Use of a pressure sensitive radiotelemetering capsule to study the canine gastric interdigestive complex

by

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Signatures have been redacted for privacy

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LIST OF SYMBOLS AND ABBREVIATIONS

AFC	Automatic frequency control
AM	Amplitude modulation
approx.	Approximately
B	Battery
C	Capacitor
ca	Circa
Ca^{++}	Calcium ion
cm	Centimeter (1 cm = 10^{-2} meter)
cm H_2O	Centimeters of water
CT-70	Frequency counter model
D_{600}	Calcium antagonist
f, F	Frequency
FM	Frequency modulation
IF	Intermediate frequency
K^+	Potassium ion
k, K	Kilo (1 kilo = 1000)
kHz	Kilohertz (1 kHz = 10^3 cycles/second)
ΔkHz	Change in kilohertz
L	Inductive coil
M	Metallic material (e.g. ferrite core)
μA	Microampere
MHz	Megahertz (1 MHz = 10^6 cycles/second)
min	Minutes

mm	Millimeter (1 mm = 10^{-3} meter)
mM	Millimole
mm Hg	Millimeters of mercury
mV	Millivolts (1 mV = 10^{-3} volts)
ΔmV	Change in millivolts
μV	Microvolts (1 μV = 10^{-6} volts)
Na^+	Sodium ion
npn	Negative-positive-negative
pF	Picofarad (1 pF = 10^{-12} farad)
pH	Scale for measuring hydrogen ion concentration of a solution
pnp	Positive-negative-positive
®	Registered trade mark
RF	Radio frequency
RM 312	Mercury cell model
R-611	Beckman recorder model
RTV	Room-Temperature-Vulcanizing
sec	Seconds
T	Turns of an inductive coil
Tr	Transistor
v, V	Volts

I. GENERAL INTRODUCTION

Simply stated, telemetering means remote metering, that is, measuring from afar. It involves the complete transmission of a measured quantity to a remote location via such means as radio waves, telephone cables, dyed blood in plastic tubes, or even ordinary wires. Thus, telemetry constitutes a communication system.

Like all other forms of communication systems, a medical telemetry system consists of the five distinctly recognizable units represented in the block diagram in Figure 1. The basic components of the system are:

1. An information source. This comprises the subject plus the appropriate pick-up equipment. The subject bears the measurand, that is, the physical quantity, property, or condition that the system seeks to measure. The pick-up equipment or transducer converts the energy or information from the measurand to another form of energy, usually electrical.

2. A transmitter. This is the electronic equipment used for generating and amplifying a radio frequency carrier signal, modulating the carrier signal with intelligence, and feeding the modulated carrier to an antenna for radiation into space as electromagnetic waves. In effect then, a transmitter codes the transduced message into a signal for

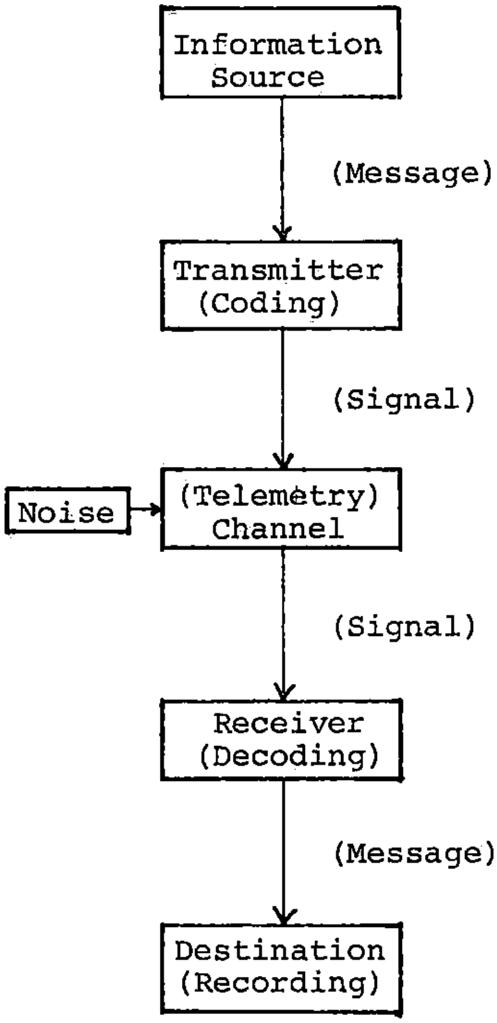


Figure 1. Block diagram of signal processing in a communication system (Drischel, 1973)

transmission through the telemetry channel.

3. The telemetry channel. This is the medium through which the transmission of the signal takes place. It can be air, wires, pneumatic or hydraulic systems, nerves, circulatory systems, practically any medium, including a vacuum, through which a signal can be propagated. It is usually in this channel that unavoidable noise superimposes itself on the signal. How much of the signal can be extracted from this noise depends largely on the quality of the receiver (Drischel, 1973).

4. A receiver. Technically, this is the complete equipment required for receiving modulated radio waves and converting them into the original intelligence, such as into sounds or pictures, or converting them into other desired information as in a radar receiver. In general, the function of a receiver in a communication system is to decode the transmitted signal into the original message picked up by the transmitter. At an appropriate point on the receiver the message can be extracted and forwarded for recording.

5. A recorder. This can be a person or a machine. Normally, a machine is used to make a permanent record of the varying electrical quantities or signals. A common industrial version records one or more quantities as a function of another variable, usually time. Other types include the cathode-ray oscillograph, facsimile recorder, kinescope

recorder, magnetic tape recorder, and sound film recorder.

In human subjects (Jacobson, 1962), the telemetry method is very convenient. It allows the subject to be in a relatively normal physiological and psychological state by interfering with his or her normal pattern of activities as little as possible. In animals (Riley and Cook, 1970, 1974), the telemetry method provides the additional advantage that an internally placed transmitter can not be disturbed.

This thesis describes the development and use of a system to monitor or telemeter the pattern of pressure fluctuations associated with gastric smooth muscle activity in dogs. The patterns of interdigestive complexes, as exemplified by the pressure recordings in each of the three dogs, were investigated using a rather simple, scientifically reliable, and inexpensive pressure-sensitive telemetering capsule capable of being swallowed without difficulty.

Each of the three dogs constituted the source of information. An encapsulated radio pill picked up the pressure fluctuations associated with gastric contractions and transmitted the signals into the air as radio waves. An FM (frequency modulated) radio receiver placed near each dog intercepted the signals, amplified them, and relayed them to a Beckman recorder which gave a permanent record of the dimensions of the original gastric pressures. This permanent record was used to determine whether the interdigestive motor activity followed a cyclical pattern.

Since previous (Jacoby et al., 1963; Wiley and Bass, 1972; Hubel and Follick, 1976) investigations of gastric motor cycles have been done by the very tedious, time consuming, and often very expensive surgical implantation of electrodes (Itoh et al., 1980) or by the uncomfortable and physiologically abnormal process of swallowing a long tube with instruments at its end (Itoh et al., 1975, 1977), the development of the miniature electronic equipment claims the important advantage of providing an easier, quicker, and cheaper alternative for physiologists who seek to investigate such physiological variables under the conditions of minimal disturbance to the subject or to his environment.

II. LITERATURE REVIEW

A. Anatomy of the Stomach

The stomach (Figure 2), the largest dilatation of the alimentary canal, is a musculoglandular organ interposed between the esophagus and the small intestine. An axis through it is shaped somewhat like the letter C rotated ninety degrees in a counterclockwise direction. It lies largely in a transverse position, more to the left of the median plane than to the right of it and forms an extensive concavity in the caudal surface of the liver. When empty, the stomach is located completely cranial to the thoracic outlet (Hartenstein, 1976).

The stomach is divided into a narrow region adjacent to the esophagus, called the cardia; a superior region above the cardiac orifice, called the fundus; a large region called the corpus, or body; and a pyloric region that communicates with the duodenum. The greater curvature is convex, and tends to extend approximately 300 mm from the cardia to the pylorus. The lesser curvature also runs from the cardia to the pylorus, but it is the shortest distance between those two parts.

The luminal surface and the wall of the stomach are illustrated in the low magnification drawing shown in Figure 2. The following layers are identified: the mucosa or mucous membrane, which contains mucus-producing simple columnar

