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[From the Laboratory of Physiology in the Harvard Medical School.]

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THE movements of deglutition, in common with many other physiological processes, were explained by the older physiologists on anatomical grounds. Thus Magendie[1] divided the act into three parts, corresponding to the anatomical regions of the mouth, pharynx, and œsophagus. The muscles of each of these divisions were considered the active agents in propelling the food onward. The function of moving the mass to the pharynx was variously ascribed to the tongue itself, to the mylohyoid muscles, and to gravity. For the second part, the movement through the pharynx, there was more unanimity of opinion, since the constrictors, especially the middle and lower, were evidently concerned.

Direct observations on the movement of swallowed masses in the œsophagus were first made by Mosso.[2] The œsophagus of a dog was laid bare and a transverse incision made through it, or a piece of it excised. A small wooden ball was placed in the canal below the excised part, and the animal was then stimulated to swallow. One or two seconds after the contraction of the pharyngeal muscles a peristaltic wave began to traverse the œsophagus. This wave did not stop at the point of excision, but in due time reappeared below and carried the ball to the stomach. Thus the act was shown to be controlled by the central nervous system. Peristalsis was so plainly the motive power that the action was never doubted. Yet this belief was soon to be questioned.

In 1880, Falk and Kronecker[3] studied the movements in the mouth and pharynx, and advanced the theory that deglutition was accomplished by the rapid contraction of the muscles of the mouth. During the act of swallowing the air-tight buccal cavity shows a manometric pressure of 20 centimetres of water. The same pressure was demonstrated to be present also in the œsophagus, but not in

[1] Magendie: Précis élémentaire de physiologie. Paris, 1836, i, p. 63.

[2] Mosso: Moleschott's Untersuchungen, 1876, xi, p. 331.

[3] Falk and Kronecker: Archiv für Physiologie, 1880, p. 296.

the stomach. This pressure was considered sufficient to force food through the œsophagus before the peristaltic wave traversed it. Another argument for rapid descent was found in the fact that cold water can be felt in the epigastric region almost immediately after being swallowed. Further, when strong acids pass through the gullet, they corrode but small parts of it, and not the entire mucous membrane, as would be the case were the acid carried to the stomach by peristalsis.

In the same year, in confirmation of the above results the well known experiments of Kronecker and Meltzer[1] were published. A rubber balloon, connected by a tube to a Marey tambour, was placed in the pharynx, and another balloon, similarly connected, was introduced a varying distance into the œsophagus. When water was swallowed the increased pressure in the pharynx was transmitted to the first tambour, which traced a curve on a rotating drum. Almost instantly thereafter the œsophageal balloon was compressed, causing the second tambour to write its curve below the first. This second curve was supposed to mark the passage of the food through the œsophagus. After a varying number of seconds the œsophageal balloon recorded another curve, caused by a peristaltic wave which carried to the stomach any fragments left in the canal.

To demonstrate that the first curve of the œsophageal balloon was caused by the passage of the swallowed liquid, Meltzer devised another experiment. A strip of blue litmus paper was placed in a stomach tube, opposite the side openings at the lower end. A long thread attached to the paper ran through the tube to the other end. The tube was now passed into the lower end of the œsophagus and an acid drink swallowed. If the litmus paper was pulled away from the side openings a second after the beginning of swallowing, it was found distinctly reddened, showing a rapid descent of the swallowed liquid. Reference to this experiment will be made later.

From these observations Kronecker and Meltzer concluded that liquids and semi-solids are not carried to the stomach by peristalsis, but are squirted down the œsophagus by the rapid contraction of the muscles of the mouth. For this purpose the mylohyoids alone are sufficient, since the middle and inferior constrictors can be cut without interfering with the act. The succeeding peristalsis is of use merely in gathering up adhering fragments and carrying them to the stomach.

[1] Kronecker and Meltzer: Archiv für Physiologie, 1880, p. 446.

To determine whether the cardia offered any resistance to this rapid passage into the stomach, Meltzer[1] tried another method. If a stethoscope is placed over the epigastrium during the swallowing of liquids, a sound can be heard from six to seven seconds after the rise of the larynx. The sound is caused by the passage of the swallowed mass, liquid and air, through the tonically contracted cardia. In a few cases the sound is heard immediately after swallowing, showing a probable insufficiency of the cardia. These phenomena led Kronecker and Meltzer[2] to modify their previous views. They now maintained that the mass is not squirted by the mylohyoids directly into the stomach, but halts a short distance above the cardia. Here it remains until carried into the stomach by the succeeding peristalsis, about six or seven seconds after the beginning of swallowing.

