The functions of the pyloric sphincter are usually considered dependent upon the physical condition and relative degree of acidity of the gastric content. Such an explanation fails in great part to account for certain phenomena associated with the processes of gastric evacuation both in health and disease. It also fails to consider the purpose of gastric motility save for mixing the gastric contents and discharging them into the duodenum at irregular periods of opening of the sphincter. However, recent work tends to show that the opening and closing of the sphincter is related, not only to the degree of fluidity and acidity of the gastric content, but also to peristalsis and the degree of tonicity demonstrated in the stomach.

Our present interest in the physiology of the sphincter was stimulated by our inability to explain, upon accepted theories, radiographic observations made upon the human stomach. We therefore undertook to study, upon laboratory animals under easily controllable conditions, the motility of the pyloric sphincter. In this study the term pyloric sphincter means that narrow band of muscle constituting the last portion of the stomach.

METHODS

Forty-four experiments were performed upon dogs in this series. All operative procedures were carried out under ether anesthesia. Unanesthetized dogs were studied radiographically. In 14 experiments records were obtained immediately following operation and while the animal was under the influence of a light anesthesia. Six dogs were studied from 5 to 18 hours after operation, no anesthesia being used during the taking of records. One animal was studied 3 days after operation, another after an interval of 2 weeks. Four animals were
operated under ether and morphine (10 mgm. per kilo) and studied at once, ether being discontinued during the observations. This procedure gave a quiet animal with a very active stomach. Although the type of sphincter action under this anesthesia was similar to that obtained under other anesthetics, it was discontinued because of the known action of morphine upon the gastro-intestinal tract. The most constant graphic results were obtained with only sufficient ether to abolish voluntary movements. Under such an anesthesia the behavior of the sphincter is more constant and uniform than in the unanesthetized animal under experimental conditions.

The operations in most cases consisted in opening the abdomen by a midline incision, entering the fundic portion of the stomach and sewing the recording apparatus in place. The gastric incision was then closed with a purse-string suture about the rubber tube leading from the anchored balloon. The opening in the abdomen was closed with a running suture. Aseptic precautions were observed in all cases in which the animal was permitted to survive 12 hours or longer. In 3 animals the muscle on either side of the pyloric sphincter was cut, thus confining action upon the apparatus to the sphincter proper.

All apparatus except the recording instruments was designed and constructed especially for this work. The apparatus is the equivalent of a balloon and is so constructed that it can be placed and maintained within the lumen of the pyloric sphincter. These balloons, or as we have termed them, pylorographs, are of three types: a, flexible, closed pylorograph; b, rigid, closed pylorograph, and c, open, flexible pylorograph.

The closed flexible pylorograph (fig. 1, a) consists of a short section of finger cot stretched over two cones of hard rubber the apices of which face each other. One cone is perforated by a small hole which leads out through a nipple on its base for the attachment of a rubber tube. When in position the rubber is pressed down upon the sloping surfaces of the cones by the tonus of the sphincter to such an extent that the recording apparatus is affected by the contraction of a width of muscle not exceeding 5 mm. This device when placed in position tends to remain there because of the V-shaped surfaces offered to the pyloric ring. Complete fixation of the pylorograph was obtained by passing a ligature around the base of each cone and securing it in the muscle.

The rigid pylorograph is similar to the one described above save that the two cones remain connected (fig. 1, b).
The open, flexible pylorograph (fig. 1, c) is constructed on the same principle as the flexible, closed pylorograph except that an open tunnel 1 mm. in diameter runs throughout its entire length. The apices of the two cones are connected by means of a piece of rubberdam tubing.

Fig. 1. Illustrations of the various types of pylorographs. A, Closed flexible pylorograph. B, Closed rigid pylorograph. C, Open flexible pylorograph. V, Air transmission vent for tube connection with water manometer. F.C., Flexible wall of pylorograph made of finger cot. T., Opening connecting stomach with duodenum. R.D., Tube of rubber dam composing inner wall of air chamber. Dotted lines indicate positions of the rubber surfaces during contraction of the sphincter.

The bases are connected by a section of finger cot. This device, the equivalent of a tunnelled cylindrical balloon, permits the sphincter to demonstrate its motility and at the same time permits material to leave the stomach.
Graphic records were obtained with tambours, and piston and bellows recorders. The pylorograph was connected with the recording apparatus through a water manometer. The manometer was adjusted to a pressure (3 to 30 cm.) which gave best results in any given case. Air transmission was used throughout.