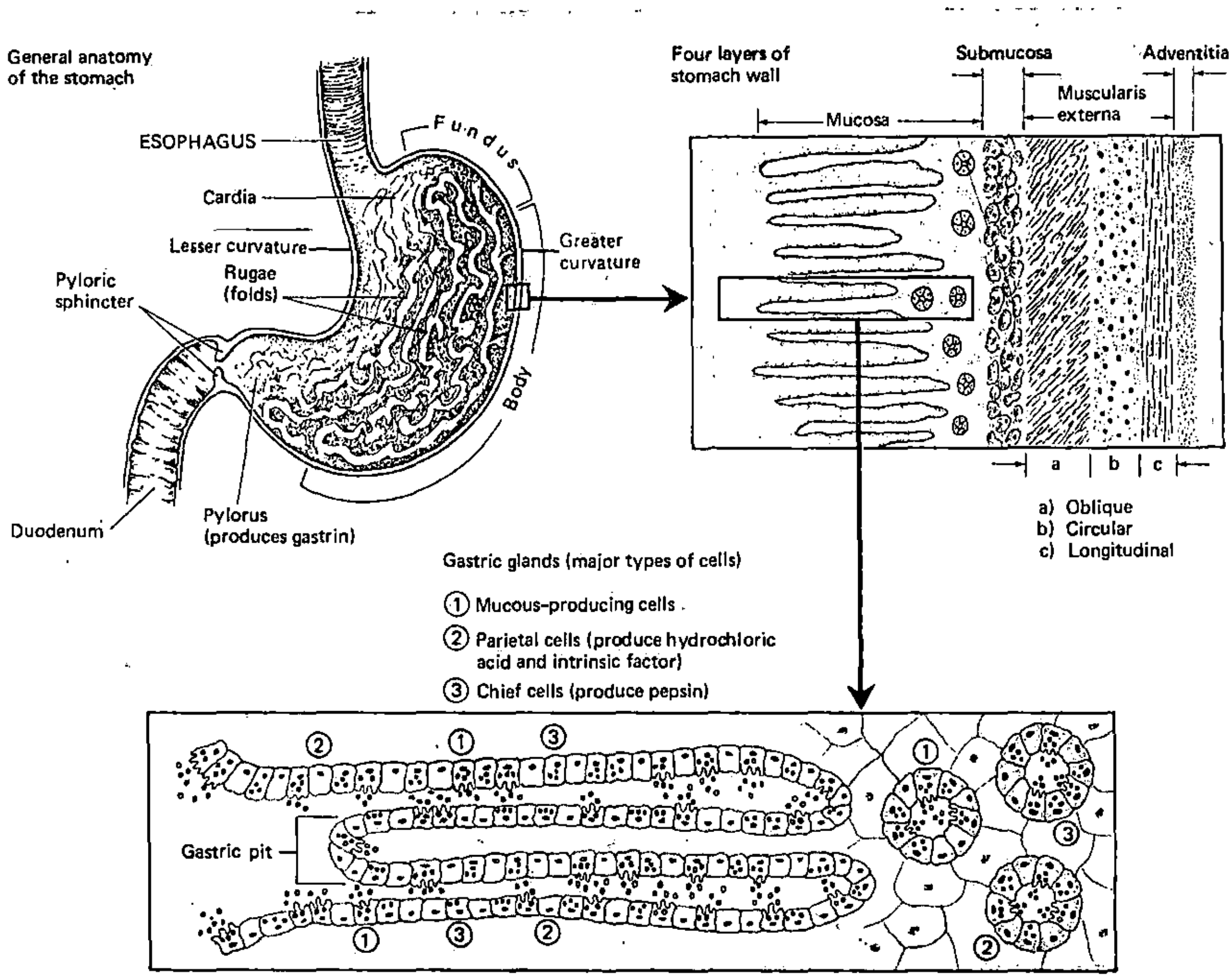


Figure 2. General anatomy of the stomach (Hartenstein, 1976)

epithelium and numerous gastric pits and glands; the loosely packed connective tissue of the submucosa layer, which is intermingled with nerves and lymphatic vessels; the muscularis externa consisting of smooth muscle; and the serosa or adventitia, which coats the smooth muscle layer externally. The serosa is very thin and consists of a small amount of connective tissue covered by a single layer of squamous mesothelial cells.

In the empty stomach, the mucosa and submucosa may be folded. These folds, called rugae, disappear when the stomach is full. There are numerous small apertures on the surface of the rugae; these open into gastric pits (high magnification in Figure 2). The mucosa is characterized by numerous invaginations of the lining epithelium into the lamina propria layer of the mucosa. Each gastric gland is thus a tubular downgrowth of epithelium into the lamina propria and has a perpendicular orientation to the stomach wall. These invaginations result in the presence of numerous unbranched or branched tubes consisting of two major regions: gastric pits and gastric glands. The gastric pits vary in length; they may extend for at least half the length of the tube in the pyloric region of the stomach, but the pits are shorter in the fundus and body of the stomach. In the cardiac and pyloric regions, the glandular portion of the tubes (the gastric glands proper) are lined principally with mucus-producing cells. In contrast, the gastric glands of the body and fundus contain many parietal cells, which produce hydrochloric acid, and chief, or zymogenic, cells, which produce proteolytic enzymes.

The muscularis externa consists of spirally arranged smooth muscle bundles oriented in three major directions: an external longitudinal layer, a middle circular layer, and an inner oblique layer. The middle layer is particularly thick in the region of the cardiac and pyloric orifices and acts as a sphincter in these regions. The motor functions of the stomach are performed by these different layers of the smooth muscle.

B. Activity of Gastric Smooth Muscle

Control of gastric smooth muscle is a complex process involving autonomic innervation, intrinsic innervation, and myogenic activity. A brief discussion of some of the aspects of these phenomena follows.

The preganglionic parasympathetic innervation of the stomach is by the vagi. Vagal activity releases acetylcholine, which stimulates contraction of the smooth muscle elements within the wall, causes relaxation of the pyloric sphincter and stimulates secretion. Postganglionic sympathetic fibers from the celiac ganglion release catecholamines which inhibit gastric smooth muscle. The vagi also carry inhibitory fibers which release an unidentified neurotransmitter (Campbell, 1966; Beani et al., 1971). Stretch of the walls of the stomach initiates afferent impulses through both the parasympathetic and sympathetic extrinsic nerves. Such long reflex pathways modulate gastric motility through the aforementioned efferent pathways either initiating, enhancing or inhibiting movements of the stomach. Stretching of the gastric walls also activates the intrinsic (myenteric plexus) cholinergic neurons; this constitutes a short reflex pathway.

The stomach is required to accommodate to an ingested meal in two ways: the organ must relax to receive a volume sometimes exceeding a litre in a matter of minutes, and it must initiate and maintain coordinated peristaltic activity to mix the contents and slowly empty itself. Both receptive relaxation (Kelly, 1977) of the stomach and increased motor activity of its wall (Code and Carlson, 1968) occur simultaneously after a meal is eaten. In order to better carry out these dual actions of storage and mixing, there is anatomic localization of gastric motor activity. Thus, the fundus and the corpus act as reservoirs whereas the antrum (initial two-thirds of pyloric region) propels, retropels, and triturates the gastric contents.

Recent studies (Morgan et al., 1981; Morgan and Szurszewski, 1980; Muir et al., 1979; Szurszewski, 1975) have shed tremendous light on the physiological basis for the topical differences among the functional parts of the stomach. Using simultaneous recordings from the canine fundal and antral smooth muscle preparations, Morgan et al. (1981) and El-Sharkawy et al. (1978) have reported that in contrast to the circular muscle of the antrum and corpus, fundal smooth muscle displays no spontaneous electrical or mechanical activity but possesses the ability to contract in the absence of action potentials. The gastric action potential which originates in the orad corpus does not propagate into the fundus in vivo (Kelly et al., 1959).

The lack of action potentials and the ability of the fundal smooth muscle cells to contract without action potentials seems to result from their low resting membrane potential. A low resting potential might inactivate an action potential mechanism such as the one present in both the antrum and the corpus. Why action potentials are not necessary can be explained by the relationship between the resting membrane potential and the voltage threshold for mechanical activity. This was revealed by the voltage-tension curves for antral and fundal smooth muscle (Morgan et al., 1981), and for corporal smooth muscle (Muir et al., 1979). When the results from fundal smooth muscle were compared to those from antral and corporal smooth muscle, the voltage threshold for mechanical activity occurred at a more negative potential and was closer to (or even more negative than) the resting membrane potential in fundal smooth muscle. Consequently, the fundus is predisposed to contract in response to relatively small depolarizations which would fail to exceed the mechanical threshold in antral and corporal smooth muscle. Hence, the ability of the fundus to contract in response to small depolarizations stems at least in part from the proximity of the resting membrane potential to the voltage threshold for mechanical activity. The fact that the mechanical threshold is negative to the resting potential in most fundal preparations explains the presence of resting tone in fundal smooth muscle.

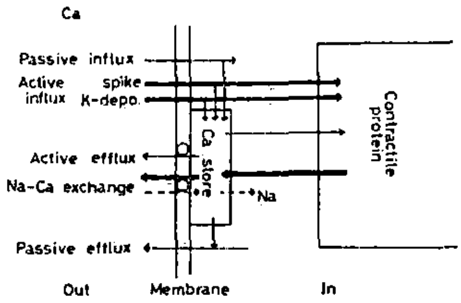
Two additional important observations were made from the voltage-tension curves by Morgan et al. (1981). First, in the fundus but not in the antrum, muscle tone increased with each increment of K^+ depolarization no matter how small the latter. This direct relationship between level of depolarization and degree of contraction appears to be characteristic of smooth muscle cells which do not produce action potentials (Szurszewski, 1977). Second, the Ca^{++} antagonist D_{600} (methoxyverapamil)[1] significantly reduced basal or resting tone in the fundus but not in the antrum. Since

[1] Knoll, A. G., Ludwigshafen, West Germany.

intracellular Ca^{++} concentration regulates contraction, these observations were consistent with the implication that Ca^{++} channels must be at least partially open at the resting membrane potential to give the fundal preparations active tone.

In 1976, Kuriyama et al. proposed a scheme for the movements of Ca^{++} ions during the resting and active states of gastric smooth muscle. In Figure 3, the thick lines indicate more dominant paths for movements of Ca^{++} ions. From their experiments with guinea pigs, they suggested that the Ca^{++} that enters during depolarization either directly or indirectly, through a Ca^{++} store, influences the contractile proteins. In the antral circular muscle, a Ca^{++}-pump appears to be the mechanism underlying the subsequent reduction of Ca^{++} ions in the myoplasm, but in the fundal and corporal longitudinal muscle a Na^{+}-Ca^{++} exchange mechanism appears more likely. The greater development of vesicles and sarcoplasmic reticulum in the circular muscle compared to the longitudinal muscle would tend to corroborate this.

Transmural nerve stimulation of canine fundal, corporal, and antral preparations (Morgan et al., 1981) has confirmed the previous reports (Campbell, 1966; Beani et al., 1971) of the presence of two transmitters, a cholinergic excitatory one and a noncholinergic, nonadrenergic inhibitory one, in the innervation of the smooth muscle tissue. In the fundus,



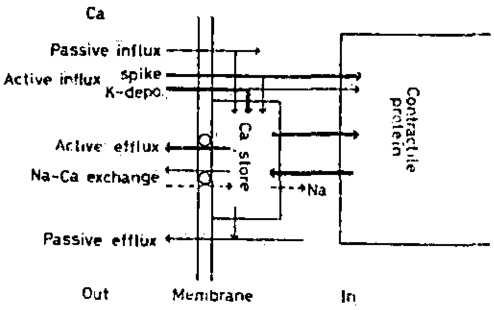


Figure 3. Schematic illustration of the possible movements of calcium ions (above in longitudinal muscle membrane; below in circular muscle membrane) (Kuriyama et al., 1976)

the response to stimulation of the cholinergic neurons is a small, graded depolarization which is always accompanied by a slow, graded contraction. The response to stimulation of the noncholinergic, nonadrenergic inhibitory neurons is a graded hyperpolarization which is always accompanied by a slow relaxation. Stimulation of the cholinergic neurons, between spontaneous muscle action potentials, produces graded depolarization of antral smooth muscle cells; however, there is no associated contraction. If the cholinergic neurons are stimulated during spontaneous action potentials, there is an increase in the amplitude and duration of the plateau phase of the action potential; this is associated with an augmentation of the spontaneous contraction.

