THE MOVEMENTS OF THE STOMACH STUDIED BY MEANS OF THE RÖNTGEN RAYS.¹

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SINCE the stomach gives no obvious external sign of its workings, investigators of gastric movements have hitherto been obliged to confine their studies to pathological subjects or to animals subjected to serious operative interference. Observations made under these necessarily abnormal conditions have yielded a literature² which is full of conflicting statements and uncertain results. The only sure conclusion to be drawn from this material is that when the stomach receives food, obscure peristaltic contractions are set going, which in some way churn the food to a liquid chyme and force it into the intestines. How imperfectly this describes the real workings of the organ studied by a new method. The mixing of a small quantity of subnitrate of bismuth with the food allows not only the contractions of the gastric wall, but also the movements of the gastric contents

¹ The first account of this work was given at the meeting of the American Physiological Society, in May, 1897 (see Science, June 11, 1897); and the later results were presented at the meeting of the Society in December, 1897. A summary of the results was published in the Proceedings of the American Physiological Society, this Journal, 1898, i, p. xiii. A report of the research was also made to the Boston Society of Medical Sciences, February 15, 1898.

² Poensgen (Die motorische Verrichtungen des menschlichen Magens und ihrer Störungen, Strassburg, 1882,) gives a comprehensive review of the literature to that date.
to be seen with the Röntgen rays in the uninjured animal during normal digestion. An unsuspected nicety of mechanical action and a surprising sensitiveness to nervous conditions have thereby been disclosed.

I. INTRODUCTORY LITERATURE.

The early writings on the subject of gastric movements are characterized by general inferences from physical laws and from the anatomical structure of the stomach. According to Galen,¹ the stomach had four functions: to draw the food from the mouth (facultas attractrix), to retain the food (facultas retenatrix) during the process of chemical digestion (facultas alteratrix), and, finally, to pass the changed material onward (facultas expulatrix). In later writings the facultas attractrix failed to appear as one of the functions of the stomach. Fallopius,² in the sixteenth century, changed the notion of the facultas attractrix by suggesting that the pylorus alone performed this office, and that the muscles of the gastric wall could help only by remaining quiet. Thus the facultas alteratrix and the facultas expulatrix are left as true gastric functions. It is with the latter activity and its effects that this paper is concerned.

The ideas of the early writers concerning the pylorus and cardia are of interest. The cardia, they were agreed, is closed during normal digestion in order to keep the food from re-entering the esophagus. The pylorus they looked upon as the ruler of the actions of the stomach. Such names as pylorus (keeper of the gate), janitor justus, and rector, which the first investigators gave to the sphincter, indicate their theories of its functions. The passage of chyme into the duodenum, the keeping of undigested food in the stomach, the act of vomiting, were all dependent, they believed, on the "will" of the pylorus.³

No substantial advance was made beyond these hypotheses until the beginning of the eighteenth century, when Wepfer and Schwartz applied the experimental method to the study of the gastric movements and laid the foundation of a more accurate knowledge. Wepfer iv vividly tested wolves, dogs, and cats, and observed constrictions following stimulation of the stomach. He remarked a general con-

¹ Galen: Opera omnia. Leipzig, 1822, iii, pp. 275, 281.
² Fallopius: Opera omnia; observationes anatomicae. Frankfort, 1600, p. 412.
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traction of the pyloric part in vomiting (pp. 152, 168, and 250), and noted peristaltic and antiperistaltic movements passing over the organ. About the middle of the stomach he frequently saw a deep constriction. The investigations of Schwartz are more valuable in that his search was for the normal action of the muscular coats. The movements, as he observed them, were generally only slight. They began either at the pylorus and passed to the left, half-way to the cardia, or started at the fundus and went to the pylorus. The contractions and relaxations, following one another, formed larger or smaller depressions and elevations, i.e., more or less definite waves.

Near the middle of the last century, Haller, after confirming the results obtained by Schwartz and Wepfer, summarized his knowledge of the motor functions of the stomach as follows: In general, contraction alternates with relaxation, so that the stomach is, now here, now there, made narrower by longitudinal or transverse depressions; then in these same places relaxation and bulging occur (pp. 260-262, and p. 276). So long as both apertures are closed the food is driven hither and thither by the shifting movements. It first takes a definite direction when the cardia or the pylorus opens. If the cardia opens, there is an antiperistalsis followed by regurgitation and vomiting (p. 281). If, on the contrary, the pylorus relaxes, a contraction, starting at the oesophagus, pushes the contents of the stomach into the duodenum. The pylorus allows the passage of fluids, but if it be stimulated by over distention or by hard pieces of food, it closes tightly (p. 277).

Such was the knowledge of gastric movements in Haller's time. A comparison of his descriptions with those in any standard work on physiology published ten or fifteen years ago will show that, despite very many researches, little advance had been made. Examinations of animals and men with gastric fistulas, studies of the stomach through the atrophied abdominal wall, and vivisection, have yielded numerous results, but these have not been harmonious, and have led to much controversy. Prominent in this mass of material as a valuable contribution are Beaumont's careful observations through the gastric fistula of Alexis St. Martin. Beaumont's work has recently been confirmed by Hofmeister and Schütz, who, with Rossbach, Hirsch, Openchowski, and others, have presented during the last twelve years

1 B. Schwartz in Haller's Dissertationes anatomicæ. Göttingen, 1746, i, pp. 337 338.
much new and interesting information. Since, however, it will con-
duce to clearness to set forth the results of these investigations in
connection with my own work, their consideration will be deferred
until later.

