the human alimentary tract by the use of a capsule containing a pressure-sensitive transducer and radio transmitter is described.

The method exploits a difficulty inherent in this new technique, namely, that of the maintenance of the link between radio transmitter and receiver.

A technique for the combined recording of pressure change and movement of the capsule is described.

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Part II The application to the study of human gastro-intestinal motility

The clinical application of the combined method of recording intestinal pressure change and movement from a telemetering capsule is the substance of this section.

METHOD

Before the capsule[1] is swallowed it is calibrated against a simple water manometer by sealing it in a glass vessel containing water maintained at body temperature. The frequency shift of the emitted radio signal is noted as small pressure increments are applied by a hand bellows. The relationship between pressure change and frequency shift has usually been found to be linear up to values of 70 cm. of water above atmospheric pressure.

Before calibration the capsule is warmed to just above body temperature for about 30 minutes, and the transmitter is activated by withdrawing, through a hole in the body of the capsule, a plastic pin which holds apart the battery contacts. This hole also serves to equalize the pressure of the air trapped inside the capsule to the atmospheric value on the day of the clinical test. It is then sealed with moisture-resistant tape and a little silicone grease is applied to the plastic diaphragm to help to prevent absorption of moisture from body fluids, which can lead to a slight distortion after a long period of immersion.

Patients are invited to participate in the test; they should so far as can be ascertained have no narrowing of the alimentary tract. The capsule is swallowed one hour after a marker meal of bismuth or dilute barium. Five hours after the first marker meal, a second meal is consumed; the pill is located by relating it to the shadow of the second marker in the stomach or to the first, which should now be outlining the ileocaecal region (Smith and Ridgway, 1961). Two further radiographs are usually taken at about eight hours and 24 hours after the beginning of the test.

[1]The capsule was manufactured by Solartron Ltd.

Recordings may be made continuously or intermittently as the capsule passes along the alimentary tract. It is generally best to plan intermissions to allow the patient to relax in what may amount to a 40-hour investigation, but, if so desired, recording may be continued throughout meals and while the subject is receiving visitors.

The capsule is normally swallowed in the morning after a light breakfast; alternatively, it may be swallowed on the previous evening with a length of thread attached to it, of sufficient length to allow it to pass overnight through the pylorus. The test can then be started the next day with radiographic confirmation that the capsule is in the first or second part of the duodenum; delay caused by waiting for the pill to traverse the pylorus is thus avoided.

A secondary site of delay after what is usually a fairly brisk transit through the small bowel may be encountered at the caecum. The capsule then passes along the colon until delayed at the rectum before being expelled. The patient's stools are collected until the capsule is identified and recovered; this is made easier if the capsule is passed before the battery activating the transmitter is exhausted. The battery life is variable, depending on the nature of the capsule components, but is usually between 35 and 70 hours.

RESULTS

STOMACH The stomach shows little or no phasic pressure activity when the capsule is lying in the

