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Papers

Physiological Concepts of the Pylorus[1]

by D A W Edwards MD MRCP (*London*)

This paper concerns the physiological behaviour of the segment of muscle between the body of the stomach and the duodenum. This segment includes the pyloric antrum and the pyloric ring or valve but cannot be accurately defined because there is no precise proximal anatomical limit; the distal limit is the beginning of the cavity of the duodenal cap.

Part of this muscle is sometimes called the pyloric sphincter. The definition of a sphincter given in the Concise Oxford Dictionary is 'a muscle surrounding and serving to close an opening'. Because of the way our anal and urethral sphincters work we are sometimes inclined to have a special interpretation of this word which influences our idea of the action of the pylorus. We think of a muscle band that closes an opening and keeps it closed, occasionally relaxing to let something through. Although the cricopharyngeal and cardiac sphincters behave in this expected fashion, the pylorus does not.

The behaviour of a sphincter can be demonstrated by manometry. The aim is to measure the pressure in the lumen of the gut and demonstrate a zone where the force imposed by the wall is greater and so closes off this segment from the rest of the gut tube. This can be done either with an open-ended tube or a miniature balloon. The open tube will not record any excess pressure in the zone as long as the fluid contents can flow freely along the segment into the gut at either end (Edwards & Rowlands 1960). On the other hand, if the segment is squeezed tight, a rise of pressure may be recorded with the open tube which will measure the squeezing force. The miniature balloon records a different property of the muscle wall, namely its resistance to being stretched by the balloon. These two methods give us a way of measuring both the positive squeezing power of a muscle structure and its power of remaining in a particular shape without actively compressing the contents of the lumen, which is a measure of the rigidity or plasticity of the muscle.

The method used is to pass the recording tips of the tubes beyond the segment of gut to be studied, and then to withdraw the tips in 1 cm steps, recording the resting pressures and the changes produced by activity of the segment at each step.

The cricopharyngeal sphincter is an example of a striated muscle sphincter which is closed all the time except during a swallow, when the continuous shower of impulses from the brain-stem stops and the muscle relaxes to allow the bolus to be pushed through by the contraction of the pharyngeal constrictors. Andrew (1956) has demonstrated the interruption of the motor impulses to the muscle in the rat, and Doty & Bosma (1956) have recorded electromyogram potentials from the various muscles involved in swallowing in the dog, illustrating how the high resting tone of the sphincter relaxes at the right moment as part of the complicated reflex process of swallowing.

The pressure record from the cricopharyngeal sphincter in man shows a high resting pressure of about 40 cm water with an open tube (Fyke & Code 1955) which falls for about 0·5 sec to the intra-œsophageal pressure during a swallow, rising again with an overshoot. The cardiac sphincter is a plain muscle structure which behaves in a similar way except that the time relations are about ten times slower. As the tip of the recording tube is drawn up from the stomach the resting pressure with an open tube rises to an average of 3 cm water above the fundus pressure for a distance of 2–4 cm, recording the positive squeeze of the muscle segment. A 3 mm diameter balloon, 10 mm long, also records a high resting pressure in the same region, averaging 10 cm water, and records the resistance of the wall of the segment to being distended to 3 mm bore. Both the open tube and balloon high resting pressures fall to the surrounding basal pressure about 1·5–2 sec after the pharyngeal phase of swallowing, remain low for a few seconds, and rise again with an overshoot as the peristaltic wave moving down the œsophagus reaches the sphincter (Atkinson *et al.* 1957).

The essential features of these two sphincters are that: (1) They are formed by a segment of the wall of the gut tube, which has a separate innervation. (2) The muscle is tonically contracted, keeping the lumen tightly closed. (3) This tonic contraction relaxes for a short and definite period of time to allow a bolus to be pushed through.

In 1956 the same method of study was applied to the pylorus (Atkinson *et al.* 1957) and in 1959 the experiments were repeated with Dr K Skyring. An open tube was pulled through the pyloric seg-

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ment from the duodenum a total of twenty-nine times in 18 fasting normal subjects and seven times in 5 normal subjects with a full stomach, but on no occasion was any evidence found of a segment with a sustained rise of squeeze pressure like that found in the cricopharyngeal and cardiac sphincters.