It will then appear that these later investigations, like the earlier
researches, disagree as to the details of the stomach movements.
Such differences in results are the proper outcome of the abnormal
conditions under which the studies have been conducted. Obviously,
in order to see the natural movements of the stomach, the organ
should be observed in its natural state, and not after it has been dis-
turbed by removal from the abdomen or by the adhesions and losses
of substance incident to gastric fistulas.

As a means of watching the gastric motor activities under normal
circumstances, Dr. H. P. Bowditch, in the autumn of 1896, suggested
the use of the Röntgen rays. The present paper is the result of the
work thus far completed. The kind assistance and stimulating
counsel of Dr. Bowditch throughout the investigation are gratefully
acknowledged.

II. THE METHOD.

The method consists in mixing subnitrate of bismuth — a harm-
less, non-irritating powder — with the food, and observing the move-
ments of the swallowed mass by means of the Röntgen rays. As is
now generally known, the picture thrown on the fluorescent screen
by the Röntgen rays is one of shadows of varying intensity; the
denser the substance, the darker the shadow. There is nothing in the
structure of the stomach to cause it to cast a different shade from that
of its neighboring organs. But the dense bismuth powder, uniformly
mixed with the food that fills the stomach, throws the dark shadow
of the stomach contents on the screen, and the changes in the shape of
the outlines indicate the intrinsic movements of the organ.

The animal used throughout the research was the cat. The meal
given before making an observation consisted of from fifteen to
eighteen grams of dry bread, softened to a mushy mass by milk,
hot water, or thin gravy, and mixed with from one to five grams of
subnitrate of bismuth, according to the purpose in hand. One or
two grams of the bismuth compound produce a dim shadow of the
stomach within which may be clearly seen the darker forms of food
containing a larger amount of the substance; three grams are
enough for ordinary observations; four or five grams are needed to
see the passage of food from the pylorus. The cat was usually kept from eating for at least twelve hours before an observation, in order that the stomach might be wholly free from contents transparent to the X-rays.

The construction of the holder on which the cat was tied is shown in the diagram (Fig. 1). It consisted of a framework supporting a sheet of black cotton cloth. The frame was made of two side pieces each 80 cm. long and 2.5 cm. square, connected at either end by blocks 2.5 cm. thick, 12.5 cm. wide, and 16 cm. long. The black cloth, which sagged for the comfort of the cat, was held by strips of wood nailed to the inner face of the frame. Through the side pieces were holes 0.6 cm. in diameter, and 5 cm. apart. Each of the leather nooses securing the legs went down through one of these holes, and up through another, in which it was made fast by forcing a pointed peg into the hole with it. The cat's head was held by two pegs, one on either side of the neck, joined above by a leather thong. One of the pegs was movable and could be put in any of the three holes, 3, 4.5, or 6 centimetres from the other peg, according to the thickness of the cat's neck.

For seeing the regular movements of the stomach the cat was tied back downward, with the fore paws in nooses at either side, and with the hind legs stretched out and fastened to the holder at the cat's right. For watching the passage of food from the pylorus, the hind legs were both fastened to the left side of the frame, so that the cat lay on her left flank. Most of the female cats would lie on the holder by the hour without making any attempt to break away or manifesting any signs of discomfort. In marked contrast was the behavior of the males. Almost without exception they seemed worried when fastened down. The interesting effects of these different ways of reacting to novel surroundings will be described later.

The cat-holder was supported at either end. Below it at a distance of 19 cm. was placed the tube generating the Röntgen rays. This tube had a self-regulating device for maintaining a uniform vacuum, —very useful in that it allowed long observations with rays of uniform intensity. A Töpler-Holtz machine, run by a small motor, produced the electrical discharge through the tube. This apparatus
was placed behind the holder. The light from the tube and the machine was shut off from the observer by drappings of black cloth, so that in the dark room where the work was carried on it was possible to use an open fluorescent screen with sides only two centimetres high. This plan was found especially valuable in that it permitted tracing the outlines of the stomach on tissue paper laid over the fluorescent surface.

III. THE ANATOMY OF THE STOMACH AND ITS RELATIONS TO THE SHADOW.

It must be constantly borne in mind that the shadows described in this research are cast by the gastric contents,—not by the stomach itself. Therefore the movements of the organ are not seen directly, but are indicated by their effect on the contained food. Variations in the length and breadth of the stomach can be inferred from changes in the outline of the shadow, but variations in the front-to-back diameter of the organ must be judged from changes in the intensity of the shadow.

The form of the active stomach soon after food has been taken is shown in outline in Figure 2. Since the several parts of the stomach are to be mentioned frequently, it will be well to recall them here in their relations to the outline. The larger, cardiac part of the organ lies to the left of a line through \( wx \). Into it the esophagus opens through the cardiac sphincter, or cardia, at \( c \). The pyloric part, which includes all of the stomach situated at the right of a line \( wx \), is closed by the pylorus at \( p \). This part has two divisions; the antrum at the right of the line \( y z \), and the preantral part of the pyloric portion, or middle region of the stomach, between the lines \( wx \) and \( y z \). The lesser curvature corresponds approximately to the anterior border of the shadow \( c \; w \; p \); the greater curvature to the more extensive sweep, \( c \; p \), along the posterior border.