Morgan et al. (1981) have claimed that the fundus is a truly tonic muscle. They explained that since in most cases they found the resting membrane potential of the fundus to lie above the mechanical threshold, the muscle must be normally tonically contracted and any hyperpolarization would reduce the basal tone. As a marked contrast, in the antrum the resting membrane potential was found to lie so far below the mechanical threshold that the antrum could not exhibit a resting tone. In the absence of action potentials, inhibitory junction potentials or the passage of hyperpolarizing current does not reduce the tone in the antrum because it contracts only when an action potential exceeds the mechanical threshold.

Thus, it can be concluded that by virtue of their electromechanical coupling characteristics, fundal, corporal, and antral smooth muscles are well suited to perform their physiologic function. The tone of the fundus and the corpus determines the volume of the canine stomach and regulates the reservoir function. The antrum, in a sharp contrast, resists changes in volume and its phasic contractions serve to mix and grind the gastric contents.

C. Interdigestive Complexes

In addition to the mixing and the peristaltic contractions of the stomach, a third type of intense contractions known as hunger or interdigestive contractions often occurs when the stomach has been empty for a long time. These are considerably stronger than ordinary gastric contractions. They are usually peristaltic and rhythmic in nature. When they become extremely intense, they often fuse together to cause a continuous tetanic contraction. Interdigestive contractions are usually most intense in young healthy animals with a high degree of gastrointestinal tonus, and they are also greatly increased by a low level of blood sugar. Usually felt in humans as hunger pains, hunger contractions do not begin until 12 to 24 hours after the last ingestion; in starvation they reach their greatest intensity in three to four days and then gradually weaken.

Alvarez (1940) has reported that as far back as 1849 Schwarzenberg commented on hunger contractions that he saw in the ileum of a fistulated dog. His patient was ravenously hungry all the time because his food ran out through a high jejunal fistula. He was able to distinguish two factors in hunger: a demand for food on the part of the tissues and a sensation arising in the digestive tract. However, it was not until 1882 that Morat recorded the first gastric contractions in unanesthetized dogs and came close to our present concept of hunger when he remarked that in connection with a strong feeling of hunger, the stomach always showed unusually active movements. Carlson became interested in Morat's remarks and by 1904, Carlson and his pupils had begun a long series of studies that threw light on almost every aspect of the hunger contraction mechanism.

According to Carlson (1913), when a recording balloon on the end of a Rehfuss tube was put into the stomach of a fasting dog, the tracings made on a kymographic drum generally showed alternating periods of quiet and activity. Activity began about two and a half hours after feeding. The first contraction bursts had durations of two to five minutes; these durations then shortened as the contractions became more powerful, until finally there were only short periods in which the stomach remained contracted. In humans, Carlson (1916) found that the feeling of hunger seemed generally to be associated with contractions that came about every thirty seconds. More rarely, there was a form of hunger activity in which there were no definite periods of contraction and rest and in which the peaks on the record became irregular both as to height and time of appearance. He further reported that the longer contractions moved from cardia to pylorus, that they resembled the waves of the digesting period and that the digestion contractions of the filled stomach passed gradually into the hunger type contractions of the empty stomach.

Todd (1930), experimenting with dogs, identified three types of hunger activity; these depended on the tonus of the gastric wall. In the first type, the tonus was poor, the contractions lasted about thirty seconds, and the intervals between them varied from one-half to four minutes. These contractions came in groups, and kept recurring for up to three hours. In the second type, the tonus of the stomach was good and the contractions followed one another in close succession. They were frequently interrupted by periods of incomplete tetanus, lasting from one to five minutes; the contractions then did not come in distinct groups but were practically continuous. He remarked that it was this type that had been seen occasionally in man and was associated with a continuous sensation of hunger. In the third type, there were periods in which there was a tetanic type of contraction with a series of rapid contractions superimposed. These periods varied in length from one to ten minutes.

Martin and Rogers (1927) made roentgenograms of an intragastric balloon which was being used to monitor hunger contractions and observed that deep contractions occurred only in the pyloric region of the stomach. These constrictions moved caudad a short distance and, at the same time, there was often some shortening of the whole gastric shadow. The taking of a little food or soda often caused the hunger distress to disappear and this suggested that an abnormal type of gastroperistalsis had been interrupted.

According to Rogers and Hardt (1915), hunger contractions were more susceptible to inhibitory influences than were digestive waves. Included in their list of inhibitory influences were sugar, quinine, sodium chloride, and weak solutions of acetic or hydrochloric acid. These caused prompt inhibition of the tonus and activity of the empty stomach. They found that chewing indifferent substances had only a slightly depressing effect on the movements of the empty stomach, whereas chewing or tasting palatable foods had a stronger inhibiting effect. They recorded that in humans the pains were inhibited for some time after giving water, dilute hydrochloric acid, alkalies, and food, but they were only slightly affected by the presence of air or carbon dioxide.

Despite all these useful contributions, Boldyreff (1904; 1911) is the only researcher who is generally given credit by modern gastroenterologists for pioneering work on the presence of contractions in the stomachs of fasting animals. Working with chronically fistulated dogs, he investigated all parts of the alimentary canal. His recordings from the fundic and pyloric portions of the stomach showed that from time to time the stomach walls contracted. Such gastric contractions had an average duration of 25-30 minutes and were broken into a regular pattern by periods of motor quiescence. He gave the average period, measuring from the beginning of one burst to the start of the next, as one-and-a-half to two hours (90-120 min).

Several recent studies (Atanassova, 1976; Papaşova et al., 1966, as cited by Papasova and Boev, 1976; Szurszewski, 1976) have sought to establish a correlation between slow potential (electrical activity) and contraction (motor activity) of the gastric smooth muscle during the inter-digestive state.

Atanassova (1976), experimenting on dogs in which bipolar ball-shaped silver electrodes were chronically implanted subserously on the wall of the stomach and duodenum, reported that during periods of relative rest, the bioelectrical activity of the muscle wall of the stomach of fasted dogs was characterized by slow potential changes of 4, 5, to 6 cycles per minute. During periods of hunger peristalsis, however, groups of spike potentials followed the slow potentials of the gastric wall. These groups of spikes had a duration of approximately 6 seconds and a period of 12 seconds.

Papasova et al. 1966, as cited by Papasova and Boev (1976), used chronically implanted electrodes and strain gauges on the gastric walls of cats and dogs. They established that the spontaneous slow wave generated by the gastric smooth muscle was always accompanied by contractions whether or not it was associated with spike potentials. They reported that the rhythmic slow waves followed by low-amplitude contractions were always recorded from the gastric wall during the relative quiescence of the stomach of a fasted dog. The appearance of strong motor activity was accompanied by the appearance of spike potentials. They found the duration of the slow potential to be within the range of 5 to 10 sec with a period of approximately 15 seconds. The burst of spikes had a duration of approximately 8 seconds and a period of 10 seconds.

Szurszewski (1976) studied isolated longitudinal muscle from the dog antrum. He reported that the strips exhibited spontaneous electrical activity which consisted of two components: a fast spike-like potential followed by a plateau-type potential. This spontaneous slow wave complex was found to measure approximately 15 mV in amplitude and 7 secs in duration with a period of 40-50 seconds.

A school of thought exists (Carlson et al., 1966; Code and Marlett, 1975) that interdigestive complexes can begin even when the stomach is not completely empty. This idea came from experiments in which radiopaque plastic spheres and saline were substituted for solid and liquid foods in an attempt to study the discriminating effect of the antrum on particle size during gastric emptying. It was found that the antrum was itself a major regulator, principally an inhibitor, of the emptying of the spheres, permitting the passage of only a sphere or two with the retropulsion of most of the spheres during vigorous antral contractions. Although such works have given important insights into the functions of the antrum, the idea that the presence of hunger contractions when spheres are in the stomach indicates the presence of interdigestive complexes when the stomach is not completely empty has recently come under critical analysis. Meyer (1980) points out that first, spheres and saline contain no food substances, such as fat, known to inhibit the emptying of liquid and solid meals; second, plastic spheres, unlike food, cannot be digested by gastric juices or mechanically fragmented, and therefore are practically nonexistent for the discriminating and sensitive chemoceptive mechanisms whose receptors are arrayed along the duodenum and proximal jejunum; therefore, the factors which control interdigestive complexes may be unaware of the presence of the spheres and saline.

Brown (1967), and Brown and Parkers (1969) began attempts to isolate an active substance from the duodenal mucosa. They had previously found that duodenal alkalinization stimulated an increase in motor activity in the autotransplanted fundic pouch of the dog stomach (Brown et al., 1966). In 1971, Brown et al. succeeded in purifying an active, immunoreactive, 22-amino-acid-residue polypeptide and named it motilin. The physiological significance of this newly isolated polypeptide remained obscure until Itoh et al. (1975) reported that motilin induces interdigestive bursts of contractions in fasted dogs.

In 1976, Itoh et al. demonstrated that motilin had no significant effect on gastric motor activity during the digestive state, which is the period when the stomach secretes acid and the intraduodenal pH is acidic. In 1978, Itoh et al. found a still closer relationship between the occurrence of interdigestive bursts and increases in plasma motilin during the interdigestive state in conscious dogs.

The relationship was that during the interdigestive state repeated episodes of high-amplitude contractions interrupted by long-lasting motor quiescence were seen to occur regularly until the next meal in the dog. Motilin concentrations were higher during the contractions than during the periods of quiescence.