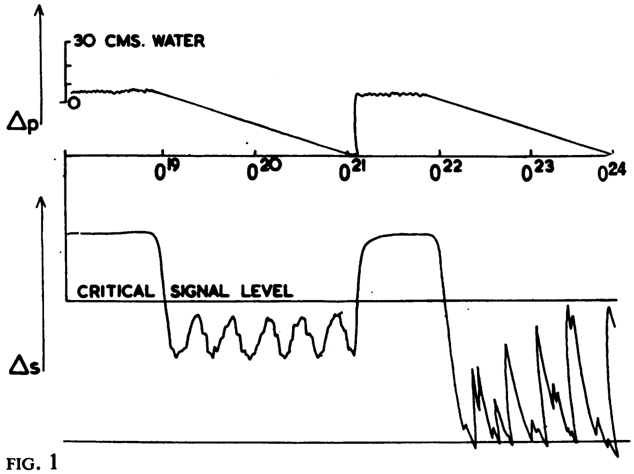

FIG. 1

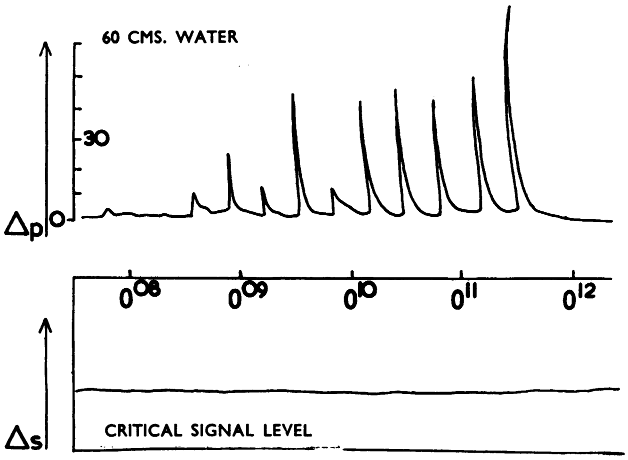

FIG. 2

FIG. 1. *Part of a recording made from a capsule lying in the body of the stomach. The upper trace ($\triangle p$) is of the intraluminal pressure sensed by the capsule, the pressure calibration being shown as water gauge above atmospheric; the lower trace ($\triangle s$) shows relative changes in signal strength resulting primarily from orientation changes between the capsule and the external aerial loop. The signal strength must be maintained above the critical level to record pressures. Each interval on the horizontal time scale, which is divided into intervals labelled in hours and minutes, represents 1 minute. In the two periods shown where pressure is recorded it can be seen that no appreciable phasic pressure changes occur, yet the periods 0^{19} to 0^{21} and 0^{22} to 0^{24} recording movements from the 'edge' of the field show regular three per minute muscular contractions.*

FIG. 2. *A typical sequence of pressure waves occurring with regular frequency at three per minute; these waves are seen as the capsule approaches the pylorus.*

fundus or the body. In Fig. 1, which is part of a recording performed from the body of the stomach, no pressure changes are seen when using the best orientated loop on the plateau of the capsular field; but on switching to a loop placed at the 'edge' of the field, the capsule is seen to be undergoing regular 20-second rhythmic movements. This effect may be due to contractions which are too weak to change the pressure within the viscus in the vicinity of the capsule, being waves of non-occluding type which allow easy equalization of pressure in the lumen proximal and distal to the wave. Another possibility is that the pyloric sphincter remains open, in accord with the view of Werle, Brody, Ligon, Read, and Quigley (1941) and reviewed by Jamieson and Kay (1959) that the pyloric sphincter remains open most of the time and closes only when an antral contractile wave approaches it.

As the capsule passes from the oesophagus to the stomach there may on occasion be very sharp pressure waves. These may be repeated several times, and are known as 'injection waves'. Phasic pressure activity is seen much more often in the antral or pyloric region; Fig. 2 illustrates a typical sequence of pressure waves after antral contractions occurring with the regular frequency of three per minute. Sequences of waves which are of greater amplitude are also seen; these may have a longer period between them, being one to two minutes apart, are associated with the passage of the capsule through the pylorus and may then be known as 'ejection waves'. On recording movements from a position at the 'edge' of the field, on the right of the abdomen, the strength of the signal will be found to increase as the capsule moves to the right.

DUODENUM AND SMALL INTESTINE Passage into the duodenum is often marked by the onset of complex

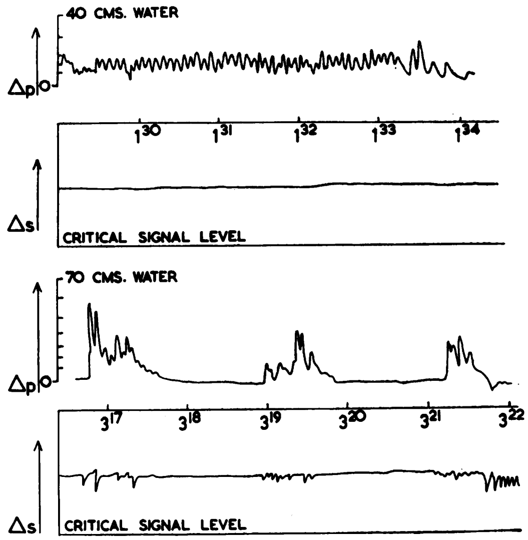

FIG. 3. *Upper: a four minute sequence of sustained type I pressure activity recorded from a capsule in the jejunum. The frequency shown of 12/13 per minute is characteristic of the upper small intestine.*
Lower: a different form of small bowel pressure activity recorded from a site lower in the ileum. Sustained type III pressure increments of about one minute's duration are seen with smaller type I variations superimposed. Note that some movements have occurred, as seen from the lower (△s) trace, during this period.