The wall of the cat's stomach consists of three coats, but as this paper deals only with the functions of the muscular coat, that alone will be described. The gastric muscular fibres are disposed in three sets: an outer longitudinal layer, a middle circular layer, and a set
of inner oblique fibres. The longitudinal fibres continue those of the oesophagus, and, radiating over the cardiac end, become more marked along the curvatures than on the front and back surfaces. Over the antrum they lie in a thick, uniform layer. The circular fibres form a complete investment, and are arranged in rings at right angles to the curved axis of the stomach. Towards the pyloric end they become denser and stronger, and at the pylorus form a thick bundle, the pyloric sphincter. Separating the antrum from the rest of the stomach, at the 2/4, is a special thickening of the circular fibres, called by the early writers the "transverse band," and described by Hofmeister and Schütz as the "sphincter antri pyloricii." The oblique fibres start from the left of the cardiac orifice, and pass as two strong bands along the anterior part of the dorsal and ventral surfaces, giving off fine fasciculi to the circular musculature; towards the antrum they gradually disappear.

The musculature of the stomach consists of smooth muscle fibres, the chief physiological characteristics of which are slowness of contraction, rhythmic alternation of contraction and relaxation, and a very great tonicity, or power of prolonged contraction. The action of these muscles in the process of gastric digestion is now to be considered.

IV. THE NORMAL MOVEMENTS OF THE STOMACH.

Since the time of Haller the chief contributors to the knowledge of the mechanics of the stomach have been Beaumont, Hofmeister and Schütz, and Rossbach.

Beaumont's famous investigations on Alexis St. Martin are recorded in almost all general works on physiology. Through a gastric fistula he introduced a thermometer-tube and observed how it was affected by the motions of the stomach. His conclusions are as follows: "The circular or transverse muscles contract progressively from left to right. When the impulse arrives at the transverse band, this is excited to a more forcible contraction, and, closing upon the alimentary matter and fluids contained in the pyloric end, prevents their regurgitation. The muscles of the pyloric end, now contracting upon the contents detained there, separate and expel some portion of the chyme,. . . . After the contractile impulse is carried to the pyloric

extremity, the circular band and all the transverse muscles become
relaxed, and a contraction commences in a reversed direction, from
right to left, and carries the contents again to the splenic extremity
to undergo similar revolutions."

In close accord with Beaumont's description of the activities of the
human stomach are the records of the investigations on the stomach
of dogs by Hofmeister and Schütz. They removed the stomach
from the body and placed it in a moist chamber, kept at body-heat
and covered with glass. Under such conditions the organ remained
active for from sixty to ninety minutes. A typical movement is de-
scribed by these observers as composed of two phases. In the first
phase a constriction of the circular fibres, deeper on the greater cur-
vature, starts a few centimetres from the cardia and passes towards
the pylorus. As the constriction proceeds it increases in strength
until a maximum is reached about two centimetres in front of the an-
trum. This annular contraction, called by Hofmeister and Schütz the
"preantral constriction," closes the first phase. Immediately there-
after the strong sphincter antri pylorici, or transverse band, contracts.
Now, while the preantral constriction is relaxing, the sphincter antri
pylorici tightens still more, and the antrum is shut off from the rest
of the stomach. As soon as this has occurred a general contraction
of the muscles of the antrum follows. Relaxation begins at the
sphincter antri pylorici and progresses slowly toward the pylorus; it
is sometimes accompanied by an antiperistaltic movement.

Although Rossbach also used dogs his results vary considerably
from those of Hofmeister and Schütz. This discrepancy is possibly
accounted for by a difference in method, for Rossbach left the
stomach in the body. The dogs were treated with morphia and
curare, and the abdomen was then widely opened, so that the move-
ments could be clearly seen. When the stomach was full Rossbach
saw deep constrictions begin near the middle and pass in waves to the
pylorus. At first these movements were weak: later, however, they
became more vigorous. The fundus remained in tonic contraction
about its contents and took no part in the peristalsis.

Before attempting to explain the difference in the records of these
observers I shall give an account of what may be seen in a cat by
use of bismuth subnitrate and the Rontgen rays.

1 Beaumont: loc. cit., p. 106.
3 Rossbach: Deutsches Archiv für klinische Medicin, 1890, xlvi, p. 296.
I. Movements of the Pyloric Part. — Within five minutes after a cat has finished a meal of bread, there is visible near the duodenal end of the antrum a slight annular contraction which moves peristaltically to the pylorus: this is followed by several waves recurring at regular intervals. Two or three minutes after the first movement is seen, very slight constrictions appear near the middle of the stomach, and, pressing deeper into the greater curvature, course slowly towards the pyloric end. As new regions enter into constriction, the fibres just previously contracted become relaxed, so that there is a true moving wave, with a trough between two crests. When a wave swings round the bend in the pyloric part the indentation made by it deepens; and as digestion goes on the antrum elongates and the constrictions running over it grow stronger, but, until the stomach is nearly empty, they do not entirely divide the cavity. After the antrum has lengthened, a wave takes about thirty-six seconds to move from the middle of the stomach to the pylorus. At all periods of digestion the waves recur at intervals of almost exactly ten seconds. So regular is this rhythm that many times I have been able to determine within two or three seconds when a minute had elapsed simply by counting six similar phases of the undulations as they passed a given point. It results from this rhythm that when one wave is just beginning, several others are already running in order before it. Between the rings of constriction the stomach is bulged out, as shown in the various outlines in Figures 3, 4, and 5. The number of waves during a single period of digestion is larger than might possibly at first be supposed. In a cat that finished eating fifteen grams of bread at 10.52 A.M., the waves were running regularly at 11.00 o'clock. The stomach was not free from food until 6.12 P.M. During that time the cat was fastened to the holder at intervals of half an hour and the waves were always observed, following one another in slow and monotonous succession. At the rate of three hundred and sixty an hour, approximately two thousand six hundred waves passed over the antrum during that single digestive period.