RESULTS

The pyloric sphincter demonstrates two types of motility; a, active rhythmic contractions (figs. 2 and 3), and b, tone waves (figs. 5 and 6). The characteristics of these two types of action are as follows.

a. Rhythmic contractions. The rhythmic movements of the sphincter are characterized by contractions and relaxations each followed by a quiescent period or pause (fig. 3). These contractions occur at the rate of from 3 to 5 per minute; that is, each cycle is completed in an interval of from 12 to 20 seconds. The phase of contraction is 4 to 5 seconds, the phase of relaxation 3 to 7 seconds; the quiescent phase plus the period of inhibition prior to contraction occupy the remainder of the cycle. These figures are necessarily only relative because of the different rates of contraction shown by various animals, the depth of the anesthesia, and also because of the general motility of the stomach and small intestines. During periods of rhythmic action of the sphincter the contractions and relaxations are uniform in degree; that is, the movements are initiated and consummated from a constant level (figs. 2 and 3). There is usually a definite degree of relaxation (inhibition) of tone immediately preceding a contraction. At times relaxation continues from the completion of contraction until the beginning of a second contraction, no definite phase of quiescence or inhibition being shown. Similar results were obtained both from the filled and recently emptied stomach.

The cycles of the sphincter are definitely altered under various conditions; also, periods of increased activity may occur; however, as will be shown in a later communication, such alterations bear a definite relation to anesthetics, trauma and the activities of the gastro-intestinal canal.

Rhythmicity of the sphincter is not lost following denervation of the stomach (fig 4).

b. Tonicity of the sphincter. The tonicity of the pyloric sphincter is gained or lost during a series of rhythmic contractions of which the heights of the individual contractions vary in proportion to the degree
Fig. 2. Pylorograms obtained from four different experiments; A, experiment 4; B, experiment 19; C, experiment 42; D, experiment 26. Animals under ether anesthesia. Graph A obtained with tambour, B and C with piston recorder, D with bellows recorder. Time, 2½ seconds in trace A, 1 second in B, C and D.

Trace A shows periods of inactivity followed by rhythmic contractions and alterations in tonicity. Traces B, C and D demonstrate periods of constant rhythmic activity. Note the variation in the height of contractions in traces A and D. The four graphs are typical of the entire series of experiments.

Note that the antrum has reached its maximum at the beginning of the sphincter's contraction, the latter reaching its greatest degree of contraction just as the antrum begins to relax.
of tonicity gained (figs. 5 and 6). On the other hand, periods of increased or decreased rhythmic contractions may appear at a time of constant tonicity (fig. 5, trace C). Waves of increased tonicity appear to result because of a lengthening in the time required for complete relaxation; that is, a second wave of contraction appears during the relaxation phase of the previous cycle. A reduction in the degree of tonicity accompanies an increased degree of lengthening of the relaxation phase of the rhythmic cycles, the rate of the rhythmic contractions remaining constant.

Fig. 4. Experiment 8; January 17, 1920. Rhythmic contractions of the pyloric sphincter following denervation of the stomach. Ether anesthesia. Time in seconds.

The rhythmicity and type of sphincter action are not altered by increasing or decreasing, within limits, the pressure within the pylorograph. However, if the pressure is greatly increased the height of the individual contractions is decreased. Longer excursions of the writing lever are recorded when the pressure in the pylorograph is low (3 to 10 cm. of water). In other words, the greater the degree of resistance offered by the pylorograph to the force of the sphincter's action the smaller becomes the excursion of the muscle while acting. The primary
RHYTHMICITY OF PYLORIC SPHINCTER

The effect of distention of the balloon in the pyloric canal is to excite the sphincter to rhythmic action. Following this there usually appears a gradual loss in tone for several moments after which the rhythmic contractions appear from a constant level. The rapidity with which the sphincter adapts its tonicity to an alteration in resistance is remark-

able. Apparently, the normal tonicity is only sufficient to close the sphincter or to approximate its surfaces against those of a body in its lumen. Non-resisting materials permit of complete occlusion of the lumen during the positive phase of the sphincteric cycle. Tonicity

Fig. 5. Experiment 24; February 9, 1920. Pylorograms obtained by use of open pylorograph. Animal operated under ether. Records begun 18 hours later. Piston recorder used for registration. Experiment checked by radiographic records. A, B and C, Sphincter action. C-C, Administration of 8 ounces of barium mixture by stomach tube. 1, 2, 3 and 4, Tone waves carrying contraction waves. Trace C shows three active and four reduced phases of activity.
of the sphincter appears to be unusually high immediately following the ingestion of food, either normally or by means of the stomach tube. Tonicity is also high immediately following the opening of the abdominal cavity. Doubtless this is reflexly the result of peritoneal irritation. Tonicity is not lost by reason of operative procedures on the stomach.