In their study of 1980, Itoh et al. measured plasma motilin concentrations and intraduodenal pH together with gastric motor activity in dogs. When the dogs were fed once a day with a meal of constant quantity and quality, it was found that 24-hour changes in gastric motor activity consisted of two major patterns, the digestive and the interdigestive. During most of the interdigestive state the cyclical occurrence of a series of high-amplitude contractions and long-lasting motor quiescence was seen to occur regularly until the next meal. Table 1 shows values obtained from Itoh et al. (1980). It illustrates a wide variation in durations and periods in regular and irregular motor patterns. They reported that none of the dogs used showed regular changes in gastric motor activity all the time during the interdigestive state; moreover, even in dogs whose interdigestive motor patterns were generally regular, irregularities sometimes occurred.

Their plasma motilin concentration and intraduodenal pH

Table 1. Canine regular and irregular interdigestive motor pattern values (Itoh et al., 1980)

Dog	Regular bursts Duration (min)	Regular bursts Period (min)	Irregular bursts Duration (min)
A	17.9 ± 0.8	77 ± 3.2	174 ± 17.8
B	25.0 ± 1.8	77 ± 5.2	332 ± 17.3
C	23.1 ± 0.9	106 ± 3.8	68 ± 27.9
D	22.8 ± 2.6	81 ± 4.1	171 ± 35.8
E	13.8 ± 0.8	90 ± 4.6	75 ± 6.6
F	24.5 ± 1.1	127 ± 3.4	68 ± 6.7
G	24.0 ± 1.3	109 ± 2.3	93 ± 19.8
H	21.9 ± 0.9	122 ± 4.6	135 ± 28.5

investigations provided information on the mechanism by which the gastric motor activity during the interdigestive state becomes irregular. They found that as long as intraduodenal pH remained between 7.0 and 8.5 the regular occurrence of the interdigestive contractions was closely associated with increases in the plasma motilin concentration. However, when intraduodenal pH became acidic, there were no typical interdigestive contractions even though plasma motilin concentration was elevated. They reported that high-amplitude contractions like the interdigestive contractions could not be evoked in the acid-secreting stomach even if the plasma motilin concentration was elevated during the interdigestive state. They concluded that acid secretion during the fasted state, the cause of which is still unknown, seemed to be one of the main factors disturbing the regularity of the interdigestive motor pattern. They hypothesized that because a decrease in intraduodenal pH was usually observed during the latter half of the interdigestive period, the spontaneous secretion of acid in the fasted stomach might possibly be due to a conditioned reflex (e.g., anticipation of food) that evoked copious acid secretion (Itoh et al., 1980).

Meanwhile, Thomas and Kelly (1979) were also attempting to determine whether the interdigestive motor cycles of the canine proximal stomach were hormonally regulated. In four dogs, a pouch of gastric fundus and orad corpus was completely extrinsically denervated by auto-transplanting it in the left pelvis. Electrodes were implanted on the pouch, the main stomach, and the proximal small intestine. Intraluminal pressure was measured in the pouch during fasting, whereas, electrical activity was recorded concurrently from the pouch, main stomach, and small intestine. Pouch motility was found to be cyclical, with bursts of large amplitude contractions occurring at periods of approximately 108 minutes and durations of approximately 24 minutes. Judging from a displayed recording of intraluminal pressure during fasting, the maximum contraction was about 100 cm of H_2O (about 74 mm Hg). They however reported 61.2 $\pm$ 4.4 cm of H_2O (about 45.3 $\pm$ 3.3 mm Hg) as the mean amplitude of contractions during the interdigestive state. The bursts of large amplitude contractions were found in the pouch at the same time that bursts of intense action potential activity were detected in the main stomach and duodenum. Feeding 100 grams of liver abolished both pouch and duodenal bursts and decreased integrated pouch pressure tremendously after 20 min. They concluded that the interdigestive motor cycles of the canine proximal stomach and their abolition by feeding are hormonally regulated.

The hormonal regulation of gastrointestinal activity, including interdigestive complexes, is the subject of intense current experimentation. Several recent studies (Keane et al., 1980; Lee et al., 1980; Poitras et al., 1980) can be consulted for further information.

D. Endoradiotelemetry

One of the earliest circuits used to telemeter internal information is shown in Figure 4. Named after its inventor, the Hartley oscillator (Mackay, 1970) still has wide applicability in monitoring pressure changes especially in

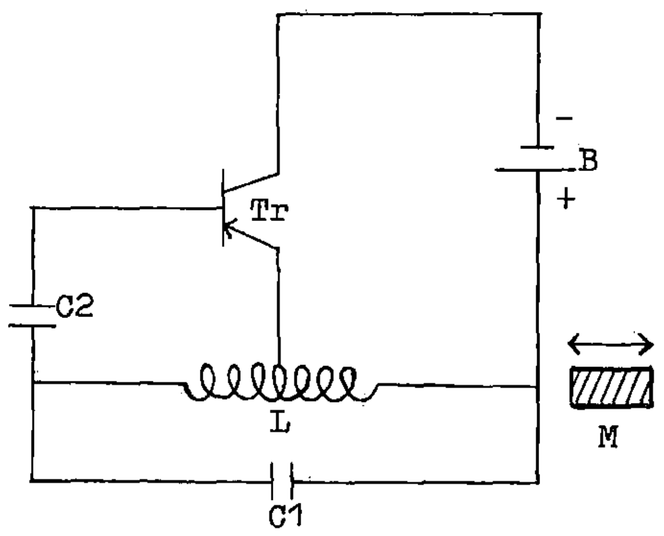


Figure 4. Original Hartley oscillator (redrawn from Mackay, 1970).

the gastrointestinal tract. It has a parallel arrangement of a center tapped coil (L) and a capacitor (C1). This parallel connection has a natural frequency of oscillation. Tr is a pnp transistor whose action maintains the oscillatory currents in the tuned circuit. A single cell battery (B) functions as the source of power for the oscillations. The second capacitor (C2) is required in the circuit to feed the signal that actually causes the maintenance of oscillations in the transistor.

If a metallic material (M) is suspended from a diaphragm and placed in the vicinity of the coil, then pressure changes on the diaphragm will cause motion of this metallic substance towards and away from the long axis of the coil, and this will in turn alter the frequency of oscillation by modifying the inductance in the circuit. If the metallic material is of ferrite, a ferromagnetic ceramic, an increase in pressure will cause a decrease in frequency. But if it is composed of some other conducting material, such as a thin piece of aluminum, then an increase in pressure will cause an increase in frequency.

The oscillator can be considered as a frequency modulated (FM) pressure-sensing radio transmitter. Figure 5 is a diagram of an FM mode of operation. The transmitter consists of all the elements from the patient to the transmitting

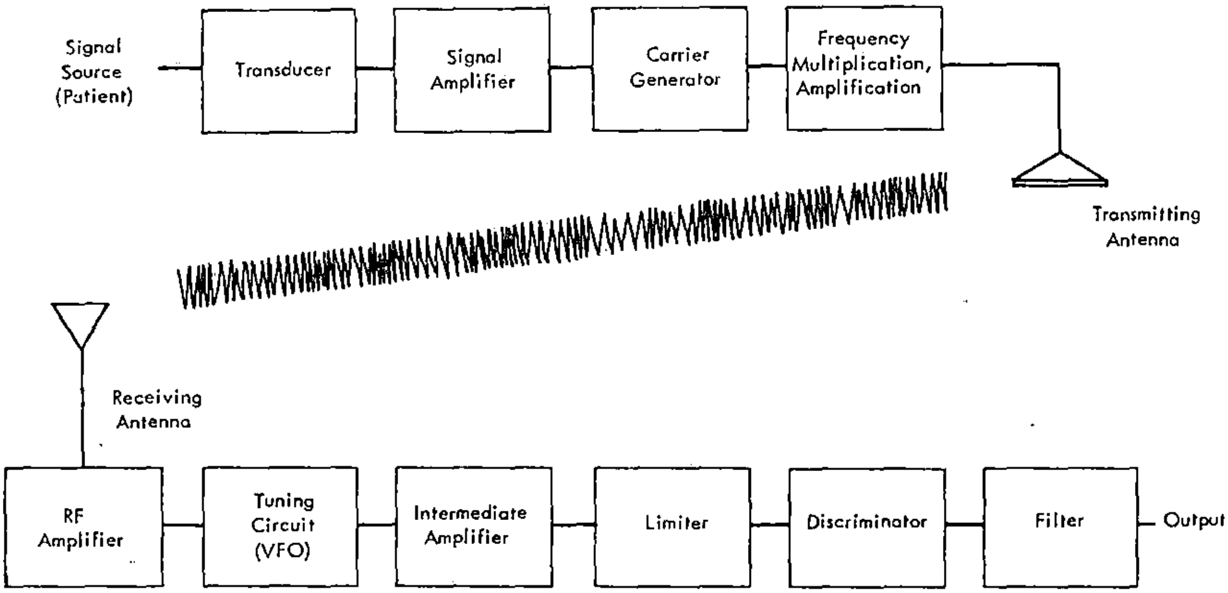
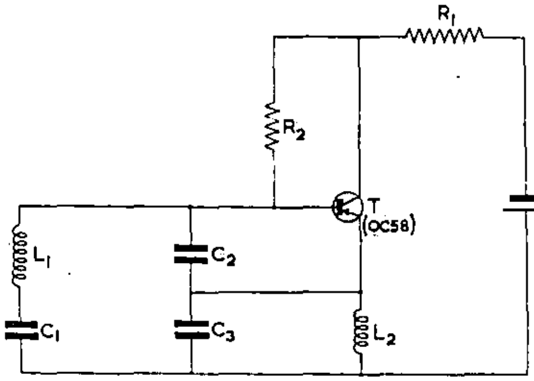


Figure 5. Simplified diagram of an FM radio system (Mackay, 1968)

antenna. The receiver consists of all the elements from the receiving antenna to the system output. The amplitude of the transmitted signal has no effect on the receiver. This step in receiving the signal provides one of the greatest advantages of FM systems; that is, small variations in amplitude of the incoming signal due to changes in orientation and attenuation play no role in reproduction of the received signal, and a limited (constant amplitude) signal is presented to the discriminator. The discriminator demodulates the signal, changing the varying frequency back to varying amplitude. This is then filtered and presented to the output. The signal is a faithful reproduction of that sent and variations of transmission strength present no significant problems.