The care with which these experiments were conducted has won general assent to their results. But the methods employed are not beyond criticism. Primarily it may be said that swallowing with one or more balloons and a stomach tube in the canal is not normal deglutition. Moreover, semi-solids were found to yield less readily to pressure than liquids, and even to be delayed in their descent.[3] Again nearly all the work was done with liquids and semi-solids; solids are not even mentioned. The investigators themselves declared that their results were true for liquids and semi-solids only, and admitted that a dry bolus could not be so swallowed. Yet the indiscriminate use of such terms as "liquid," "swallowed mass," and "bolus," easily leads to an inference that the results of these investigations are true for the swallowing of food of all consistencies. A difference in rate, however, certainly exists in respect to consistency, and it was to discover the actual movement of solids, semi-solids, and liquids in the normal œsophagus that the present work was undertaken.

Over a year and a half ago it was suggested by Prof. H. P. Bowditch that if some substance opaque to the Röntgen rays were swallowed, it could be seen in its passage to the stomach and the nature of its movement thus determined. Anæsthesia could be dispensed with, — a desirable condition, since observers had found that it inter-

[1] MELTZER: Centralbl. für die med. Wissenschaften, 1883, p. 1.

[2] KRONECKER AND MELTZER: Archiv für Physiologie, 1883, Suppl. Bd., p. 337, 351.

[3] KRONECKER AND MELTZER: *ibid.*, p. 337.

fered greatly with the deglutition reflex.[1] It would be unnecessary to open either the abdominal or the pleural cavity. The reflex stimulus of food moreover would be better than electrical stimulation of the superior laryngeal nerve. In short, the animal would swallow normal food under practically normal conditions. At Dr. Bowditch's suggestion and with his valuable assistance — which we gratefully acknowledge — we made the following series of experiments.

To render the swallowed mass opaque subnitrate of bismuth was used. The salt is tasteless, practically inert, and can be fed in large quantities without harm. In order that observations could be made by more than one person, all experiments were conducted in a dark room. On the side of the animal opposite the Crookes tube was placed an open fluorescent screen on which the different tissues of the animal were outlined with varying degrees of light and shade. Among these shadows the swallowed mass appeared as a darker object, and thus its motion could be studied.

For the first experiments the goose was selected. The head and neck were held stationary by a tall pasteboard collar which allowed free movement of the head without constriction of the neck. The fluorescent screen was placed against this collar at a uniform distance of thirty centimetres from the tube. When a bolus of corn meal mush mixed with bismuth was placed in the pharynx it descended slowly and regularly, and occupied about twelve seconds in passing over a distance of fifteen centimetres. The screen was marked at intervals of two centimetres with cross lines, by means of which the relative rate in different parts of the œsophagus could be studied. A vibrator marking tenths of a second was interrupted whenever the bolus crossed a line. An average of over one hundred such observations showed that the rate became slightly slower as the bolus proceeded.

In order to test liquids, molasses was mixed with bismuth to such a consistency as to drop easily from a glass rod. When this was fed with a pipette it passed slowly and regularly down the œsophagus, clearly by peristalsis. The rate was about the same as for solid food. In both these experiments, the addition of water would sometimes cause irregularities in the descent. Microscopic sections from four different parts of the œsophagus of the goose showed no histological difference.

In the experiments on the cat, the animal was placed on its back and

[1] MELTZER: Journal of experimental medicine, 1897, ii, p. 457.

left side on a holder. The extremities were secured by straps. The head was held between two upright rods connected above by a thong; this allowed free movement of the head without resistance to the passage of food. Shreds of meat dipped in bismuth were ordinarily masticated and swallowed without difficulty. For soft solids bread and milk were used, so fluid as to be easily drawn up into a pipette. The insolubility of the bismuth salt rendered the study of liquids more difficult. Strong solutions of potassic iodide and other salts and suspension of bismuth in acacia and molasses were tried; but a simple mixture of milk and bismuth, shaken in a test tube and immediately drawn up into a pipette, was found most practicable.

Inasmuch as the movement of these different foods varied in different parts of the œsophagus, it will be convenient to divide the latter into three sections. The first or cervical portion extends from the pharynx to the thorax, the second or thoracic from here to the lower half of the heart, and the third comprises the rest of the canal. The relative length of these three parts is about in the ratio of 9:8:6.