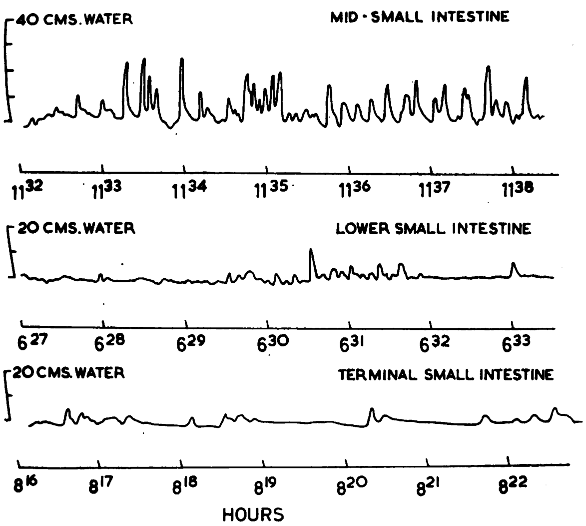

FIG. 4. *A series of recordings from different levels of the small intestine showing relative values for pressure activity at these levels.*

multi-periodic pressure waves with irregular movements as the capsule moves to the right to leave the stomach; the basal pressure may rise as the capsule enters the duodenum. (In one or two instances this sequence of changes has been observed, but has been succeeded by the resumption of wave patterns indicative of gastric activity. The pill must have moved backwards from the duodenum into the stomach.) The capsule then moves quickly round the duodenal loop to the left to reach the upper small intestine.

Figure 3 shows records obtained shortly after the capsule entered the small intestine and may therefore be assumed to have the characteristics associated with upper jejunal activity. The upper tracing shows type I and the lower are type III waves, with type I superimposed on them. The description of these wave forms follows the classification devised by Templeton and Lawson (1931) and subsequently generally adopted by most workers. In both instances the signal level is also shown. In the upper record the activity of the bowel was not accompanied by visible alteration of signal level but this does not necessarily mean that movement has not occurred. It is much more likely that in this position of the aerial loop relative to the capsule the effect has been minimized. (Figure 6 of Part I illustrates the converse of this, that change of movement may be detected, but that by choosing another site in the 'plateau' part of the field phasic pressure can also be displayed.) It may be added that a difficulty in development of our combined method is that at this stage recording from the 'plateau' and from the 'edge' of the field may not yet be done simultaneously.

In general, the pressure waves occur more frequently in the jejunum than in the ileum (Fig. 4). In the uppermost reaches of the jejunum the pressure changes during activity follow one another more rapidly than they do further down the intestinal tract. At lower levels the pressure changes decrease in amplitude. In the ileum both amplitude and frequency lessen markedly, and as the capsule approaches the end of the ileum its rate of progress may be inferred approximately from the relative nearness of the capsule to each of the four abdominal loops. As it approaches the ileocaecal valve 'to-and-fro' movements may be recorded by observing the changing signal level with progression towards the right side, when recording from the 'edge' of the field (Fig. 5). This is in contrast to the immobility of the capsule seen immediately after it has passed through into the caecum. Large increments of basal pressure may be built up in the terminal ileum; at other times the capsule may pass through without significant change of pressure being detected.

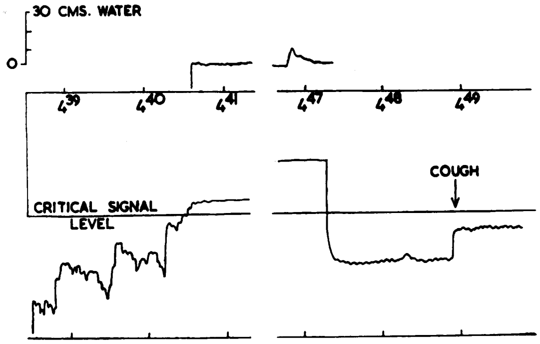

FIG. 5. *Movement recorded from a capsule as it approaches the ileo-caecal valve (left) with that ordinarily seen shortly afterwards, when the capsule has passed into the caecum (right).*