From the above review, it will be manifest that my observations of the movements of the pyloric part agree closely with those of Rossbach, but differ considerably from the harmonious results of the work of Beaumont, and Hofmeister and Schutz. Beaumont's methods, however, may be justly criticised on the ground that the thermometer-tube which he held in the stomach was wholly unlike food and very liable to bring about unwonted contractions in so sensitive an organ
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as the stomach. Further, the movements observed by Hofmeister and Schutz, as Ewald has pointed out, may easily have resulted from the abnormal stimulus due to lack of blood—a potent cause of peristalsis. And it will be shown later that the accounts given by these investigators describe very well the actions of the stomach when stimulated by an unusual irritant. In this connection it may be added that since the publication of the preliminary notice of my work, Roux and Bathazard, using the Rontgen rays, have published the results of observations on the stomachs of the dog and man, similar to those thus far described in this paper.

The fact that my observations and those of Roux and Bathazard were conducted under normal conditions, and that the conditions of Rossbach's experiments were more nearly normal than those of the other observers mentioned, warrants the conclusion that the pyloric part has a more important function than that of merely expelling the contents of the stomach into the intestines. After summarizing the description given by Hofmeister and Schutz, Ewald, for a priori reasons, declares: "I cannot accept this view. The plain fact that the pyloric portion secretes a strongly digesting fluid containing pepsin and hydrochloric acid, proves it to be an important part for the pепtonizing function of the stomach." The account of the remarkable manner in which the pyloric portion performs this function must be deferred until the movements of other parts of the stomach have been considered.

2. Movements of the Pyloric Sphincter. — Rossbach mars his otherwise careful work by declaring that the pylorus is tightly closed during the whole digestive period of from four to eight hours; and that then the sphincter relaxes and the peristaltic waves empty the stomach. That this is not the normal action of the sphincter has been shown by several observers. Hirsch watched dogs with duodenal fistulas and saw food come from the stomach at intervals of one-fourth of a minute to several minutes. Roux and Bathazard

2 Cannon: Science, June 11, 1897, p. 902.
3 Roux et Bathazard: Comptes rendus de la soc. de biologie, 1897, 10 S, iv, pp. 704, 785, and Archives de physiologie, 1898, 5 S, x, p. 85.
5 Rossbach: Deutsches Archiv für klinische Medizin, 1890, xlvi, p. 317.
6 Hirsch: Centralblatt für klin. Medizin, 1892, xiii, p. 994.
7 Roux et Bathazard: Comptes rendus de la soc. de biologie, 1897, 10 S, iv, p. 705.
maintain that in dogs food enters the duodenum at the completion of each wave of constriction. Observations on the cat, however, do not support their view, but agree rather with the statement of Hirsch.

In cats fed with bread mixed with subnitrate of bismuth, ten or fifteen minutes elapse after the first constriction in the antrum before any food can be seen in the duodenum. When food does appear it is spurted through the pylorus and shoots along the intestine for two or three centimetres. Not every constriction-wave forces food from the antrum. On one occasion, about an hour after the movements began, three consecutive waves were seen, each of which squirted food into the duodenum. The pylorus remained closed against the next eight waves, opened for the ninth, but closed once more against the tenth and eleventh. For each of the four succeeding waves the sphincter relaxed, but blocked the food brought by three constrictions that followed: and in this irregular way the food continued passing from the stomach. Near the end of gastric digestion, when the constrictions are very deep, it may be that the pylorus opens for every wave.

When a hard bit of food reaches the pylorus, the sphincter closes tightly and remains closed longer than when the food is soft. This action of the sphincter was shown by giving with the regular food of the cat a dry, hard pellet of equal parts of starch paste and bismuth subnitrate, about the size of a pea. The food itself contained merely enough bismuth to throw a dim shadow, near the centre of which the pellet could be clearly seen as a dark object. The continual passing of the contraction-waves finally brought the little ball to the pylorus. When it arrived there, five grams of bismuth subnitrate were introduced into the stomach through a tube in the oesophagus. This was done in order that the food passing into the intestines after the ball came to the pylorus, might be distinguished from that which had gone on before. By kneading the stomach the bismuth was distributed, as shown by the uniformly black shadow. The pellet could still be seen near the end of the antrum when the constrictions passed over it. Now, although the waves continued to run regularly, the very black food did not gather in the intestines in sufficient amount to be recognized until forty-two minutes after it had been introduced. And when, finally, the food did show itself in the intestines, its shadow contrasted strongly with that of the food which had already passed on. The slowness of the expulsion is not to be regarded as wholly due to the
hard mass. No doubt the kneading of the stomach mixed the contents of different parts of the organ and brought to the pylorus food not yet sufficiently digested to be passed by that selective sphincter. But this does not explain the whole delay. Food similar to that given here except that it contained no hard particles has usually been seen as small masses in the intestines within fifteen minutes after being swallowed. A part of the delay was evidently, therefore, caused by the hard pellet. Further evidence on this point was secured when, on one occasion, the sphincter was seen to open only seven times in twenty minutes following the arrival of a hard particle of food at the pylorus. The conclusion may therefore be drawn that hard morsels keep the pylorus closed and hinder the passage of the food into the duodenum.