Fig. 6. Experiment 13; January 9, 1920. Ether anesthesia for operation. Double flexible enterograph. Records obtained 3 days after operation upon the conscious animal. A, Sphincter contractions. B, Duodenal contractions. Note periods of heightened tone of the sphincter at times of pronounced activity on the part of the duodenum (3 and 4). X, Synchronous points. Time in seconds.
The approach of the pylorograph or examining finger to the antral region causes marked contraction of the pars pylorica. Only under the influence of a deep or surgical anesthesia does the sphincter lose tone completely.

SPECIAL EXPERIMENTS

In dog 25 in which a permanent gastric fistula had been established, it was possible to insert the finger into the antrum and even through the pyloric canal into the duodenum without placing the animal under ether or causing it much discomfort. The primary effect of the finger in the antrum was to excite a state of violent and maintained contraction. Under a constantly applied pressure contracture passed off and the finger was finally permitted to pass through the sphincteric canal. With the finger in the canal one could distinctly feel pressure applied rhythmically during the positive phases of the sphincteric cycles. The sphincter never relaxed completely nor drew away from the finger during the relaxation phase or the period of quiescence. The observation that an initial irritation of the antrum causes a heightened degree of tonicity in the pars pylorica corroborates the generally accepted views as to the functions of these parts in relation to solid objects in the stomach.

In an effort to throw more light on the function of the sphincter the following experiment was performed. An open pylorograph (fig. 1, c), as described above, was anchored in the pyloric canal. Graphic records were begun 18 hours following operation (fig. 5). At this time the sphincter demonstrated powerful contractions which occurred irregularly. The animal was then placed on the radiographic table and given an 8-ounce meal of barium sulphate and milk by means of the stomach tube. Immediately following the withdrawal of the tube a marked tone wave appeared on the graphic tracing, superimposed upon which was a series of contractions of varying degree (fig. 5, A-I). This was followed by a series of smaller waves each of which lasted from 3 to 7 minutes. Four such tone waves are shown in tracings A and B of the same figure. As previously stated, these tone waves are built up during a series of rhythmic contractions and lost through a series of gradual and prolonged relaxations. At X in figure 5 a series of relaxations permitted the recording lever to drop below the tone level held by the sphincter prior to the administration of the meal. At points marked Y and Y-1 there is a total absence of rhythmic contraction although the tonicity of the sphincter at Y-1 is markedly above
that at Y where the level is lower than the pre-meal normal. A radiogram taken at the height of a rhythmic contraction (P.1), and at a time of relatively high tonicity, showed the antrum in a state of high tonicity with the pyloric canal closed. As time went on these severe tonic contractions gradually gave way to a constant tone level and rhythmic contractions of varying height (fig. 5, c). The stomach emptied itself of the barium mixture in less than 80 minutes. At the end of this time a second meal was given. Rapid distention of the operated stomach easily produces vomiting. This difficulty was overcome by using a small catheter as a stomach tube. The type of sphincter action shown in tracing C was continued for 4 hours, at the end of which time the stomach was completely free from the second meal.

Fig. 7. Experiment 27; February 19, 1920. Ether used throughout experiment. Records begun immediately following operative procedures. Tambour myograph and piston recorder used to obtain graph. Because of construction of the myograph the contraction phase is recorded as the downstroke; relaxation the upstroke. Note the regularity of contraction and the tone level changes.

This experiment seems of special interest because it demonstrates that a foreign body in the pyloric canal through which the gastric contents may pass does not alter the normal progress of gastric evacuation. Further, it supplies information from both the experimental and the radiographic standpoint which indicates that the sphincter is rhythmic in its activities. The development of tone waves in this case does not differ in character from those observed by other types of recording apparatus through which the gastric contents may not pass.

A third type of experiment was performed to check the graphs obtained by means of the closed and open types of pylorographs. In these experiments, three in number, a tambour myograph was attached to the exterior of the sphincter, the animal being immersed in a tank of warm saline solution. The type of rhythmic contractions and tone
waves shown in figure 7 are common to the three experiments, and they show no fundamental variation from tracings obtained with other types of apparatus. The animal (no. 27) from which this figure was obtained had been fed about an hour before the experiment started. Often a gurgling noise was audible as material was forced from the antrum into the duodenum, these occurring during a wave of contraction of the pars pylorica.