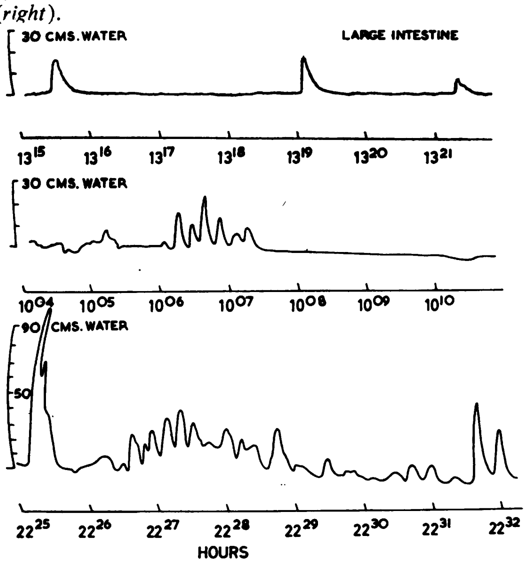

FIG. 6. *Three examples showing the variable nature of pressure activity normally recorded from a capsule in the large intestine.*

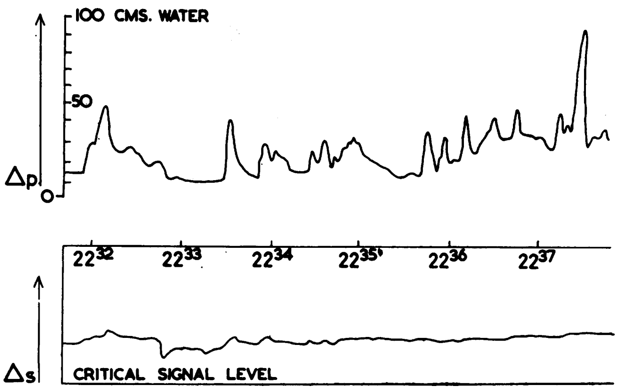

FIG. 7. *Complex build-up of pressure in the left colon recorded in the morning shortly after breakfast.*

COLON In the caecum (Fig. 6) there are generally longer periods between bursts of activity. The most common colonic change is the type II wave occurring at a frequency of about two per minute, though type I and type III waves also occur quite frequently. The latter are waves of a much higher amplitude than in the small bowel. Figure 7 shows complex phasic activity in the left colon just above the rectosigmoid junction. In this case the large irregular waves are followed by a gradual build up of basic pressure. Heightened activity of this type can often be seen before defaecation in the morning. In the left colon, where the contents are more dense, pressure changes appear to be of greater amplitude and to build up slowly; the signal strength (Fig. 7) may be unaltered. This may indicate that pressure activity in the colon is not closely linked with propulsion. Basal pressure in the left colon may fall when flatus is passed.

In general, we have been impressed by the irregular onset of intestinal motor activity, as far as can be judged from the assessments made at a single site, and by the long spells of inactivity which follow after it. Activity tends to follow meals, while inactivity may occur for long periods, throughout the alimentary tract, during sleep.

ARTEFACTS When evaluating the results of this method care has to be taken to distinguish true local pressure changes and changes which reflect merely the overall trend in intraluminal pressure, as influenced by various extraneous factors.

The technical artefact of overcoupling was discussed in Part I.

In some viscera which are adjacent to each other, pulsation may be transmitted from the wall of one viscus to the other. Although in the ascending colon phasic activity is very variable from subject to subject, it is unusual to record pressure or orientational change of as great a frequency as in the small bowel. The fact that such waves are also not generally seen in more conventional tube methods of studying intestinal activity leads us to the belief that these effects might be due to pulsation transmitted from other organs. We have often seen the effects of gastric activity transmitted to a capsule lying in the transverse colon. However, waves of higher frequency than this have been detected from time to time. Cardiovascular impulses may have been transmitted giving rise to quite unrecognizable fast wave forms, the frequency of which are too high for the present recording system. These effects have been seen during the passage of the capsule along the oesophagus near to the aortic vessels (Fig. 8) and in the rectosigmoid when the capsule is alongside the iliac vessels (Fig. 8); they appear transiently and