It seemed possible, although unlikely, that the pyloric segment was so short that an open tube or a single miniature balloon might slip through and simply record a short blip on the tracing. To overcome this possibility we used a chain of four 7 mm diameter balloons, recording synchronously, which were arranged in such a way that there was no part along a 5 cm long cylinder that could not record a laterally applied force. This balloon chain was pulled through the pyloric segment in 1 or 2 cm steps so that at some stage the chain must have straddled the pylorus. Although this cylinder was pulled through twelve times in 7 normal fasting subjects and seven times in 6 normal subjects with a full stomach, again no segment with a sustained resting pressure, due either to squeeze or to resistance to stretch, could be demonstrated. Under the conditions of this experiment the pyloric segment did not significantly resist being distended to a bore of at least 7 mm most of the time, and was clearly not a tonically contracted muscular ring, keeping the lumen tightly closed.

Dr Skyring and I carried out a second series of experiments in 1959 with larger balloons of 10, 12, 15 and 20 mm diameter in an attempt to measure the bore of the pyloric channel and its capacity to be distended without resisting. The balloons were passed into the duodenum in 4 subjects, inflated with a measured volume of air, and drawn back in short steps in a total of 8 series of withdrawals.

The 10 mm balloon occasionally produced a rise of pressure, the 12, 15 and 20 mm more frequently. On some occasions it was not possible to pull the 15 and 20 mm balloons through from the duodenal cap and the balloons were deflated before they could be withdrawn. On one occasion the 10, 12 and 15 mm balloons recorded a rise of pressure as they came through the pyloric segment, indicating that the wall was resisting their distending force, but a few moments later the 20 mm diameter balloon slipped through without a rise of pressure, showing that the muscle had relaxed again. These two series of experiments suggested that, in the conditions of the experiment, the pyloric channel, most of the time, offers little or no resistance to being stretched to 7–12 mm diameter or even occasionally up to at least 20 mm diameter.

The emphasis is on *most of the time*. The pylorus closes firmly at times. In the experiments in which a cylinder of four balloons was pulled through the pylorus, the pyloric region itself could be identified on the tracings because the tracing from the duodenal cap is characterized by bursts of short based spikes, and the tracing from the pyloric antrum by broad based pyramids occurring three times a minute. About every 60–90 sec a giant wave, 50–100 cm water high, lasting about 5 sec, appeared in all four tracings simultaneously, involving the pyloric antrum, the pyloric segment, and the proximal part of the duodenal cap. This type of activity appears in bursts during much of the time of recording from the pyloric channel, but the frequency of the bursts over periods of an hour or more has not been determined, nor is it known whether the behaviour of the segment is influenced by the presence of the recording tube. These waves must squeeze the antrum-pylorus-duodenal cap segment approximately simultaneously, and in doing so would force the contents of the segment out in both directions, back into the stomach and forward into the duodenum.

Discussion

It seems possible that this rhythmic contraction might have a pump-like action, filling in diastole from the stomach and emptying in systole in both directions, squirting the contents of the segment, with at best a 50% efficiency, into the duodenum. The basal pressure in the stomach and duodenum is determined largely by the hydrostatic pressure due to overlying viscera and in pressure records is constant over long periods of time so that there is no gradient of basal pressure between the stomach and the duodenum. Filling of the pump in diastole from the stomach may therefore depend upon gravity or phasic changes in antral pressure. The duodenal lumen is continually subjected to phasic changes of pressure, produced by contraction of its wall, which are propulsive and which can be demonstrated by manometry, or their effects seen at fluoroscopy. Occasional bursts of retroperistaltic activity can be shown by these methods but most of the time the duodenum empties itself rapidly in a forward direction, acting as a continuously moving conveyor belt, and it is this action which is most likely to form a non-return valve for the pyloric segment pump.