Recently developed gastrointestinal radio transmitter circuits (Farrar and Zworykin, 1959; Jacobson and Nordberg, 1961; Watson et al., 1962) have not changed significantly from the original Hartley oscillator. For instance, a so-called Clapp oscillator (Figure 6a) used by Watson et al. (1962) is a modified Hartley oscillator in which an additional capacitor C3 has been added and the inductance coil has been split into L1 and L2. The inductance is created by wire wound on a small ferrite pot core and the magnetic circuit is completed by a disc of ferrite. The inductance depends on the air gap between this disc and the core,



Radio pill circuit.

Components

L_1 *90 turns of 47 s.w.g. (Pot core B 65501 M 25 O L) (R. H. Cole Ltd.)*
L_2 *300 turns of 47 s.w.g.*
C_1 *and* C_3 *0·001 micro-farad (Hunts Ltd.).*
C_2 *0·003 micro-farad (Hunts Ltd.).*
R 47k (Fortiphone Ltd.).
T 2N207 (Philco).
B RM312 (Mallory Battery Ltd.).

Figure 6a. Clapp oscillator (Watson et al., 1962)

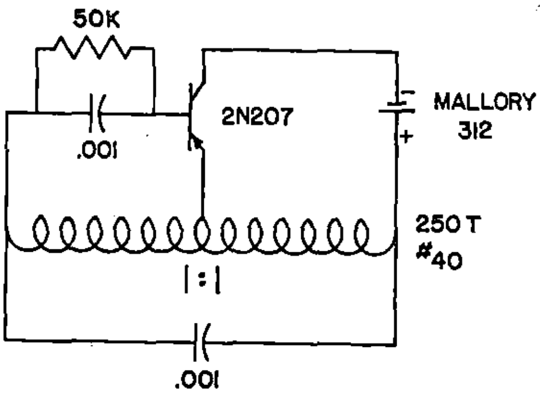


Figure 6b. Mackay oscillator (Mackay, 1959)

variations in the gap causing a change in the inductance, and this in turn leads to a change in frequency of oscillations. The carrier frequency is in the band 300 to 500 kHz and the modulation caused by a positive pressure decreases the frequency by approximately 20 kHz.

Figure 6b is another example of a Hartley oscillator (Mackay, 1959) modified to monitor temperature and pressure simultaneously from the human stomach. The 50 kilo-ohm base resistor prevents blocking action; the same Hartley principle that pressure changes on a diaphragm move a ferrite core to cause changes in the radio frequency of transmission underlies the function of this circuit.

Although swallowable pills, otherwise known as endo-radiosondes represent some of the earliest applications of telemetry to the field of biomedicine (Farrar and Zworykin, 1959; Jacobson and Mackay, 1957), most of them are still single channel devices for measuring temperature (Mackay, 1959; Nagumo et al., 1962), pH (Jacobson and Mackay, 1957) and pressure in a swallowable capsule (Farrar and Zworykin, 1959). Mackay's circuit (1959) for the simultaneous transmission of temperature and pressure may technically be called a dual-channel system, but otherwise a genuine multi-channel swallowable device has been extremely difficult to realize even with the advent of integrated circuits, due to the technically uncompromising miniature size specification set by such swallowable transmitters.

III. MATERIALS AND METHODS

A. Modified Hartley Oscillator

The transmitter used in this project is a modification of the Hartley oscillator which was described in the Literature Review section. A schematic diagram of this modified oscillator is illustrated in Figure 7. While Hartley's fundamental circuit was meant to operate just below the commercial AM broadcasting band, that is, around 400 kHz, slight modifications produced a unit which operates at 100 MHz levels.

The large resistor from collector to base functioned primarily to limit power drain and avoid waste of power; it also helped to prevent oscillations due to temperature changes. The oscillator coil and antenna consisted of number 22 wire wound around a nylon form. Through initial circuit analysis and subsequent experimentation it became evident that approximately four turns of the coil were needed to cause the system to oscillate at approximately 100 MHz and thus render the system detectable by the FM band (88 to 108 MHz) of the radio receiver. The four turns also produced the best radiating or transmitting results.

The RM 312 is an Hg-cell with an initial voltage of 1.35 volts. This could generate and maintain a constant operating voltage of about 1.2 volts for at least 72 hours. A silicon

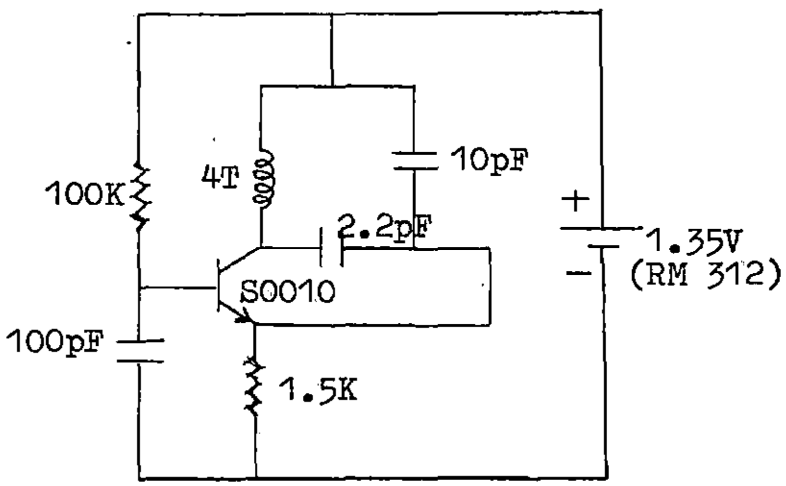


Figure 7. Modified Hartley oscillator

npn transistor (S0010) with automatic gain control was used to ensure a constant high frequency transmission. A ferrite or ferromagnetic ceramic core was used. Hence, pressure and frequency variations were inversely proportional to each other. Orientation sensitivity was minimized by the use of a ferrite core that was as light as possible.

A change in temperature can shift the output frequency of the transmitter. In this project, such a change was convenient because an immediate change in frequency after the dog had taken a sip of cold water indicated that the transmitter was still in the stomach and that it had not yet advanced into another portion of the gastro-intestinal tract.

A common problem during construction of the transmitter was saturation of the transistor, in which case no signal would be obtained. When this happened, simply disconnecting the collector junction of the transistor and reconnecting it at the same point as before caused the transmitter to oscillate.

B. Mechanical Layout of the Transmitter

Figure 8 illustrates how the circuit in Figure 7 was encapsulated for swallowing. The ferrite core whose motion caused the frequency changes was placed near the coil. The transmitter responded to changes in position of the core.

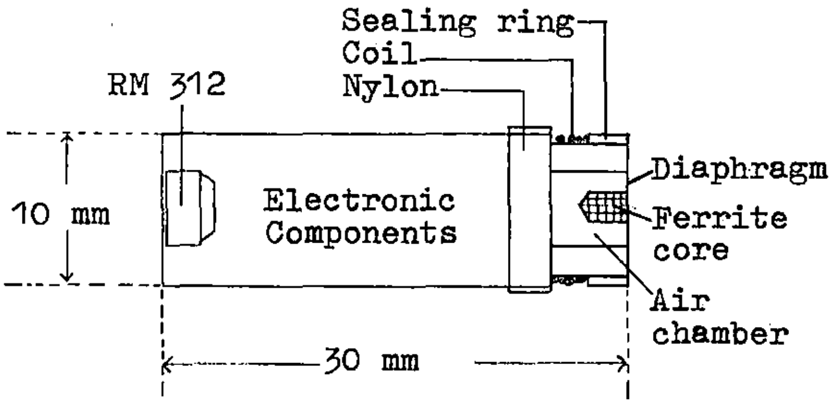


Figure 8. Mechanical layout of the transmitter

Changes in pressure could be sensed because a force in the air chamber restored the core to its initial position (frequency modulation). This restoring force was not provided principally by the elasticity of the diaphragm; rather, it was the compressibility of the air trapped behind the diaphragm which supplied the force, and as long as no leaks from the air chamber occurred, this force stayed fairly constant. Thus, air leakage from behind the diaphragm was carefully avoided by means of a sealing ring.

The construction design ensured that the diaphragm assembly could be quickly replaced in case of damage such as could occur during recovery from the body or during the cleaning process which was necessary before the capsule could be used in another experiment. The design also sealed off the battery end from the diaphragm.

C. Encapsulation of the Transmitter

A unique aspect of an implant or swallowable system is that it must be constructed to function while completely immersed in a body fluid. For this reason, the device had to be packaged in a material that could withstand the acidic contents of the stomach, as well as the fluids in other parts of gastro-intestinal tract.

After experimentation with different materials, silastic® medical-grade adhesive and rubber (silicone type A)[1] were found to be most suitable. The silastic® type A showed minimal signs of deterioration even after several weeks of immersion in an acid medium (pH = 3).

The silastic® medical-grade adhesive is an easily applied, translucent, nonflowing, soft paste, resembling white vaseline. The term "medical-grade" is applied to those silicones that fulfill a long history of successful implantation in animals and humans. They are manufactured under pharmaceutically aseptic conditions, and are especially quality controlled for medical purposes. Upon curing, they provide autoclavable bonds that are nonreactive and nontoxic to surrounding tissues. The silastic® type A is an example of the so-called Room-Temperature-Vulcanizing (RTV) silicone rubber which means that it does not require addition of a catalyst, since ambient water is enough to cause vulcanization to occur. However, because the water must penetrate the mass, its cure generally requires up to 30 minutes. A full cure can require 24 hours (Braley, 1970), but 30 minutes was sufficient for this application.

The physiological and chemical inertness of the silastic® medical-grade silicone rubber is why the diaphragm and the sealing ring in Figure 8 were both made of this material.

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[1]Dow Corning Corporation, Medical Products, Midland, Michigan 48640, USA.

