Intraluminal force transducer measurements of human oesophageal peristalsis

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SUMMARY A force transducer has been developed to measure peristaltic propulsive force ('pull') in the oesophagus. Utilizing a mercury-in-Silastic strain gauge to which a sphere has been attached, this transducer can be calibrated to measure value for force, work, and power. Variability in force values were found between different peristaltic waves at the same site, between different sites in the same subject, and between different control subjects. Control subjects' patterns did not change when the subjects were studied on separate occasions. Patients complaining of dysphagia, who had normal radiographs and manometric tracings, revealed force values that were significantly different from control values. This device should prove useful in the quantitation of oesophageal muscle function.

An important motor function of the oesophagus is the aboral propulsion of solids and fluids. This paper describes the construction and application of a transducer which does directly measure the oesophageal force of propulsion. Abnormal force values have been detected by this transducer in patients without anatomical oesophageal narrowing, whose manometric tracings and radiographs are within normal limits.

Methods

CONSTRUCTION

The transducer consists of a mercury-in-Silastic strain gauge attached to a plastic sphere (Fig. 1). A propulsive force exerted on the sphere will result in elongation of the columns of mercury contained in the Silastic tubing. This elongation produces an increase in electrical resistance which can be recorded and converted to values of force. After the propulsive force has ceased the elasticity of the Silastic tubing returns the columns of mercury to their resting length.

The strain gauge is fabricated by following the method described by Parrish, Strandness, and Bell (1964). The active portions of the gauge consist of mercury-filled Silastic medical grade tubing (Dow Corning Company HS-10606) 1 cm in length, ID 0.762 mm and OD 1.651 mm. The U-shaped end wire (23 mm in length) and the short connecting wires

Fig. 1 Schematic illustration of force transducer.

(15 mm in length) are solid copper with enamel insulation (Beldenamel no. 18), 1.06 mm in diameter. The short connecting wires are soldered to stranded lead wires (Belden no. 830 26 AWG), which are then encased in polyvinyl tubing, 2.5 mm OD. These connecting wires and the U-shaped end wire are then forced snugly into the mercury-filled Silastic tubing after prior treatment of the Silastic tubing with xylene to impart temporary pliability. Shrink tubing (Alphlex 3/32) is used to strengthen all joints. Gauge resistance from lead to lead is approximately 0.4 ohms. A smooth plastic sphere 10.6 mm in diameter is tied to the U-wire with nylon filament. Manometric catheters are cemented to the polyvinyl tubing carrying the lead wires, so that the side openings of the catheters are located 1 cm and 8 cm upstream from the sphere.

The leads from the transducer are connected across a modified a-c Wheatstone bridge, as described by Elsner, Eagan, and Anderson (1959),

(Helmer Instrument Company, Seattle, Washington). The bridge is coupled to a Sanborn 350-1100B carrier preamplifier whose output is graphed by a Sanborn 350 series direct writing recorder. The transducer is calibrated by suspending weights ranging from 1 to 200 g from the vertically supported transducer. The output of the transducer can thus be related to grams of force applied (Fig. 2A). Displacement calibration of the transducer is performed on a linear calibrator (Brady Instrument Company, Windsor, Ontario, Canada) Egan, (1964). The gauge is suspended from two parallel steel bars that can be separated by a micrometer drive. Change in output of the transducer can be related to linear displacement of the transducer (Fig. 2B). Since both force and displacement can be related to transducer output, it is possible to construct a composite graph (Fig. 2C). The slope of this graph represents force per unit elongation, and is the same as the spring constant of a coiled spring. Continuing the analogy, work done on the device by the oesophagus can be expressed as $W = 1/2 kx^2$, where work is expressed in ergs, k is the spring constant, and x represents displacement in mm. Average power developed during performance of this work can be calculated by dividing the work done by the time necessary to do the work ($P = W/t$).

SUBJECTS

Oesophageal force measurements were performed on 13 subjects free of oesophageal symptoms, gastrointestinal surgery, and neuropathy, and were performed on eight subjects who complained of dysphagia. The symptom-free group shall hereafter be referred to as the 'control group', and the group with symptoms shall be known as the 'dysphagia group'.

