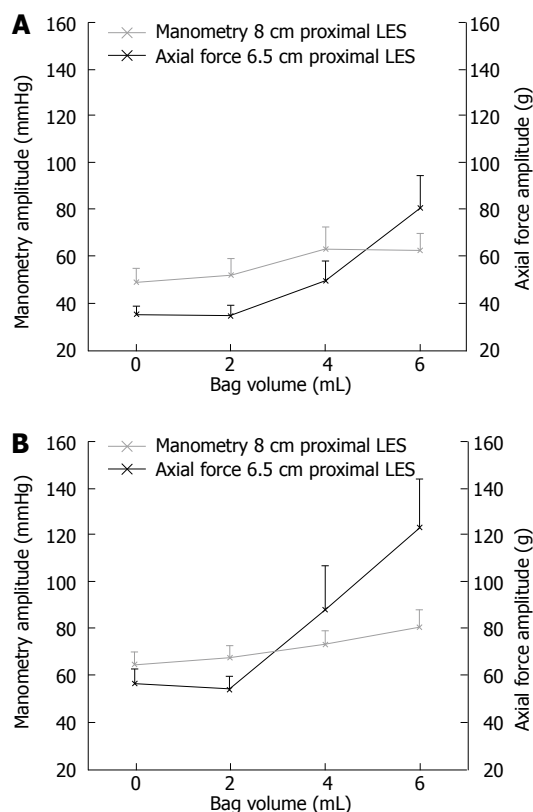


Figure 3 Swallow test with increased bag volume. A: Dry swallow; B: Wet swallow. The pressure was recorded 8 cm proximal to the lower esophageal sphincter and the axial force was recorded 6.5 cm proximal to the lower esophageal sphincter. Both graphs show that the increased amplitude for axial force was greater when compared to manometry during both dry and wet swallows. Data are presented as mean \pm SE from 10 volunteers.

can reveal abnormalities not seen at rest^[28]. Thus, a “challenge test” could provide a more sensitive test when recorded with axial force. This would be of great interest when applied to patients with motility-related diseases.

AXIAL FORCE RECORDINGS IN PATIENTS

Axial force is not a widely used technique and only a limited number of patients have been examined. In one study, a group of eight subjects complaining of dysphagia were examined. Radiography failed to reveal an organic narrowing of the esophagus, and no abnormal motor activity was observed by the fluoroscopist. Furthermore, the manometric examination did not reveal any dysfunction of peristalsis. On the other hand, axial force recordings clearly separated these subjects from healthy controls^[11]. The patients were divided into two subgroups, one which had abnormally high amplitudes, and the other with abnormally low amplitudes. In 30 gastro-esophageal reflux patients with erosive disease and normal manometry, six patients showed impaired axial force amplitudes. This was based on a protocol with ten wet swallows (10 mL) for each patient. A similar pattern was shown in the same study where six out of twelve patients suffering from functional dysphasia had impaired axial force amplitudes but normal manometric amplitudes^[17]. These

results point in the direction of diagnosis being based on both manometry and axial force. If the result of multiple modalities can be provided by one examination, it will minimize the number of investigations and inconvenience for the patient without affecting the final diagnosis. Axial force has been measured simultaneously with manometry and, if not incorporated in the same catheter^[11,13,19], manometry can be recorded next to the axial force probe^[12,17]. The information gained from such investigations would be pressure and axial force generated by esophageal contractions. The preliminary results from studies in the last forty years have indicated that axial force recordings add further information to traditional manometry, and it remains unanswered why axial force is not more widely used.

CONCLUSION

Axial force measurement provides additional and more physiological information about the swallowing function compared to manometry. In future studies, combined axial force recordings and manometry may provide more useful information on esophageal muscle function in basic and clinical studies, especial protocols where a challenge test of the esophagus is incorporated will be of major interest in basic and clinical studies. It has been suggested that manometry could subgroup gastro-esophageal reflux disease patients into those requiring partial or total fundoplication treatment^[29-31]. However, studies have not been able to prove that preoperative manometry could predict postoperative outcome in terms of dysphagia^[32-34]. Measurement of axial force is more likely to identify patients who would develop postoperative dysphagia, although proof awaits clinical studies.

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