The beginning of deglutition was noted by one observer by a finger on the larynx; the same observer called out when the bolus arrived at the thorax, heart, and stomach respectively, while the other observer noted the time. The movement of solids will first be considered. The descent the entire way was by peristalsis, but the rapidity varied. The duration of the movement in the cervical portion was two and a half seconds, and in the thoracic region a little less than two seconds. At the lower end of the heart there was sometimes a slight pause. In the lower section, from the heart to the stomach, the movement was decidedly different. The rate was always very slow. The distance was less than one-third of the entire canal, yet the time consumed in this part ranged from six to seven seconds, or three-fifths of the entire time of descent. The character of the movement here was also peculiar. Whereas in the upper sections the passage was uniform and regular, with a slight acceleration in the thoracic region, here it was apparently irregular, for the bolus descended about one centimetre with each inspiratory movement of the diaphragm, and remained stationary or descended very slightly during expiration. Thus a series of hitches seemed to carry the bolus to the cardia. A probable explanation of this peculiar movement is that the stomach and lower œsophagus were pulled down with each descent of the diaphragm. This would make the movement appear irregular although it was really a slow peristalsis.

It may be well to remark here that this movement was invariably observed in the cat with every kind of food.

Semi-solids, namely, a mush of bread and milk, descended in the same way as solids; but the rate was slightly faster in the upper œsophagus, for the bolus took about a second less to reach the cardiac level. From here the rate was the same as with solids.

For liquids one and a half to two seconds sufficed for the descent to the midheart region. Here there often occurred a long pause — from a few seconds to a minute or more. Then the œsophagus apparently contracted above the liquid, which slowly passed on to the stomach as already described. Sometimes it seemed as if a swallowing movement, evidenced by a rise of the larynx, started the peristaltic wave. Again, several swallows would succeed one another before the liquid passed on. A few times the bismuth and milk seemed strung out along the œsophagus; some more liquid descending would gather this up, and the whole mass assuming an ovoid form would move into the stomach.

Thus in the cat the total time for deglutition varies from nine to twelve seconds. The lowest section presents no change ascribable to a difference in consistency, while in the upper sections the rate does slightly increase with the more liquid character of the food.

In experiments on the dog, bismuth enclosed in capsules or wrapped in shreds of meat was fed as the solid. The general phenomena were as follows. With the rise of the larynx there was a quick propulsive movement of the bolus, which descended rapidly for a few centimetres, sometimes as far as the clavicle. From this point the rapidity was diminished; yet no pause was observed; the bolus simply moved more slowly. This rate was then continued to the stomach without a slackening of speed in the diaphragmatic region, as was observed in the cat. Semi-solids moved in the same way as solids. The total time of descent from larynx to stomach was from four to five seconds.

Liquids gave even a more decided squirt in the beginning of the movement. To render the œsophagus as lax and free as possible, the head of the dog was released from the upright rods and held by the hands after the food was placed in the mouth. Sometimes the liquid descended rather rapidly as far as the heart, at other times no further than the clavicle; then without a pause it passed on slowly and regularly, reaching the stomach in about the same time as solids and semi-solids.

Thus in the dog and cat but little variation was seen in the swallowing of liquids and solids. The liquids pass somewhat faster in the upper œsophagus. But in some animals the difference of rate with foods of varying consistency is much more marked. In the horse, for instance, mere observation shows a decided variation in the rate of movement in the œsophagus. Liquids shoot along the gullet, while solids move clearly by peristalsis. To determine the rate of solids one hand was placed on the larynx of a horse to note the beginning of swallowing and the other hand near the shoulders, where the bolus could be easily felt in its passage. The time consumed by the bolus in passing over a certain distance was measured by a stop watch. The rate obtained for solids, such as hay or grain, was from thirty-five to forty centimetres a second.

For semi-solids, a mixture of bran and water was made, thin enough to run easily between the fingers. Each bolus was watched by a separate observer with a separate watch. The average rate obtained was the same as for solids.

Liquids in the horse pass with a rapidity too great to be affected by peristalsis. Another force must be sought. Among the various muscles supposed to be effectual in moving food into the pharynx, the mylohyoids were shown by Meltzer[1] to be essential. The styloglossi were cut by him without much interference with deglutition, but section of the mylohyoid nerves rendered the act impossible. The activity of these muscles in the horse during swallowing is easily perceived by the hand. Their energetic contraction is a sufficient explanation of the rapid passage of water through the œsophagus. The motion here is more than five times as rapid as that of solids and semi-solids.