The dysphagia group were separated from a larger group of patients with more classic x-ray and manometric findings of oesophageal motor disease. All complained of intermittent dysphagia, usually of many years' duration. Only three of the eight patients had sought medical advice for this symptom. The other five patients were in hospital for a variety of non-gastrointestinal problems, and dysphagia was discovered on a careful system review.

Dysphagia was usually experienced substernally and was brought on by solids, but not by liquids. Dysphagia was relieved by repeated swallowing or by washing the food down with water. None of the individuals were forced to regurgitate a bolus that had become arrested. Table I gives the clinical characteristics and investigative results in these subjects.

Each subject swallowed the transducer assembly into the stomach, where it was electronically balanced. The accompanying pressure catheters were infused

Fig. 2 Calibration curves for force transducer. 2A is a graph of force in grams plotted against output in arbitrary units. 2B relates displacement in mm to the same units. 2C is a composite graph relating force to displacement. The slope of this graph is the spring constant, k , of the device.

by a Harvard apparatus 600-900 constant infusion pump at 2.4 ml/min. The assembly was then withdrawn until the sphere had passed through the lower

Patient	Age	Sex	Radiograph	Oesophagoscropy	Manometry	Other Diseases
S.S.	52	M	Normal peristalsis, 20 mm Schatzki ring, no arrest of bread bolus	No	Normal	Syringomyelia
H.D.	55	M	Normal	No	Normal	Guillain-Barré
J.H.	39	M	Progressive peristalsis, but 'weak'	No	Normal	Muscular dystrophy
H.D.	57	M	Normal	No	Normal	Alcoholism
E.T.	43	F	Normal	Normal	Normal	—
L.S.	34	M	Normal	No	Normal	—
D.B.	31	M	Normal	Minimal oesophagitis	Normal	—
J.W.	43	M	Normal	No	Normal	—

Table I *The patients studied*

oesophageal sphincter. The force values developed by five dry swallows, at each 2 cm level, from lower oesophageal sphincter to upper oesophageal sphincter, were then recorded. Only deglutitions which produced manometric evidence of peristalsis were counted. A minimum interval of 20 seconds between swallows was maintained. The force values developed by each peristaltic wave were calculated by correcting the observed output from the gauge by use of a graph (Fig. 2A). To facilitate comparison between different subjects, the length of each oesophagus from lower sphincter to upper sphincter was considered to be 100% and the levels at which measurements were made were converted to percentages of the whole.

To study the effects of a standard stimulus on peristaltic force, five subjects from the control group swallowed the transducer assembly with a 30 ml balloon attached 5 cm above the proximal manometric tip. Air was then injected into and withdrawn from the balloon at various rates and volumes. Also studied were the effects of wet swallows (10 ml in volume) at different temperatures (25°, 60°, 2°). To provide a substance expected to alter frictional forces in the oesophageal lumen 10 ml of salad oil was also swallowed by one subject. In order to determine whether peristaltic force remained constant at each level over a period of time, six of the control subjects swallowed the assembly on three separate occasions, approximately two weeks apart.

Results

The transducer assembly is easily swallowed and the presence of the sphere in the oesophagus produces no sensation whatsoever. No output is recorded from the transducer assembly when it is in the gastric fundus. As the assembly is withdrawn the sphere encounters the lower edge of the gastroesophageal sphincter. An increase in force is recorded.

Once the sphere is pulled through the oesophageal sphincter, a drop in transducer output is noted.

Deglutition causes a monophasic wave to be inscribed. The accompanying pressure tip simultaneously records the passage of the peristaltic wave (Fig. 3). Occasionally, respiratory variations are superimposed on the monophasic wave. This can be eliminated by holding the breath. If the pressure tips record a simultaneous non-peristaltic contraction, no output is recorded from the force transducer.