3. Activity of the Cardiac Portion.

The part played by the fundus apparently has not hitherto been properly appreciated. It has been regarded as the place for peptic digestion or as a passive reservoir for food; but it is in fact a most interestingly active reservoir.

The action of the cardiac portion will be best understood by comparing the appearances the stomach presents at various stages in a digestive period. In order to show these stages I carefully made a set of three tracings of the out-
lines of the stomach as soon as possible after a cat had finished eating, and another set of three every half hour thereafter, until the contents had disappeared (Figs. 3, 4, and 5). These tracings were made by placing white tissue paper over the fluorescent screen, and drawing with a thick lead pencil, easily seen, as much of the boundary of the stomach as I could at the end of each expiration. Between the times for making the drawings the cat was allowed to rest quietly on a mat, but care was taken to lay her in the same position on the holder for every drawing. The drawings of each set were afterwards fastened over one another, so that the lines coincided as closely as possible. Another piece of tissue paper was then put over these, and all four sheets were laid on an illuminated pane of glass. It was thus easy to get a composite tracing, which, considering the movement imparted to the stomach by respiration, and the dimness of the shadows in the later stages of digestion, probably represents more exactly than any single drawing the outline of the stomach for each successive period.

A comparison of these drawings shows that as digestion proceeds the antrum appears gradually to elongate and acquire a greater capacity, and that the constrictions make deeper indentations in it. But when the fundus has lost most of its contents, the longitudinal and circular fibres of the antrum contract to make it again shorter and smaller. Its change of form, however, compared with the rest of the stomach, is slight.
The first region to decrease markedly in size is the preantral part of the pyloric portion. The peristaltic undulations, caused by the circular fibres, start at the beginning of this portion, and gradually, by their rhythmic recurrence, press some of the contents into the antrum. As the process continues, the smooth muscle fibres with their remarkable tonicity contract closely about the food that remains, so that the middle region comes to have the shape of a tube (Fig. 4—1.30 P.M. to 2.30 P.M.), with the rounded fundus at one end and the active antrum at the other. Along the tube very shallow constrictions may be seen following one another to the pylorus.

At this juncture the longitudinal fibres which cover the fundus like radiating fingers, and the circular and oblique fibres reaching in all directions about this spherical region, begin to contract. Thus the contents of the fundus are squeezed into the tubular portion. This process, accompanied by a slight shortening of the tube, goes on until the shadow cast by the fundus is almost wholly obliterated (Fig. 5—5.30 P.M.).

The waves of constriction moving along the tubular portion press the food onward as fast as they receive it from the contracting fundus; and when the fundus is at last emptied they sweep the contents of the tube into the antrum (Fig. 5—5.00 P.M. to 6.00 P.M.). Here the operation is continued by the deeper constrictions till finally (in this instance, at 6.12 P.M.) with the exception of a slight trace of food in the fundus, nothing is to be seen in the stomach at all.

The food in the fundus may possibly be
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Slightly affected by the to-and-fro movements of the diaphragm in respiration. With normal breathing the upper border of the cardiac portion swings through about one centimetre; with dyspnea, or deep breathing, through one and a half or two centimetres. Since the lower border does not move so much, the contents are gently pressed, and then released from pressure, at each respiration. The pyloric portion is moved very little by the diaphragm, the oscillation being less than a half centimetre.

Moritz has pointed out the value of an organ like the stomach for holding the bulk of the food and serving it out a little at a time so that the intestines may not become congested during their digestive and absorptive processes. All of the advantages supposed to be thus secured to the intestines may be claimed also for the stomach itself. For the preceding description indicates, and experiments to be described later prove, that the stomach is composed of two physiologically distinct portions: the busy antrum, over which during digestion constriction-waves are running in continuous rhythm; and the cardiac part, which is an active reservoir, pressing out its contents a little at a time as the antral mechanism is ready to receive them.

V. The Movements of the Stomach in Vomiting.

The appearance of the stomach during vomiting has been studied particularly by Oenchowskii. He says that when an emetic is given there follows a quivering of the stomach wall, which, beginning near the pylorus, shows itself later in the antral and middle regions of the stomach. The quivering afterwards passes into a contraction, most strongly marked in the antral part, since the peristaltic waves running down to the antrum from above are continually growing deeper. At the same time the fundus expands spherically. The increased contraction in the pyloric part drives the contents towards the more dilated portion, and thence they are forced into the esophagus by abdominal pressure.