Meltzer's experiment to measure the rate of liquids in man by passing a stomach tube containing litmus paper was repeated by us with some modifications. Congo red paper was used, since it is more sensitive than litmus; it also furnishes a means of differentiating between mineral and organic acids, as the discoloration produced on Congo red by mineral acids is removed by ether. It was thus possible to distinguish between the discoloration produced by gastric regurgitation and that produced by the swallowed liquid. For the swallowed liquid one-half per cent lactic acid was found most satisfactory, as the color produced by it on Congo red test paper is almost instantly discharged in ether. By this method the paper

[1] Kronecker and Meltzer: Archiv für Physiologie, 1880, p. 299.

was found discolored within half a second after the rise of the larynx, certainly too short a period for a peristaltic wave to carry the liquid to the neighborhood of the cardia.

The X-ray method lends itself less successfully to the study of deglutition in man than in the other animals we have studied. The thickness of the thorax, the distance of the œsophagus from the surface, and the relation to dense tissues, render the observation of a swallowed mass difficult, especially when the mass is in rather rapid motion. The few observations which we have to report were made on a seven year old girl placed in the sitting posture. Gelatine capsules containing bismuth were used for solids, and were traced to a point below the heart. The motion was very regular, and apparently due to peristalsis, for the bolus descended without a hitch or irregularity of any kind. Sometimes the capsule became fixed in the upper œsophagus at about the level of the second rib. Repeated swallows of water would fail to dislodge it. An interesting point was noted here. With each attempt at swallowing, the capsule would rise slightly as if the œsophagus was pulled up with the rise of the larynx; then the capsule would descend to its former position.

Semi-solids — a mush of bread and milk — could be seen about as far as solids, *i. e.* to just below the heart. The motion of the mushy bolus was the same as with solids, except that the rapidity was perhaps slightly greater.

It should be noted here that with the human subject, as well as with the horse, our results for semi-solids differ from those derived by Meltzer's method; for according to his statements semi-solids, like liquids, are squirted down the œsophagus and are not propelled by peristalsis, as has been the case in our observations.

Liquids — bismuth and water — were seen only in the neck and upper thorax. Here there was a decided squirt. With the rise of the larynx the liquid was seen to pass rapidly through the pharynx and well down into the thoracic œsophagus before it was lost to observation. The rate, however, by estimation was less than that of liquids in the horse.

There remains to be considered Meltzer's latest investigation,[1] in which he endeavored to ascertain whether liquids remain above the cardia till the arrival of the peristalsis, or ooze down before. An experimental answer was secured by Meltzer by the following

[1] Meltzer: Journal of experimental medicine, 1897, ii, p. 453.

method. The abdominal and gastric walls of an anæsthetized dog were incised and a tube (vaginal speculum) introduced. Through this the entrance of food into the stomach could be observed directly. In repeated experiments no liquid was seen to pass through the cardia before the arrival of the peristaltic wave. An incision through the diaphragm near its anterior origin showed that the swallowed liquid was not squirted as far as a point an inch above the diaphragm. To observe the œsophagus nearer its beginning, the upper three ribs were resected on the left side. Thus the swallowed liquid was seen to shoot along the œsophagus before any peristalsis reached this point. The resection of the fifth rib exposed the œsophagus half way between the bifurcation of the trachea and the diaphragm. Here a bulging was sometimes observed immediately after the beginning of the act, and the swallowed mass remained there until a peristaltic wave carried it down. If the mass swallowed was small, or was projected with moderate force, it might not even reach as far as the bifurcation. From these experiments Meltzer concluded that in animals as in man, liquid food is not carried down the œsophagus by peristalsis, but is thrown rapidly into a deep part of the canal. The depth reached depends on the quantity swallowed, the force used, and the tonicity of the lower part of the œsophagus.

The difference between these methods of Meltzer and those employed in our experiments has already been mentioned; and merely his results, which were obtained with liquids alone, need be considered here. According to our observations on the dog, there was no distinct pause at any part of the canal. The movement simply became slower, and continued at this rate until the stomach was reached. Neither was the rate through the diaphragmatic part of the œsophagus slower than through the thoracic. The quick propulsive movement noticed in the dog was observed with solids and semi-solids as well as with liquids, but the liquids descended further down the canal before the movement changed to the slower peristalsis. While this difference was evident to the eye, the total time consumed by liquids in passing from pharynx to stomach was not enough shorter than the time for solids and semi-solids to be determined by our measurements.