Variation in output was observed when the transducer was maintained at the same level and the subject swallowed repeatedly. The coefficient of variation for one such experiment was 32%. An attempt to decrease the variation by using balloon distension rather than deglutition as a peristaltic stimulus was unsuccessful. With balloon distension, the coefficient of variation at any one balloon volume ranged from 13 to 39%.

Several other factors were found to influence transducer output. Increasing the size of the sphere from 6.9 mm to 10.6 mm more than doubled the output (Table II). Ingestion of 10 ml of salad oil in one subject decreased output by more than 50% in five subsequent deglutitions. No significant difference was found between force values following dry swallows and those following a swallow of 10 ml of water at 25°, 60°, and 0°C. No significant change in force values stimulated by balloon inflation was observed as balloon volume was varied from 5 ml to 15 ml and as the rate of injection was varied from 1.25 ml/sec to 10 ml/sec.

Sphere Diameter (mm)	Force (grams)
No sphere	0.0
6.9	15.9
7.8	16.6
9.0	30.6
10.6	37.8

Table II *Relationship between sphere size and transducer output*

As the sphere was moved from one end of the oesophagus to the other, certain regional differences

Fig. 3 Peristaltic force ('pull') in the oesophageal body. The assembly is located in the lower third of the oesophagus. The top two tracings are from infused (2.4 ml/min) catheters 7 cm apart. The bottom tracing is from the force transducer, whose sphere is 1 cm below the distal catheter. DS signifies dry swallow. The recorder speed in this and subsequent figures is 2.5 mm/sec. Note the difference in attenuation in the two pressure channels. Two dry swallows produce two values for pull of 105 and 90 grams.

Fig. 4 Force values of 13 control subjects. Pull values in grams are plotted against oesophageal length. The lower oesophageal sphincter would be to the left of 0 percentile. The oesophageal sphincter would be to the right of 100 percentile on graph. Each point is the mean value of 13 subjects. The bars represent ± 1 standard deviation.

became apparent. Figure 4 shows the values for force obtained from the control group. The large values for standard deviation demonstrate wide variability in mean force values between different control subjects when measured at the same oesophageal site. The largest force values are found in the

lower one-third of the oesophagus. Values then decline in the middle one-third, and reach lowest values in the upper one-third, only to rise again as the sphere approaches the upper sphincter.

When work and power values are computed, the same general distribution of values is obtained. Table III compares work and power values with the

Oesophageal Site	Force (g)	Work (Ergs)	Power (Microwatts)
0	32.5	1 459	35.2
10	48.8	2 433	63.7
20	46.3	2 410	85.7
30	35.4	1 555	70.5
40	32.6	1 257	62.2
50	33.0	1 287	64.1
60	33.4	1 160	54.5
70	29.0	870	52.6
80	21.4	727	43.2
90	23.5	732	61.2
100	34.5	1 424	128.2

Table III Control subject values

force values obtained from the control subjects. Power values were at a maximum at the upper end of the oesophagus where duration of the peristaltic wave was the shortest. In subsequent examination of patients with dysphagia, the calculation of work and power offered no additional information not presented by force values. Therefore, work and power values are not routinely calculated.

Fig. 5 Reproducibility of force values from six control subjects studied at intervals of two weeks. Force values in grams are plotted against oesophageal length. Each line represents values obtained in one study.

When the same individuals are repeatedly studied, each individual's force profile remains constant over time. This is demonstrated by Fig. 5 which graphs force profiles from six control subjects obtained at three sessions separated by two-week intervals. Visually, each subject's patterns seem stable, even though there are marked variations in the force profiles between different normal subjects. When subjected to a three-way analysis of variance, it is found that sites of the oesophagus are significantly different (F value 7.4; $P < 0.001$). Variation between control subjects is also highly significant (F value 16.9; $P < 0.001$). However, there is no significant

difference when an individual is compared to himself on different days (F value 3.2; $P > 0.05$).

Comparison of force values and infused pressure values (squeeze) obtained on the same swallow from sites 1 cm apart reveals that these two measurements occasionally vary widely, high force values being associated with low squeeze value and vice versa. Figure 7 is a graph of 170 comparisons of force and infused pressure values obtained from a control subject. Although there is a relationship between these two measurements, the r value of 0.75 indicates that this is not a close relationship.