The same phenomena occur when a cat is given apomorphine hypo-

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2 By study of the pressure at various parts of the stomach in man, Moritz (Zeitschr. f. Biologie, 1895, xxxii, p. 359), and von Pfungen (Cbl. f. Physiol., 1887, i, p. 220), have inferred that the fundus must be quiet and that the motor functions are performed by the pyloric part. Leven has also expressed the same conclusion: Traité des maladies de l’estomac, Paris, 1879, p. 16.
3 Oenchowskii: Archiv fur Physiologie, 1889, p. 552.
dermatically. First the upper circular muscles relax and become so flaccid that the slightest movement of the abdomen changes the form of the fundus. Then there are apparently irregular twitchings of the fundus wall. Soon a deep constriction starts about three centimetres below the cardia, and, growing in strength, moves toward the pylorus. When it reaches the transverse band the constriction tightens and holds fast, while a wave of contraction sweeps over the antrum. Another similar constriction follows. In the interval the transverse band relaxes slightly, but tightens again when the second wave reaches it. Perhaps a dozen such waves pass; then a firm contraction at the beginning of the antrum completely divides the gastric cavity into two parts. This same division of the stomach into two parts at the transverse band is to be seen when mustard is given. Now, although the waves are still running over the antrum, the whole preantral part of the stomach is fully relaxed. A flattening of the diaphragm, and a quick jerk of the abdominal muscles, accompanied by the opening of the cardia, now force the contents of the fundus into the cesophagus. As the spasmodic contractions of the abdominal muscles are repeated, the gastric wall again tightens around the contained food. Antiperistalsis I have seen only once; then, while the cat was retching, a constriction started at the pylorus and ran back, over the antrum, completely obliterating the antral cavity.

It will be recalled that the principal difference between the movements of the stomach and their effects as described by Beaumont, and Hofmeister and Schütz on the one hand, and Rossbach, Roux and Hathazard, and myself on the other hand, is that the former observed constrictions completely dividing the stomach at the transverse band, and the antrum then squeezing its contents into the intestines; whereas the latter have seen the constrictions moving forward as narrowing rings, but not separating the gastric cavity into two parts.

With the exception of peristalsis in the antrum, the gastric movements at the beginning of emesis are almost exactly the same as those Beaumont, and Hofmeister and Schütz, declare to be the normal contractions of the stomach. Their observations were made, however, when the organ was subjected to unnatural stimulation. In the excised stomach, observed by Hofmeister and Schütz, not only were all nervous connections severed, but likewise all flow of blood to the organ was entirely stopped, and the cutting off of the blood supply is regarded as one of the most powerful predisposing causes of peristal-
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The thermometer-tube used by Beaumont was an irritant to the stomach, as he himself admits. "If the bulb of the thermometer," he writes, "be suffered to be drawn down to the pyloric extremity, and retained there for a short time, or if the experiments be repeated too frequently, it causes severe distress, and a sensation like cramp, or spasm, which ceases on withdrawing the tube, but leaves a sense of soreness and tenderness at the pit of the stomach." Moritz also noticed that a rubber sound introduced into the human stomach proved to be a source of irritation. It seems reasonable to suppose, therefore, that these observers did not see the normal movements, but the actions resulting from abnormal irritation.

VI. THE EFFECT OF THE MOVEMENTS OF THE STOMACH ON THE FOOD.

In my first observations on the active stomach a bulging of the stomach-wall was to be seen in front of the passing waves. But as food did not immediately appear in the intestine, and as, after the pylorus relaxed, the gastric contents did not diminish rapidly enough to allow the supposition that all of the food squeezed forward by the waves was immediately forced through the pylorus, it was assumed that a part, at least, of the food under pressure was forced back towards the cardia through the constriction ring. This inference was stated in the preliminary notice of my work. Roux and Bathazard also observed the passage of the undulations over the pyloric part, but state merely that the function of the constrictions is the propulsion of food into the intestine, without mentioning what must be regarded as a very important function, namely, the mixing effect of the waves.

Most writers have agreed that the result of the active and passive movements of the stomach is to force the contents hither and thither, thus mixing them and the gastric juice together. Two observers, Beaumont and Brinton, have attempted to explain the manner of the mixing. Beaumont, after noting how the thermometer-tube, used by him to indicate the gastric motions, was affected, describes the circulation of the food as follows: "The bolus as it enters the cardia turns

1 Mall: A study of the intestinal contraction. Johns Hopkins hospital reports, i, p. 70.
4 Cannon: Science, June 11, 1897, p. 902.
to the left; passes the aperture; descends into the splenic extremity; and follows the great curvature towards the pyloric end. It then returns, in the course of the small curvature, makes its appearance again at the aperture, in its descent into the great curvature, to perform similar revolutions. 1 Brinton 2 bases his theory of the circulation of the food on an analogy between the movement of a constriction over the stomach, and the passage of a septum with a central perforation along the interior of a cylinder full of liquid. The result in both cases, he declares, must be a peripheral current of advance, and a central current of return. Thus in the stomach there would be peripheral currents from the cardia along the walls of the stomach to the pylorus, where they would unite and run as an axial current back to the cardia.

Certain a priori objections may be urged against each of these conclusions. In the first place, Beaumont's observations were made on a subject having a gastric fistula, and the adhesions between the stomach and the abdominal wall would prevent the fundus from acting quite normally in relation to its contents. Beaumont's conclusions, furthermore, are based on the movements of a thermometer-tube introduced through the fistula, and on the recognition of particles of food which he had seen before as they passed the fistulous opening: the first method, as has been shown, made the conditions in the stomach more abnormal than they were previously; the second gave uncertain knowledge of the course of the food when out of the observer's sight. Brinton's hypothesis states the probable movements of fluid contents acted on by a passing constriction. But it may be objected that the conditions assumed by him do not exist in all parts of the stomach. For, not only is there no peristalsis visible in the fundus, but with the usual food the fundus contents are not liquid. Moreover, the constrictions at the beginning of the pyloric portion are very slight, and move slowly. The food in front of them is, accordingly, not under much greater pressure than the food behind them. The axial current which might result, therefore, could not be strong enough to go far into the cardiac portion.