For these reasons the following concept of the pyloric segment is suggested: the pylorus is a thick-walled connecting piece between the stomach or hopper and the small intestine or conveyor belt, which acts in two distinct ways: (1) It acts *statically* as a filter by virtue of the relative narrowness of its bore, holding back lumps of food, but capable of varying its bore from nothing to 20 mm or more like a long iris diaphragm. (2) It acts *dynamically* as a pumping machine which provides one of the important motive powers for emptying the stomach. It does not therefore prevent gastric emptying by acting as a sphincter in the way that the cricopharyngeal and cardiac sphincters work, but promotes gastric emptying by acting as a pump.

How can these experimental findings be reconciled with the radiological appearance of the pylorus? There are some points of agreement; the fluoroscopic appearance of the behaviour of the pylorus is quite different from that of the cricopharyngeal and cardiac sphincters; barium does flow through the pylorus most of the time; and the barium column can be seen to vary its width from nothing to a wide channel. The main points of difference seem to be first, that the pyloric shadow appears narrow or obliterated more often than might be expected from the pressure tracings; secondly, that movement of the shadow occurs giving the appearance of barium being pushed by a gastric peristaltic wave against a closed pylorus, or the pyloric antrum appears to balloon out proximal to a constriction; and thirdly that barium sometimes flows into the duodenum without detectable pumping action of the pylorus, and will do so after a pylorectomy. The following discussion is an attempt to find a way out of these difficulties and explain the radiological appearances.

The pyloric segment has an inner circular layer of fibres, and an outer longitudinal. The circular fibres are increased in number and commonly bunched up to produce a thickening of the wall of the segment about 2 cm along the lesser curve side and about 4–5 cm along the greater curve. Formalin and rigor mortis make these fibres contract giving the familiar dissecting-room and pathology-pot appearance of a well-defined thick ring of muscle, but sometimes at laparotomy or at autopsy it may be difficult to distinguish any local thickening, and the pyloric region must be identified by the pyloric vein. Some of the longitudinal fibres continue into the duodenum, but the deeper layers are turned inwards to be inserted into the circular layer in the region of the pyloric ring. When the circular fibres contract the lumen will be narrowed, and when the longitudinal fibres contract the muscle will be bunched and the lumen encroached upon. It is possible that those longitudinal fibres which are inserted into the circular fibres at the pyloric ring may be able to open the ring, but they could only do so by contracting against the resistance to compression of a distended pyloric antrum as though they were pulling round a pulley wheel. The important point is that there is otherwise no active process which will pull open the lumen of the pyloric segment or the duodenal cap; the lumen can be widened only by an adequate pushing force from within the lumen. After active contraction with change in shape the muscle may remain fixed, resisting any attempt to stretch it, behaving like a rigid structure; or it may relax its tone, giving way to any pressure which can overcome the viscosity of the muscle, exhibiting plasticity again. The important feature of this mass of muscle seen at fluoroscopy is that it is a relatively formless, writhing, fluid mass, constantly varying its shape, relaxing and contracting in all directions, behaving in a manner quite different from that of the cardiac sphincter.

This property of writhing contraction with alternate rigidity and plasticity may explain the first point of difference, the frequency with which the barium shadow is narrowed or nipped off. Fluoroscopy shows the shadow changing its shape, but does not measure the forces involved in this process. Very little force may be required to change the shape of a bag of fluid, so little that if a miniature balloon opposed it, there would be no detectable rise of pressure. A study of ciné-radiographs of barium moving in the pyloric region with simultaneous recording of pressure from a chain of balloons in the area has demonstrated this on four occasions. There may, therefore, be a narrowing of the barium shadow, but this does not necessarily mean a change of intraluminal pressure, nor does it necessarily mean that the muscle is exerting a powerful force either in promoting or obstructing the flow of barium. The second point in this connexion is that once the pyloric segment has been narrowed down by a positive contraction, the barium shadow will retain this shape until there is a pushing force from within the lumen which will broaden the shadow, or until the muscle is pulled into another shape. The discrepancy between the appearance of the barium shadow and the pressure record may be resolved in this way.