Fig. 6 A comparison of pull and squeeze values obtained from a control subject. Values of pull are compared with simultaneously measured squeeze values recorded from a site 1 cm proximal to the sphere of the transducer.

In the study of abnormal individuals whose manometric tracings were diagnostic of their conditions, no new information was gained. When aperistalsis was present as in scleroderma and achalasia, no output was recorded from the device. In one

	Normal	S.S.	H.D.	J.H.	H.C.	E.T.	L.S.	D.B.	J.W.
0	32.5	0	48.4	13.2	0	53	161.6	47.4	30.6
10	48.8	7.4	37.0	14.6	17.2	99.2	198.2	41.0	43.4
20	46.3	11.0	35.2	23.4	30.3	89.6	116.8	54.8	58.6
30	35.4	12.0	26.0	19.2	22.4	71.0	87.0	71.4	69.4
40	32.6	13.8	18.4	8.4	20.8	95.2	87.8	55.8	88.8
50	33.0	12.8	14.0	6.4	24.0	80.4	95.6	56.6	60.2
60	33.4	10.4	10.6	3.2	0	54.0	72.0	38.7	65.0
70	29.0	8.0	7.4	0	0	71.6	68.4	67.6	58.6
80	21.4	18.2	6.8	0	0	68.0	42.8	22.4	46.2
90	23.5	29.2	15.7	0	6.4	39.8	38.0	39.8	31.0
100	34.5	37.4	38.7	0	3.4	41.8	59.4	67.2	36.6

Table IV Force values at each 10th percentile of the length of the oesophagus in eight subjects with unexplained dysphagia compared with mean force values for 13 normal subjects¹

¹All values in grams of force. Italics denote $P < 0.01$; bold denotes $P < 0.001$.

patient with classic manometric findings of diffuse spasm, pull values exceeding normal values by 2 standard deviations were recorded during peristaltic contractions. When the pressure tips showed simultaneous contractions, no output was recorded.

The force values determined in the eight patients with intermittent dysphagia, but normal radiographs and manometric findings, are shown in Table IV. Although dysphagia is a common clinical feature, the force values define two subgroups, one of which has abnormally high values, the other having abnormally low values.

Discussion

If a new device is to be introduced for the measurement of gastrointestinal smooth muscle activity, what should be expected from such a device? The mechanical function of such a device should be understood. It should be easy to fabricate and calibrate; it should be safe, durable, and inexpensive. Most importantly, it should provide information not obtainable by current methods of study. The force transducer described in this communication would seem to meet these requirements.

The mechanical factors influencing this transducer are easily understood. The mercury-in-Silastic gauge produces an electrical signal proportional to the amount of elongation of the gauge. This elongation can be calibrated in terms of grams of force. When the strain gauge is connected to the test sphere, aboral peristaltic forces directed on the sphere by the oesophageal muscle cause elongation of the attached gauge and hence a representation of propulsive force in grams. Simultaneous contraction of the oesophagus on the gauge causes no output; force values are recorded only when peristaltic contractions are present.

The size of the attached sphere is a major determinant of the force values obtained during peristalsis. Within the limits of sphere size studied, output varied directly with sphere size. The 10.6 mm sphere was selected for routine use because it was the largest size sphere which could comfortably be withdrawn through the upper oesophageal sphincter. This size was not large enough to stimulate secondary peristalsis by its presence, nor did it cause any substernal sensation in the subjects who swallowed it.

Another variable which might be expected to influence recorded force values is the frictional force between the sphere and the mucosa of the oesophagus. Such frictional forces are difficult to measure, but the observation that ingestion of salad oil caused a marked decrease in force values of subsequent deglutitions would suggest that these frictional forces might be important. During the

reported studies, a slow constant infusion of water was used in the oesophagus which might be expected to provide a uniform environment. Differences between individuals in frictional forces may well still exist.