As an adhesive, it was also used to seal all the points around the nylon-diaphragm unit where leaks were suspected. After the battery had been slipped into place, the entire construction was pushed into a tube of silastic ® medical-grade silicone rubber sheeting and made into a completed capsule as shown in Figure 9.

D. Calibration of the Transmitter

Following encapsulation, calibration was done at atmospheric and increased pressures. The transmitter was placed in a flask in which the pressure could be raised through a series of steps. It was found extremely convenient to use the rubber bulb from a blood-pressure measuring cuff to increase pressures in a controlled fashion. In this case successive steps corresponded to increases in pressure of 10 mm of Hg, as judged by a manometer. The transmitted signal was picked up by a loop antenna around the flask, fed through a receiver and demodulator, and applied to a recorder set for slow speed. The pressure characteristic is shown in Figure 10. The overall output plotted against the applied input yielded a linear response up to 40 mm of Hg. Beyond 40 mm of Hg the system became nonlinear. Further experimentation showed that pressures greater than 110 mm of Hg could be measured without distorting the linearity,

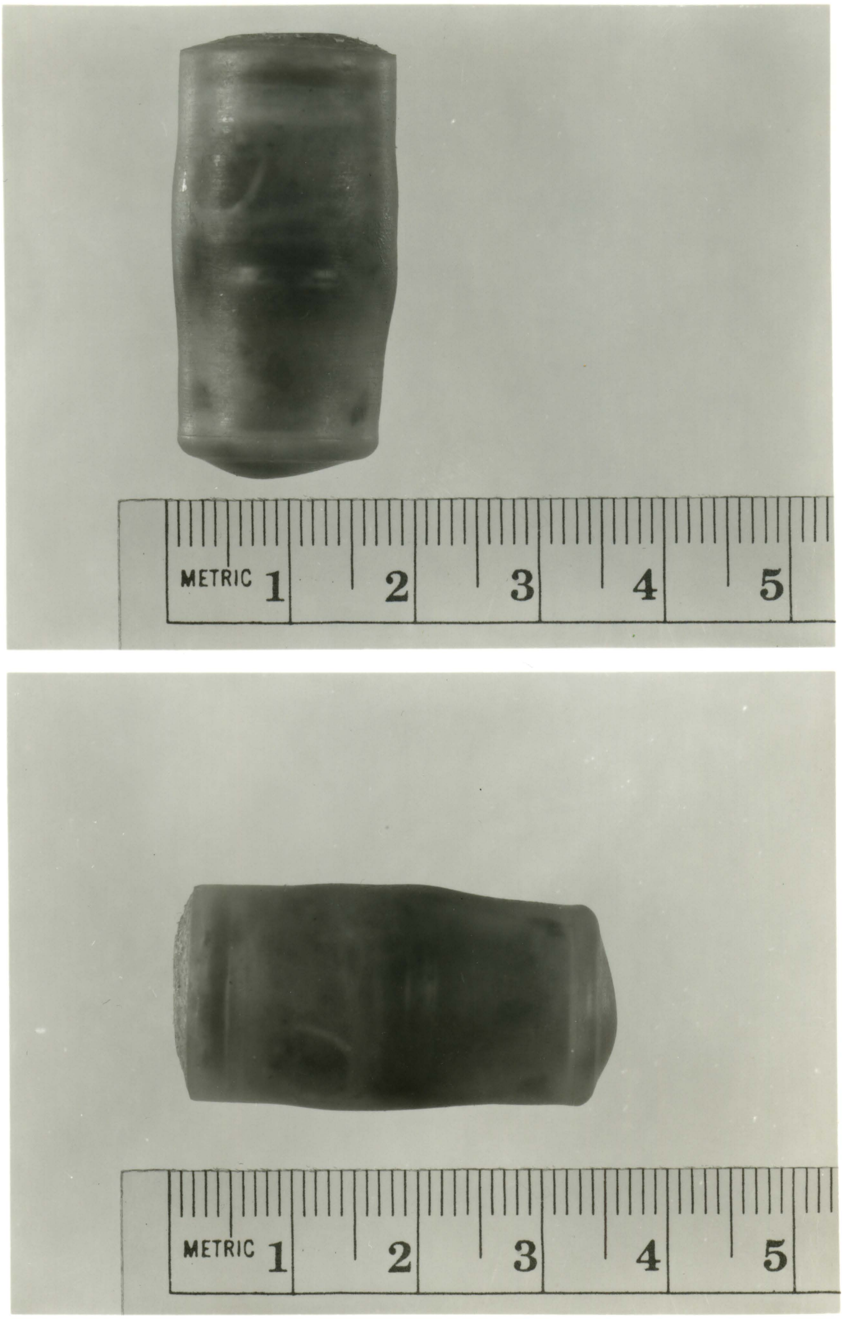

Figure 9. Completed FM radio telemetering transmitter (above: diameter ≅ 10 mm; below: length ≅ 30 mm)

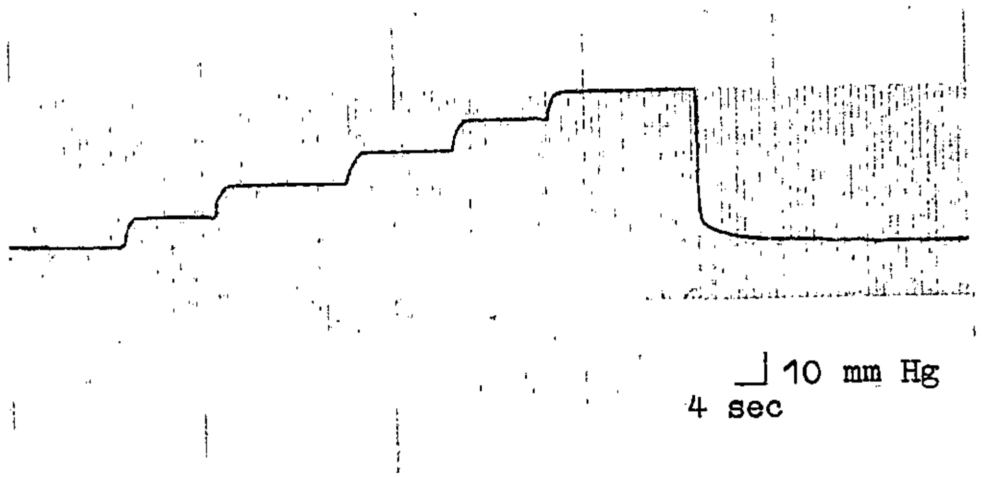

Figure 10. Recorded signal as pressure on the transmitter is increased in a series of steps

simply by increasing the thickness of the diaphragm, but this in turn reduced the sensitivity below the point of usefulness in terms of this experiment. The transmitter used in this exercise was very stable at a sensitivity of 40 mV/10 mm Hg. Higher sensitivities were possible but again stability considerations made it impractical.

A temperature-sensitive reactor was not used in this transmitter circuit. But, fortunately, any changes in frequency due to component variations, particularly in the transistor, caused the frequency to decrease whereas the air which was contained within the pill expanded with increases in temperature causing the frequency to increase; this tended to cancel out the two effects (Jacobson and Mackay, 1957).

E. Data Acquisition Process

The electronic pill (Figure 9) was sterilized prior to swallowing. This rendered it aseptic and thereby prevented any possible infection in the stomach due to contamination of the pill during the process of construction. To achieve this condition of asepsis, the capsule was completely immersed in a zephiran chloride solution for a minute or two. Following sterilization calibration was quickly rechecked.

A dog, which had been deprived of food for 24 hours (water was given at 12 hours to prevent dehydration), was anesthetized by intravenous injection with thiopental, an ultra-short acting barbiturate. The electronic pill was pushed down the esophagus into the stomach. This location was confirmed by fluoroscopic examination. A piece of veta-fil attached to the device was then sutured to the upper palate or, on one occasion, was passed through the nasal cavity and anchored using a button at the tip of the nose. This ensured that the device stayed in the stomach and transmitted information only from that portion of the gastrointestinal tract.

Once in the stomach, the transmitter was ready to pick up the message, code it, and finally transmit it to the receiver through the telemetry channel. It was possible to extend the useful working area of the transmitter by using a supplementary antenna of several turns of wire wrapped around the thoraxo-abdominal area of the dog. Alligator clips were soldered to the two ends of this wire and then coupled to the antenna of the receiver.

In this study the radio receiver was of the entertainment type shown in Figure 11. The receiver is inexpensive, rugged, well-engineered, reliable, uses readily available batteries, and covers both the AM (530-1600 kHz) and the FM (88-108 MHz) bands. Whenever the transmitter