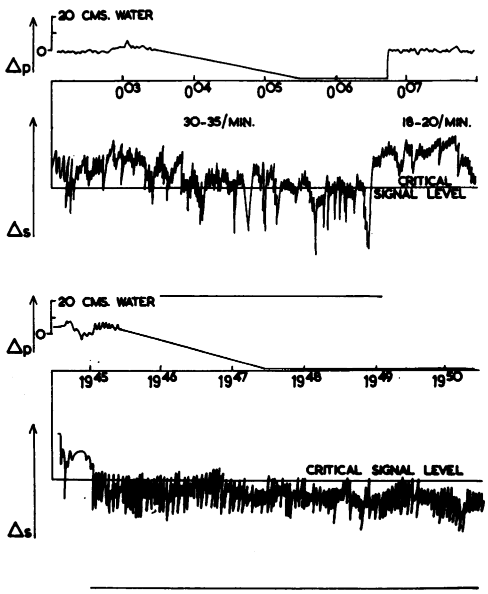

FIG. 8. *Two examples of very rapid orientational effects recorded from a capsule lying in the oesophagus (upper record) and from a capsule in the recto-sigmoid region (lower record).*

are easily recognized. The fast nature of the waves suggests, however, that it may alternatively be the expression of mass movements.

Sudden changes of intra-abdominal pressure, as when coughing and straining, lead to sharp rises in intraluminal pressures. Sometimes when recording from the colon, a slight rise in basal pressure is seen as the bladder distends before micturition, with a corresponding fall afterwards. Movements related to the respiratory excursion of the diaphragm may distort the record when the capsule is in the transverse colon. The rhythmicity of this may easily be checked by recording from the 'edge' of the field when the rhythmic to-and-fro movements of the capsule can be observed. The periodicity of the movements is respiratory, but is not always in phase with the diaphragmatic excursions; perhaps this is due to transmission of the effects from the diaphragm to the transverse colon, especially to the swinging movement set up if the colon is pendulous, since the timing of the movement seems to lag a little behind that of respiration.

DISCUSSION

A method of measuring pressures in the alimentary tract using a telemetering capsule has been extended to record movement of the capsule as well as the phasic pressure changes.

Continuous recordings of movement and pressure is useful at certain locations, notably in relation to passage through the sphincters. Near the pylorus characteristic sequences of classical antral pressure waves occur; the onset of irregular movements soon after this becomes associated with multiperiodic waves typical of small intestinal motility. Passage through the ileo-caecal valve is characterized by sudden cessation of movement after bursts of brisk transport. The capsule appears to have moved to the right. Typical ileal waves are replaced by the caecal ones which are larger and very much less frequent. These in turn are predominated by type II waves which are the most common wave forms in the colon and are not propulsive.

As recorded by this technique, the clinical interpretation of the basal pressure level is not yet clear and emphasis is placed on the phasic nature of the changes. Because of the use of expendable units, it is only occasionally practicable to do a second check on the behaviour of each capsule *in vitro* after it has been passed. The basal pressure level varies also with changes in the hydrostatic pressure in the abdominal space surrounding each particular digestive organ; this can change quite markedly with traction on various tissues, with postural effects, and with changes in atmospheric pressure.

At two sites in particular, movement or orientational change alone may be more informative than pressure recording and could probably be used to indicate whether the muscular activity of the organ is within normal range or not. These sites are the body of the stomach and the caecum where the contractions may not always be sufficient to occlude the lumen and induce typical pressure waves. In a large number of subjects constant rhythmicity of contractions has been observed over long periods, with little corresponding pressure change. This response of 'movement without pressure' could also be due to a change in shape rather than volume of the stomach, or to the escape of gastric contents through the pyloric sphincter. In the caecum the most characteristic feature is the quiescence seen after the much more brisk activity in the small bowel.

It is also possible that at times the capsule may be lying with its sensing end close to the mucosal wall. In such an event, the small intestinal effects could be exaggerated, and it is interesting to note that sometimes movements can apparently be transmitted from adjacent vessels, from small intestine to large bowel, and in particular from the diaphragm to the stomach and the colon.

SUMMARY

A method for recording the phasic pressure changes that occur during gastro-intestinal digestive activity is described, along with an additional technique for relating this information to short-term orientational changes, as recorded by variations in the coupling between the transmitting capsule and a simple aerial loop placed over the abdomen.

The pressure wave forms and movements recorded from stomach, pylorus, small intestine, ileocaecal valve, and colon are described.

Artefacts due to transmitted movements and the effects of changes of intra-abdominal pressure are also mentioned.

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