It is easily possible to test experimentally the validity of these two theories by watching the action of pieces of food which throw a black shadow in a dimly-outlined stomach. For this purpose little paste pellets of bismuth subnitrate, with starch enough to keep the

form, were given with the customary meal. These pellets, it was found, did not break up in the stomach during the gastric digestion of soft bread. Several times I have been fortunate in getting two of the little balls in the axis of the stomach and about a centimetre apart. As the constriction-wave approached them, both moved forward, but not so rapidly as the wave. Now when the constriction overtook the first ball, the ball moved backward through the constricted ring, in the direction of least resistance. The wave then overtook the second ball, and it also passed backward to join its fellow. At the approach of the next wave they were both pushed forward once more, only to be again forced backward, one at a time, through the narrow orifice. As the waves recurled in their persistent rhythm, the balls were seen to be making progress — an oscillating progress — towards the pylorus; for they went forward each time a little farther than they retreated. This to-and-fro movement of the pellets was much more marked in the antrum, where the waves were deep, than in the middle region. On different occasions from nine to twelve minutes have elapsed while the balls were passing from where the waves first affected them to the pylorus; which means that on the way they were moved back and forth by more than a half hundred constrictions.

If the pylorus does not relax, it is evident that a wave approaching it pushes the food into a blind elastic pouch, the only exit from which is through the advancing constricted ring. The constrictions are deeper near the end of the antrum, and the rings are small; consequently the food is squirted back through them with considerable violence. As has been noted, the pylorus opens less frequently for a while after a solid piece of food comes to it. In such a case the slow driving waves squeeze the hard morsel and the soft food about it up to the sphincter, only to have the whole mass shoot back, sometimes half way along the antrum. Over and over again the process is repeated till the sphincter at last opens and allows the more fluid parts to pass. Hofmeister and Schutz, and Moritz have disclaimed any selective action of the pylorus, and declare that solids are driven from the pylorus to the fundus by antiperistalsis. The action of the pylorus which I have seen, however, is more like that described by the earlier investigators; for during digestion there was no antiperistalsis, and the sphincter, separating the fluids from the solids, caused the solids to remain and undergo a tireless rubbing. Frequently when several of these balls have been given at the same time, they
have all been seen in the antrum after the stomach was otherwise empty. Here they remain to be softened in time by the juices or to be forced through the pylorus later, for solids do pass into the intestine. Thus when the teeth neglect their work the stomach attempts to perform their function; the relative inefficiency of the gastric method of grinding and its interference with the normal gastric activities point an obvious hygienic moral.

During the process of digestion the food in the cardiac portion gives no sign of currents. Balls which lie in the fundus immediately after the food is ingested, keep their relative positions until the cardiac portion begins to contract, and then move very slowly towards the antrum. Moreover, the food in the fundus of a cat has the same mushy appearance when examined after gastric peristalsis had been active for an hour and a half that it had when ingested. The contents of the antrum, on the other hand, look quite different and have the consistency of thick soup. The inactivity of the food in the fundus can also be proved by feeding first five grams of bread and bismuth, then five grams without bismuth, and finally five grams again with bismuth in it. The stomach contents are thus arranged in two dark layers along the curvatures, with a light layer between. Tracings made on tissue paper show that ten minutes after peristalsis commenced, the stratification had entirely disappeared in the pyloric part, but that an hour and twenty minutes thereafter the layers were still clearly visible in the cardiac region.

The value of the circulation of the food, as described by Beaumont and Brinton, lay in the supposition that the contents of the stomach were thus brought near to the secreting gastric wall, and that the gastric juice could thus more readily exert its action. Although my observations do not support their theories of mixing currents running throughout the stomach, they still show that the pyloric portion is an admirable device for bringing all of the food under the influence of the glandular secretions of that region. For, when a constriction occurs, the secreting surface enclosed by the ring is brought close around the food lying within the ring in the axis of the stomach. As this constriction passes on, fresh areas of glandular tissue are continuously pressed in around the narrow orifice. And also, as the constriction passes on, a thin stream of gastric contents is continuously forced back through the orifice and thus past the mouths of the glands. The result of this ingenious mechanism is that every part of the secreting surface of the pyloric portion is brought near to every bit
of food, before the latter leaves the stomach, a half hundred times or more, as evidenced by the moving ball.