This point leads to the second and third difficulties, the failure of the shadow at the pylorus to move in the face of apparent forces, and the converse, the movement of barium from the stomach into the duodenum without any visible pumping action of the pyloric segment. The key to the understanding of these paradoxes is that flow requires a pressure gradient, but absence of flow may be the result of either a resistance to flow greater than the propulsive force, or simply a lack of a propulsive force.

Several forces might propel barium from the stomach or act to distend the lumen of the pyloric segment.

(1) *Gravity:* The amount of the gravitational force will be proportional to the height of the barium column and the difference between the specific gravity of the barium suspension and that of the surrounding tissues. The barium commonly used has a specific gravity of 1·2 and the abdominal viscera of 1·06. Theoretically a column of barium 10 cm high, in the abdominal cavity, will exert a differential pressure of $10 \times (1{\cdot}20-1{\cdot}06) = 1{\cdot}4$ cm water. The driving force of gravity is therefore often very small, but if the resistance to flow into the duodenum is negligible, because the duodenal wall is relaxed, this small force will be adequate to cause flow of barium. On the other hand, if the lumen is closed with a resistance to stretch of only 2 cm water pressure, this will be adequate to stop flow, but will not be detected with certainty on a pressure record.

(2) *The propulsive activity of the stomach:* The so-called peristaltic activity of the stomach, the deep-cutting waves which move down from the fundus, rarely if ever push barium forwards. During violent activity seen by fluoroscopy there may be no change in pressure in different parts of the stomach until the muscle is contracted down to a tight ring, completely occluding the lumen. This occlusion is a rare event except in the pyloric antrum, and the effect of the deep cutting waves is to agitate and mix the contents of the stomach but not to propel them.

(3) *The pyloric pump:* The pyloric antrum contracts about three times a minute, producing a rise of pressure in a miniature balloon. Every fourth, fifth or sixth wave is accompanied by a simultaneous contraction of the proximal part of the duodenal cap and the pyloric ring, forming the pyloric pump previously described. These waves seem to form the main propulsive activity of the stomach although they are clearly not essential to emptying since the stomach empties at approximately the same rate after a pylorectomy.

(4) *The duodenal or small intestine pump:* This process removes barium or food from the stomach by acting as a continually moving conveyor belt and is not, strictly speaking, a force propelling barium from the stomach. It is probably important after a Billroth I or Polya partial gastrectomy and after gastroenterostomy. It is only necessary for gastric contents to seep into the small intestine lumen for them to be carried away, and little or no gradient of pressure is required to feed the conveyor belt. The probable importance of this conveyor belt mechanism is illustrated by the marked delay in gastric emptying which occurs in systemic sclerosis when the plain muscle of the duodenum and small intestine is atrophic so that this part of the gut becomes immobile, although the stomach itself remains active.

These are the forces which may be involved in promoting emptying of the stomach. Resistance to flow may be produced by resistance to stretch of the pyloric segment or pyloric ring, or by the duodenal cap or beyond. The forces involved may be only a few cm of water pressure, but they may be adequate to withstand the propelling forces.

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Some Radiological Aspects of Pyloric Disease

by David Edwards MRCP FFR (*London*)

The stomach was subdivided into four parts on a histological basis by Aschoff in 1923. He named the zones the cardia, the body, the vestibule and the pylorus. The term vestibule is not now frequently used and has largely been replaced by the anatomical term the pars pylorica or the pyloric antrum. In such an easily distensible organ as the stomach these subdivisions do not form well-marked anatomical entities but it is generally accepted that the pyloric antrum represents that portion of the stomach which lies distal to the incisura; this only approximately defines that region of the mucosa containing the pyloric glands. Its size and shape varies greatly with the patient's build and the degree of distension of the stomach. Distally the pyloric antrum narrows down to form the pyloric ring, a passage of uniform diameter with a sharply defined termination in the base of the duodenal cap. An attempt was made to define the length of the normal pyloric ring by examining 70 consecutive, normal barium meals in which the limits of the ring appeared to be sharply defined. The mean length of the ring was 6·7 mm with normal limits of 1·0 to 12·0 mm. Any pyloric ring which exceeds 12 mm in length should be carefully examined with grave suspicion.