SCHEMATIC DIAGRAM

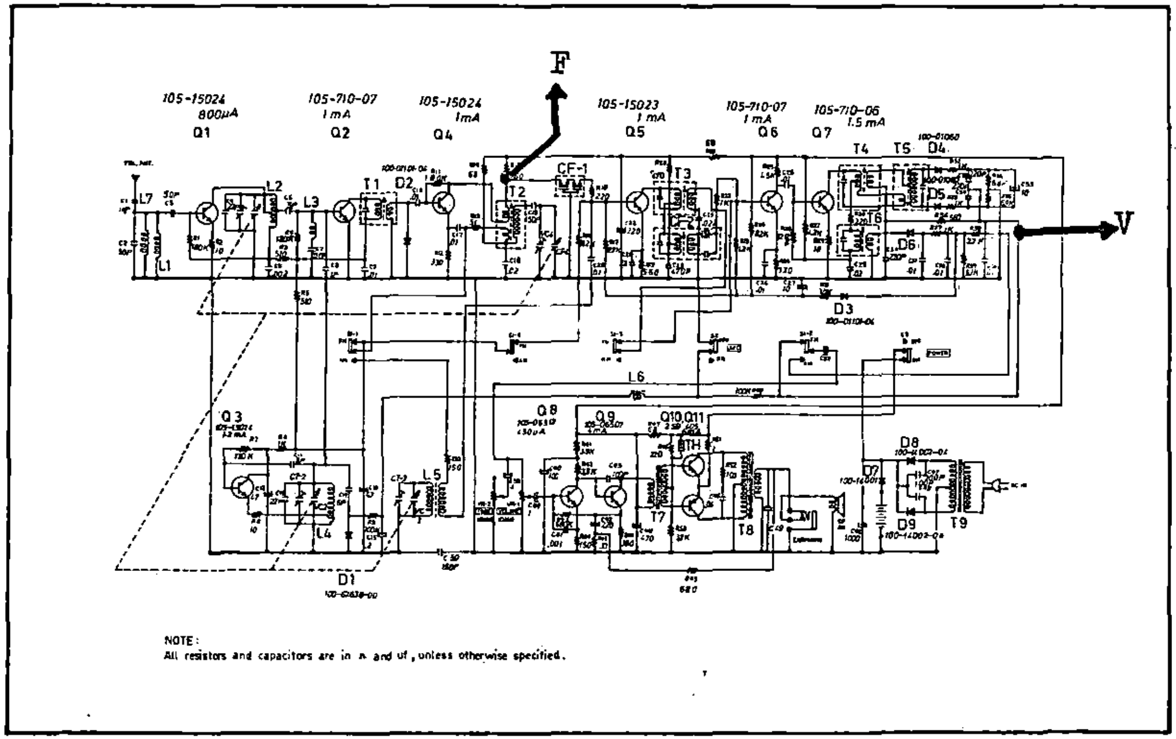

Figure 11. Radio receiver circuitry

was turned on and the receiver tuned to its steady frequency, nothing could be heard. Only modulation led to a sound at the speaker of the receiver. Also each time the transmitter was switched off or on, a click was heard at the time of switching. All these observations were clear indications that both the transmitter and the receiver were functioning in excellent coordination.

The FM receiver (Figure 11) is a so-called superheterodyne in which an incoming signal is mixed with the signal from a local oscillator to give an intermediate frequency (IF) of 10.75 MHz. This frequency is amplified and passed on to a filter that passes a fixed narrow range of frequencies (10.75 $\pm$ 0.05 MHz). In Figure 11 the arrow labelled F points to the position on the circuit where the IF can be tapped off and fed to a frequency counter for display.

With frequency modulated signals there are usually some small percentage changes in the frequency, and unless some subcarrier oscillator is used, this change will be in the radio carrier frequency itself[1]. The subcarrier has the advantage that a given frequency shift can be a large percentage change of the information-carrying frequency, yet will displace the overall radio frequency by a small percentage.

[1]Personal communication. Joe Riley, electronics engineer, National Animal Disease Center, Ames, Iowa.

Instead of using a subcarrier oscillator and redesigning the circuitry shown in Figure 7, an FM receiver equipped with automatic frequency control (AFC) can be used. Such an FM receiver incorporates a device for correcting small frequency changes. Discriminators for doing this are based upon properly tuned resonant circuits. This means that any slow variations in the output from the discriminator constitute drift, probably in the receiver itself, and are fed back to automatically retune the receiver in such a direction as to eliminate the discriminator signal, thus locking the receiver to the transmitter frequency as far as slow changes are concerned. This way any slow change in the transmitter frequency, even if it is real, is rejected as drift, and not recorded in the signal output, but all rapid components are considered to represent useful information.

The label V in Figure 11 shows the point at which the amplified output voltage was tapped away from the receiver and the signal fed to the Beckman R-611 dynograph for permanent recording. The Beckman R-611 dynograph recorder is a direct writing oscillographic recorder; it consists of five major components: input coupler, preamplifier, driver amplifier, galvanometer and a chart drive. The arrangement is illustrated in Figure 12. The preamplifier is a sensitive single-channel unit which amplifies the input from the level

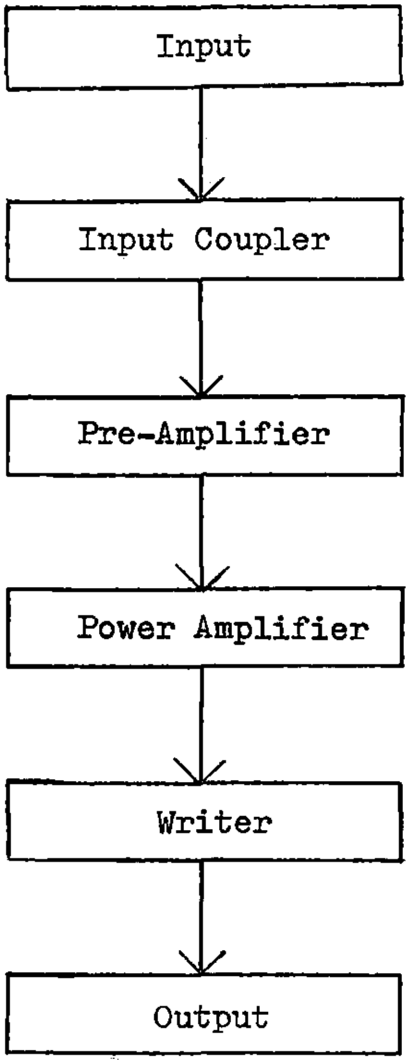

Figure 12. Essential components of the Beckman recorder

supplied by the receiver to a level which can be accepted by the driver amplifier. It has high input impedance, high common mode rejection ratio and low input noise. These characteristics ensure a true and precise recording of the input. The power amplifier adds additional gain to the signal. It also provides zero suppression, pen position control, high pass filtering, and the power necessary to drive the galvanometer. The galvanometer is an electro-mechanical device using a moving coil to drive the pen and cause it to write a permanent record of the input on the chart.

In each of the three dogs used, changes in gastric interdigestive motor activity were recorded without interruption for at least 24 hours. Experiments were terminated at that time so that the animals, which had been without food for 48 hours, could be fed.

IV. RESULTS AND DISCUSSION

A. Transmitter

The completed capsule (Figure 9) met most of the specifications governing other swallowable units (Watson et al., 1962; Jacobson and Mackay, 1957; Mackay, 1959) in terms of size, sealing, power, and design requirements.

In terms of energy per unit volume and constant voltage over the discharge period, the 1.35 volt, inexpensive, replaceable RM 312 mercury cell used to power the transmitter was satisfactory. It must be emphasized that it is imperative to select fresh batteries because it was observed that the battery life of old batteries can be considerably shortened and can cause loss of the signal before the end of the 24-hour recording period. If a long term study is desired, the nickel-iron-cadmium rechargeable cell has been recommended (Watson et al., 1962). The pill may be prepared with such a battery in place, and it need never be opened if an external recharging connection is provided. However, for studies of intermediate length, Hg-cells should be satisfactory since with a fresh RM 312 Hg-cell transmission continued for more than 48 hours after the 24 hours of operation inside the canine stomach.

The calibration results, as pressure on the transmitter was increased in a series of steps, are shown in

Table 2. THe carrier frequency is in the FM band 88 to 108 MHz (IF = 10.7 ± 0.05 MHz) and the modulation caused by a positive pressure of 40 mm Hg is such as to decrease the frequency linearly by approximately 22 kHz, and to increase the amplitude linearly by 160 mV. In comparison, the Clapp oscillator (Watson et al., 1962), operating in the 300 to 500 kHz band, yields linearly 20 kHz for a 40 mm Hg pressure change.

The characteristics of the silicon rubber of the diaphragm and the encapsulation did not permit any obvious degenerative effects of gastrointestinal fluids on the transmitter. Long-term changes may be possible but this was not verified. Since most of the resiliency of the system is supplied by the trapped air, any minor

Table 2. Typical calibration values for the transmitter

Applied pressure (mm Hg)	Voltmeter or Beckman R-611 (mV)	(ΔmV)	Frequency counter (CT-70) (kHz)	(ΔkHz)	
0	0	0	10730.0	0.0	↑
10	40	40	10724.5	5.5	
20	80	40	10719.0	5.5	Linear
30	120	40	10713.5	5.5	
40	160	40	10708.0	5.5	↓
50	201	41	10702.3	5.7	↑
60	242	41	10696.7	5.6	
70	276	34	10691.8	4.9	Nonlinear
80	312	36	10685.9	5.9	
90	356	44	10677.8	8.1	
100	394	38	10670.5	7.3	
110	431	37	10661.9	8.6	↓

disintegrative effects on the diaphragm over a 24-hour recording period could be ignored. There was some residual drift which could possibly be due to gas and water vapour diffusion into the capsule, but while such a minimal drift could interfere with long-term absolute measurements, it did not interfere with the observation of the interdigestive patterns.

B. Recordings

Figure 13 typifies the regularly patterned interdigestive contractions recorded from all dogs. This motor pattern was considered regular because it consisted of a series of high-amplitude contractions followed by long-lasting motor quiescence. Defining the duration of each burst as from initiation to termination of the burst, the recording in Figure 13 reveals a cyclical pattern of regular contractions during the interdigestive state of the dogs. Similar findings were reported by Boldyreff (1911), Roborgh (1966), Grivel and Ruckebusch (1972) and Itoh et al. (1980), all of whom used nontelemetric methods of study.

The period of the interdigestive contractions was taken to be the length of time from the termination of one burst of interdigestive contractions to the termination of the next. Such periods were sometimes regular for the first several hours of recording, and then, the recording became a mixture of regular and irregular periods similar to the

Figure 13. Canine regular gastric motor patterns in interdigestive state

results reported by Itoh et al. (1980). Table 3 shows mean duration, period and amplitude values for the regular patterns from the 3 dogs studied here. From Boldyreff (1904, 1911), Thomas and Kelly (1979), and Itoh et al. (1980) it can be generalized that during a regular motor pattern, a duration of about 13 to 30 minutes and a period of approximately 77-127 minutes are identifiable. The duration values in this study were in the range of those cited above, but the period values were considerably shorter. The highest mean amplitude of regular contractions, shown by dog C, reached only 11.06 $\pm$ 0.8 mm Hg in contrast to a mean of 61.2 cm of H_2O (45.29 $\pm$ 33 mm Hg) reported by Thomas and Kelly (1979). Given the differences in methods of investigation and the large variability among dogs, the results reported in this study seem reasonable.