VII. Salivary Digestion in the Stomach.

The absence of movement in the fundus would seem to give the food during its stay there little opportunity to become mixed with the gastric juices and thus to undergo peptic digestion. The truth of this supposition can easily be proved experimentally by feeding a slightly alkaline meal and later testing the chemical reaction of the contents of various parts of the stomach. A cat which had been without food for fifteen hours was given eighteen grams of mushy bread made slightly alkaline with sodium carbonate. One hour and a half after the cat had finished eating, she was killed and the stomach laid bare by opening the abdomen. A very small hole was then made through the wall in the fundus region, and another similar hole was made into the antrum. By means of a glass pipette food was extracted first from the periphery of the fundus, this food was slightly acid. The cleaned pipette was then introduced two and a half centimetres into the fundus contents and the food thus extracted gave the original alkaline reaction. Specimens of the liquid contents of the antral and middle regions, taken from various depths, were all strongly acid. A dog killed an hour and three-quarters after eating showed similar differences between the reactions of the food in the fundus and the food in the pyloric portion. So, as a matter of fact, the food does not become acid at a uniform rate in all parts of the stomach, as would be the case if Beaumont's and Brinton's theories of mixing currents were true. Moreover, if the facts accorded with their notions, the saliva, which ceases to act in the presence of more than 0.003 per cent free hydrochloric acid, and is destroyed when the percentage of acid proteids is large, would manifestly have its service as a ferment limited to the relatively short time during which the stomach contents, in the process of thorough mixing, were reaching that degree of acidity. There is, however, no movement of food in the fundus, and the alkaline food received from the oesophagus remains alkaline in this region for a considerable period. The nutriment, therefore, if well chewed and thus mixed with saliva, can undergo salivary digestion in the fundus for a considerable period without interference by the acid gastric juice.

From all these observations the conclusion must be that the fundus acts as a reservoir for the food, in which the digestion of sugars and starches may take place; and that the pyloric portion with its simple but marvellous peristaltic mechanism, by a single process, triturates the food, brings it near to the active glands, stirs it thoroughly with their secretions, and expels the products into the intestines.

VIII. The Inhibition of Stomach Movements during Emotion.

Early in the research a marked unlikeness was noticed in the action of the stomachs of male and female cats. The peristalsis seen with only a few exceptions in female cats failed to appear in most of the males, although both had received exactly the same treatment. Along with this difference was a very striking difference in behavior when bound to the holder; the females would lie quiet, mewing occasionally, but purring as soon as they were gently stroked. The males, on the contrary, would fly into a violent rage, struggle to be loose from their fastenings, bite at everything near their heads, cry loudly, and resist all attempts to quiet them. On account of this difference only female cats were used for some time; and the significance at first attributed to the action of the males, was almost forgotten when the following incident recalled it, and suggested that the excitement caused the suspension of the stomach movements. On October 23, 1897, a male cat was fed at 12.00, but was not placed on the holder till ninety minutes later. The waves were passing at the rate of six a minute. The cat fell into a rage and the waves suddenly stopped.

A few days later an observation on a female with kittens explained the absence of gastric movements in the males. While the peristaltic undulations were coursing regularly over the cat’s stomach, she suddenly changed from her peaceful sleepiness, began to breathe quickly and struggled to get loose. As soon as the change took place, the movements in the stomach entirely disappeared; the pyloric portion relaxed and presented a smooth rounded outline. I continued observing, and stroked the cat reassuringly. In a moment she became quiet and began to purr. As soon as this happened the movements commenced again in the stomach; first a few constrictions were visible near the end of the antrum, then a few near the sharp bend in the lesser curvature, and finally the waves were running normally from their habitual starting place. By holding the cat’s mouth closed between the thumb and last three fingers and covering her nostrils with
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The index finger, she could be kept from breathing. At the first sign of discomfort the fingers were removed. This experiment was repeated a great many times on different cats, and invariably the evidence of distress was accompanied by a total suspension of the motor activities of the stomach and a relaxation of the antral fibres.

No amount of kneading or compression of the abdomen with the fingers, short of making the cat angry, would cause the waves to stop; so that the cat's movements, in themselves, were not the source of the inhibition. And since expressions of strong feeling on the part of the animal always accompanied cessation of the constriction-waves, the inhibition was probably due to nervous influence. It has long been common knowledge that violent emotions interfere with the digestive process, but that the gastric motor activities should manifest such extreme sensitiveness to nervous conditions is surprising.

Summary.

1. By mixing a harmless powder, subnitrate of bismuth, with the food, the movements of the stomach can be seen by means of the Rontgen rays.

2. The stomach consists of two physiologically distinct parts: the pyloric part and the fundus; over the pyloric part, while food is present, constriction-waves are seen continually coursing towards the pylorus; the fundus is an active reservoir for the food, and squeezes out its contents gradually into the pyloric part.

3. The stomach is emptied by the formation, between the fundus and the antrum, of a tube along which constrictions pass. The contents of the fundus are pressed into the tube and the tube and antrum slowly cleared of food by the waves of constriction.

4. The food in the pyloric portion is first pushed forward by the running wave, and then by pressure of the stomach wall is returned through the ring of constriction; thus the food is thoroughly mixed with gastric juice, and is forced by an oscillating progress to the pylorus.

5. The food in the fundus is not moved by peristalsis and consequently it is not mixed with the gastric juice; salivary digestion can therefore be carried on in this region for a considerable period without being stopped by the acid gastric juice.

6. The pylorus does not open at the approach of every wave, but only at irregular intervals. The arrival of a hard morsel causes the
sphincter to open less frequently than normally, thus materially interfering with the passage of the already liquefied food.

7. Solid food remains in the antrum to be rubbed by the constrictions until triturated, or to be softened by the gastric juice, or later it may be forced into the intestine in the solid state.

8. The constriction-waves have, therefore, three functions: the mixing, trituration, and expulsion of the food.

9. At the beginning of vomiting the gastric cavity is separated into two parts by a constriction at the entrance to the antrum; the cardiac portion is relaxed and the spasmodic contractions of the abdominal muscles force the food through the opened cardia into the oesophagus.

10. The stomach movements are inhibited whenever the cat shows signs of anxiety, rage, or distress.