The results obtained from the various types of experiments and radiographic studies are similar to each other, therefore the movements described for the pyloric sphincter may be considered as representative of normal functioning of this organ.

DISCUSSION

The closure of the pyloric sphincter, according to the prevailing theories, results because of: a, the presence of solid masses in the antrum which mechanically excite the mucosa of this region; b, an insufficient acidification of the gastric content; and c, the presence of acid chyme in the duodenum. Following liquefaction and acidification of the gastric contents these mechanical and chemical stimulants cease and the sphincter relaxes to permit the ejection of chyme into the duodenum.

The theory of an "acid control of the pylorus" (Cannon) does not account for the rapid discharge of water and solutions of neutral egg white from the stomach, neither does it explain the rapid clearance of the stomach in certain pathological conditions. In part the theory of fluidity accounts for the rapid evacuation of the stomach following the ingestion of fluid masses. However, this does not explain the processes involved in the control of the sphincter. Granting that the two theories do explain a certain number of facts relative to the control of the pylorus, we still have to account for pyloric activity when functioning in the absence of acid. That is, something more than fluidity and acid is necessary to open the sphincter to permit the passage of material into the duodenum. Granting that the sphincter is open, all theories agree that peristaltic contractions in the stomach are directly responsible for the discharge of gastric contents. Hence it may be assumed that intragastric pressure and peristalsis bear some definite relation to the activities of the sphincter. That posture and peristalsis do act in such a manner as to facilitate the emptying of the stomach has been pretty definitely shown.
Neilson and Lipsitz (5) have shown that posture to a great extent determines the time of retention of water in the stomach. Individuals lying on their right side retain less of a given amount of water at the end of a stipulated time than individuals assuming other positions. Cole (2), from a study of serial radiograms of the human stomach, has shown that the activities of the sphincter bear a definite relationship to the activities of the antrum in that the amount of contraction of the sphincter is in proportion to the activity of the gastric waves. He has also shown that during the active phase (contraction) of every gastric cycle the pyloric ring is open and a small portion of the gastric contents is propelled through its lumen into the reservoir cap. The terminal wave (peristaltic) which has meanwhile been advancing toward the sphincter, upon attaining it, effects its closure. The recent article by Luckhardt, Phillips and Carlson (4) clearly demonstrates that both in man and dogs the pyloric sphincter opens for the ejection of chyme with the arrival at the sphincter of powerful advancing rings of contraction and a general increase in the tone of the musculature of the stomach as a whole. Their observations demonstrate that a more definite relation exists between the muscular activity and the opening of the sphincter than between the opening of the sphincter and the reaction of the gastric contents. Ivy (3) made the suggestion prior to the appearance of the paper by Luckhardt, Phillips and Carlson, that the rhythmic discharge of water from the dog’s stomach is such that it could very well correspond to peristaltic activity.

Such observations clearly demonstrate that the functions of the pyloric sphincter are dependent, in part at least, upon gastric motility. Our observations also tend to show that the sphincter because of its rhythmic type of motility acts in such a manner as to supplement gastric motility. Further observations to be reported later also show that the rhythmic contractions of the sphincter bear a definite and constant relation to the motility of the stomach (fig. 3).

SUMMARY AND CONCLUSION

1. A method is described for recording the motility of the pyloric sphincter.
2. The pyloric sphincter of the dog demonstrates rhythmic activity or cycles of motility which occur at the rate of from 3 to 5 per minute.
3. A single cycle of motility is characterized by a phase of contraction, relaxation and quiescence followed by a definite phase of inhibition prior to a subsequent contraction.
4. The sphincter demonstrates tone changes, such changes being gained or lost because of shortening or lengthening of the relaxation phase of the rhythmic cycles.

5. The observations here reported, therefore, show that the pyloric sphincter of the dog possesses the property of rhythmic contractility, the degree of which is influenced because of changes in tonicity.

BIBLIOGRAPHY

(1) Cannon: This Journal, 1898, i, 359; The mechanical factors of digestion, Longmans, Green and Co., New York, 1911; This Journal, 1907, xx, 283.


(3) Ivy: This Journal, 1918, xlvi, 420.

(4) Luckhardt, Phillips and Carlson: This Journal, 1919, l, 57