The transducer measures isometric force developed by a peristaltic wave. During registration of peristaltic force, the sphere is displaced only 2-3 mm. Thus, these measurements differ from earlier attempts to quantitate peristaltic force by registering isotonic force, as did Mosso (1876) and Schreiber (1904). Isotonic force values, as reported by these workers and from preliminary experiments in this laboratory, are considerably lower than isometric force values.

These measurements should also be differentiated from the oesophageal propulsive force as measured by Winship and Zboralske (1967). These workers stimulated it by distending a fixed balloon with volumes ranging from 3 to 25 ml of air. Unlike the present studies, the oesophageal propulsive force was seen as long as balloon distension was maintained and it was not related to peristaltic activity either above or below the balloon.

The present force measurements are triggered by deglutition rather than by the presence of the sphere in the oesophagus and are clearly related to peristalsis as detected by intraluminal pressure recordings. It is not possible at the present time to know whether the oesophageal propulsive force and the present peristaltic force measurements are caused by the same muscular activity.

Does this proposed new device present information which is not obtained by present methods of investigation? In the evaluation of oesophageal peristalsis, radiology allows the calculation of the velocity of the peristaltic wave and the evaluation of the presence or absence of peristalsis. It suffers from the disadvantage of subjectivity and some inter-observer variation (Mandelstam and Lieber, 1970). No direct measurement of muscular force can be obtained by radiographs.

Most quantitation of oesophageal motor function has been performed by intraluminal fluid-filled catheters connected to external pressure transducers, although small transducers have been used to measure pressure changes directly (Fyke and Code, 1955; Millhon, Hoffman, Jarvis, Cross, Millhon, and Crites, 1968). With infusion, fluid-filled catheters can measure the force with which the lumen has been obliterated ('squeeze') (Pope, 1970). Wave velocity and the presence or absence of peristalsis can be established with more accuracy than is possible by the use of radiographs.

The force transducer allows measurement of a new variable in the quantitation of oesophageal

smooth muscle activity. Although related to the intensity of squeeze as shown by Fig. 6, there are often wide discrepancies between squeeze and peristaltic force on any one swallow. High values for squeeze may coexist with low force values or the converse may be true.

Of physiological interest is the fact that force values vary widely at the same site from swallow to swallow, that the mean values of force obtained from different sites in the same oesophagus also vary widely, and that force profiles from different control subjects do not resemble one another. These same sources of variation are found when 'squeeze' is measured (Pope, 1970). Such variations demand that an adequate number of deglutitive responses be sampled and that the site of sampling be carefully defined. It is indeed fortunate that the force profile of any one individual when tested on different days remains constant, thus suggesting that effects of pharmacological agents or disease process might be able to be recognized as they disorganize a previously recorded force profile.

Even though force values in control subjects vary markedly, there are individuals whose force patterns are clearly different from those obtained from control subjects. These individuals are symptomatic in that they complain of dysphagia, often of many years' duration. Their symptoms are characteristic of an oesophageal motor disorder. Yet in the patients presented in Table I, radiographs failed to reveal an organic narrowing of the oesophagus and no abnormal motor activity was seen by the fluoroscopist. More sensitive manometric recordings failed to reveal any disorganized peristalsis. Force values clearly separate these individuals from control normal subjects. The series of these abnormal subjects is still too small to know if those with either abnormally high or abnormally low force values represent homogeneous groups. They clearly do not fit into any presently recognized clinical classification of oesophageal motor disorders. Objective proof of their motor dysfunction can only be

detected by measurement of force values.

The exact interplay between longitudinal and circular muscle responsible for these force values remains to be defined. Although the choice of sphere size remains arbitrary, this transducer offers an easily constructed stable device which can be accurately calibrated and whose geometry is known. Force values obtained by this transducer, although displaying a fair amount of variation between swallows, sampling site, and control individuals, are still able to detect individuals complaining of dysphagia whose other tests are normal. Preliminary experiments suggest that it can be used to quantitate muscular forces in other portions of the gastrointestinal tract such as stomach and small bowel. It is hoped that this new tool will allow further understanding of normal and abnormal gastrointestinal muscle function.

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