A gastric motor pattern that did not conform to the criteria for the regular pattern was regarded as an irregular motor pattern. Figure 14 shows an example of an irregular interdigestive motor pattern. It was observed that usually, irregular contractions lasted much longer (over 3 hours) than the mean duration of regular bursts (about 12 to 18 min) due to the absence of conspicuous motor quiescence. This is in agreement with the findings of Itoh et al. (1980) in Table 1. In all three dogs the irregular patterns began not earlier than the last quarter of the total 24-hour

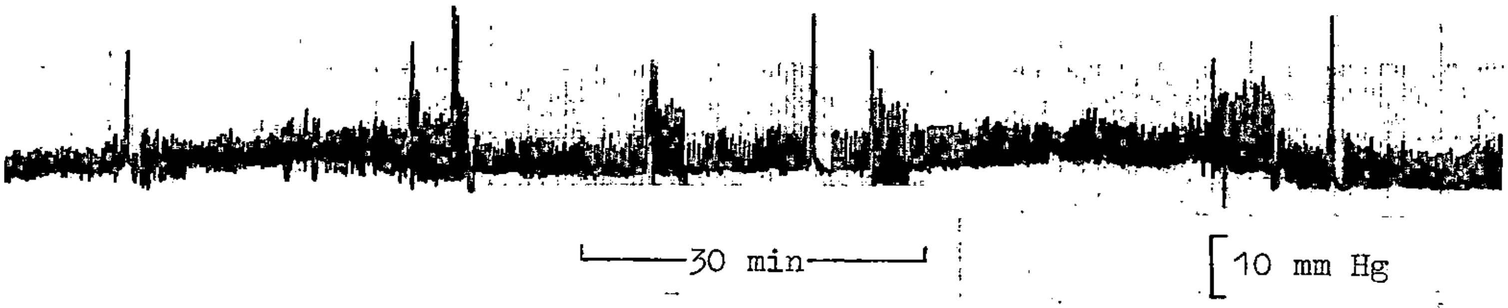

Figure 14. Canine irregular gastric motor patterns in interdigestive state

Table 3. Mean duration, period and amplitude of regular interdigestive contractions

Dog	Regular pattern Duration (min)	Period (min)	Amplitude (mm Hg)
A	13.9 ± 0.4	27 ± 0.8	10.46 ± 0.7
B	11.6 ± 0.3	51 ± 1.4	9.89 ± 0.5
C	17.6 ± 0.6	33 ± 0.9	11.06 ± 0.8

recording period. Once irregular contractions started, they continued uninterrupted by any motor quiescence until the dog was fed. Superimposed on the basic irregularities were regular bursts. Since recording was terminated after 24 hours, it was not possible to observe whether or not the typical regular bursts of contractions took place again after many hours of irregular motor pattern as reported by Itoh et al. (1980).

Judging from the mean amplitudes of the recordings in Figures 13 and 14, it can be concluded that the contractile force of irregular contractions is less than the contractile force of the regular bursts. This essentially agrees with Itoh et al. (1980) who reported the mean value of the irregular contractile amplitudes as being less than one-fourth of the typical regular contractile amplitudes.

Figure 15 shows the effect of feeding. The recorder

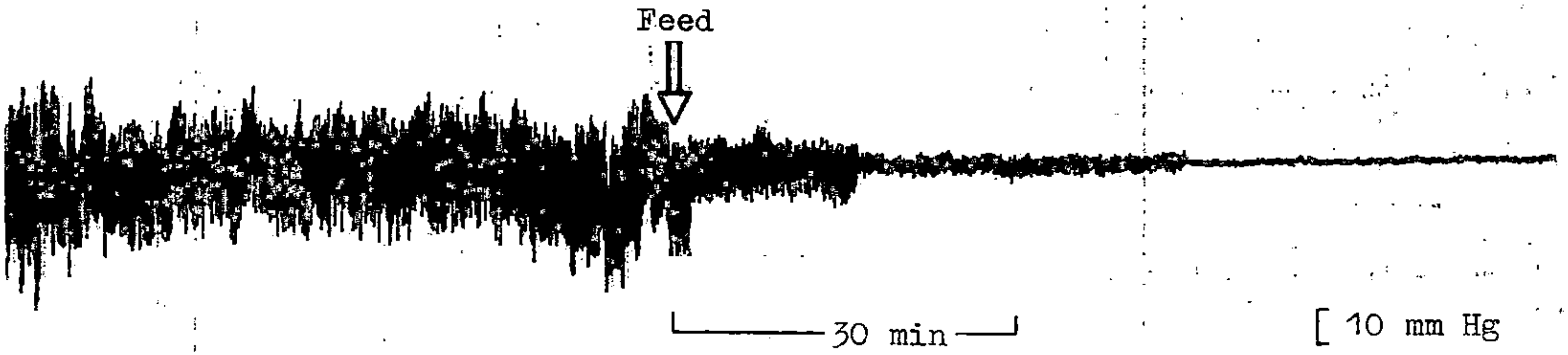

Figure 15. Effect of feeding on gastric interdigestive motor cycles

sensitivity was decreased to exaggerate the feeding effect. It was observed that all dogs were experiencing irregular patterns at the time they had to be fed. About 16 min after feeding, the patterns became abolished completely; this agrees well with the 20 min reported by Thomas and Kelly (1979). According to Itoh et al. (1980), the abolition occurred for both irregular and regular interdigestive motor cycles. This could not be observed in these experiments since none of the dogs was fed while exhibiting a regular pattern.

It is important to note that the baseline is not stable enough to guarantee reliable measurements of absolute pressure. The capsule worked well for this study mainly because a baseline shift was not important. The main interest was to determine whether the unit could pick up the cyclical patterns associated with the interdigestive complexes, and whether these complexes were affected by feeding the animal; therefore relative pressure changes were sufficient. Also, frequency cut-offs (Figure 16) during intense hunger contractions were not uncommon. This could not be controlled by merely scaling the sensitivity of the Beckman recorder down to a lower value. Thus, if one's interests are oriented towards evaluation of the corresponding absolute values of the interdigestive contractions, one will need to redesign the circuit shown in Figure 7 with emphasis on increasing

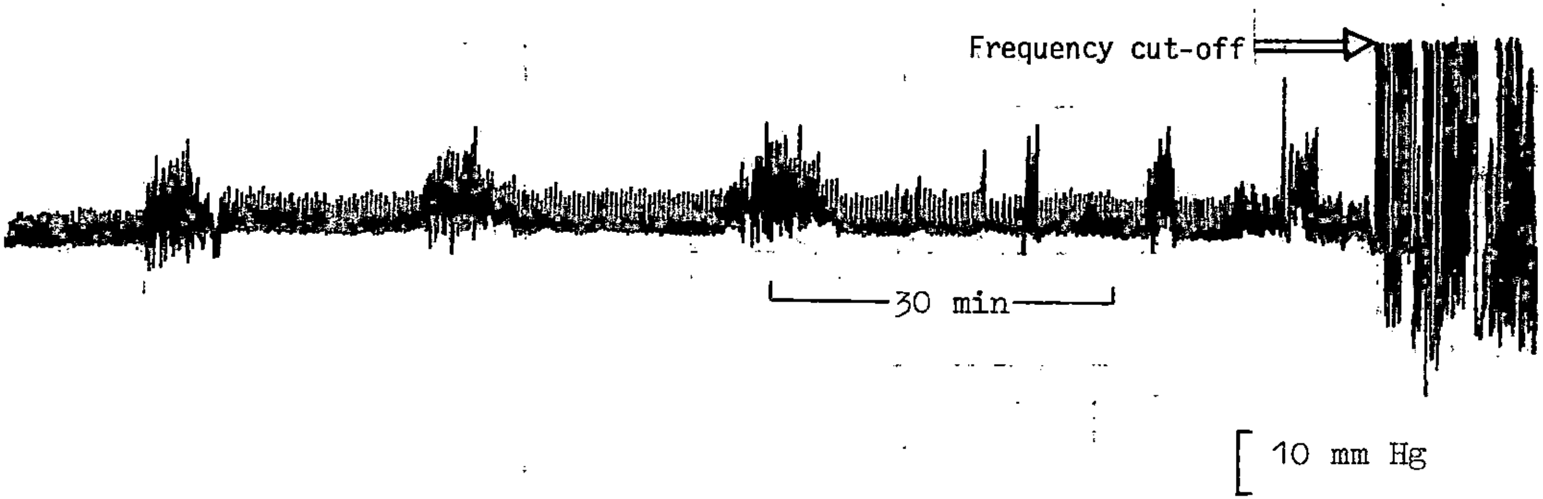

Figure 16. Illustration of frequency cut-offs during intense hunger contractions

the bandwidth.

Finally, the transmitter was anchored such that it contacted mostly the antral section of the stomach; hence it can be said that most of the gastric motor activity recordings came from the antral portion of the canine stomach. However, anchorage alone would not guarantee that the gastric interdigestive activities were being recorded from the antral portion of the canine stomach at all times because of the possibility that the transmitter would experience retropulsion due to antral activity.

V. CONCLUSIONS

In this study it has been possible to obtain records of canine gastric pressure fluctuations during the inter-digestive state by using a pressure-sensitive radio pill and a radio receiver. These recordings were similar to those obtained through traditional methods involving more cumbersome applications of contractile force transducers.

The records proved the existence of a clearly cyclical pattern in the gastric pressure fluctuations of all three dogs during the period of fasting. Some patterns were regular and dominated the first half of the records; others were irregular and predominant in the second half of the recording period. A specific pattern of alternations between regular and irregular cycles could not be observed probably due to the relatively short period of recording. Hunger contractions were usually more intense during the regular periods.

The pressure sensitive radio transmitting capsule thus possesses potential for the study of gastrointestinal inter-digestive complexes in clinical research. It can be swallowed without difficulty; the subject experiences virtually no sensation once the capsule is in the stomach. The recordings are completely free from any surgical influence. The observations can be reliable and readily available, and since the signal does not have to travel along a pneumatic tube, the frequency response is good. Once the circuit is designed, a transmitter is always easy and cheap to assemble, and its combination with an equally inexpensive but reasonably good quality receiver allows telemetry at minimum cost.

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