Intestinal smooth muscle electrical potentials recorded from surface electrodes*

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Abstract—*Electrical recordings have been made from cutaneous electrodes placed on the trunk with a view to establishing the source of the slow potential changes which can be recorded. Cutaneous recordings have been made on 16 normal subjects in both the fasted and fed states, and in some cases simultaneous recordings have been made from electrodes attached to the end of a naso–gastric tube and sucked onto the stomach wall. Frequency and correlation analyses have been used to help interpret the potential changes.*

A significant frequency component at approximately 3 cycles/min (average 3·02 ± 0·21/min) was found in 88% of the stretches of record analysed. It is shown that this is the basic electrical rhythm of the stomach. In a smaller number of recordings (28%), a significant frequency component at 10–12 cycles/min was found. The source of these rhythms has not been proven, but is likely to be from either the small or large bowel.

Keywords—*Intestinal e.m.g., Surface electrodes.*

Introduction

It is 50 years since Alvarez (1922) made some electrical recordings from cutaneous electrodes, which showed waveforms similar to those which can be recorded directly from the mucosal wall of the stomach. A few subsequent workers have made similar recordings (Sobakin, Smirnov and Mishin, 1962; Nelson, 1967); but the method has not been widely adopted. This slow growth has been caused by the technical difficulties in recording, and in extracting consistent information from the records. The last decade has seen a large increase in the understanding of the origins and function of the basic electrical rhythm (b.e.r.) of the smooth muscle of the gut. While most of this work has used recordings from mucosal or implanted serosal electrodes, the advantage in being able to use surface electrodes would be considerable.

The smooth muscle wall of the gut consists of many fibres (lengths approximately 100–400 μm) arranged in a matrix (Burnstock, 1970). As intestinal smooth muscle behaves as a syncytium (Bozler, 1948), the control of physiological function must be transmitted from cell to cell. While several mechanisms for this transmission have been proposed, the most widely accepted hypothesis is that electrical spikes are propagated by local current flow through low-resistance connections between cells (Prosser, 1962; Barr, 1963; Nagai and Prosser, 1963 *a* and *b*; Barr, Dewey and Evans, 1965). The 'tight junctions' often seen between cells

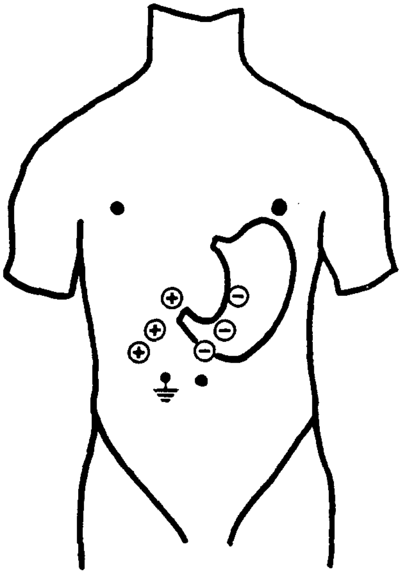

Fig. 1 Position of surface electrodes on the trunk. Three pairs were placed over the gastro-duodenal area. The cathode of the upper pair was halfway between navel and left nipple and the anode 8 cm to the right. The electrode separation of the other channels was also 8 cm. Electrodes for the impedance pneumogram were placed on either side of the trunk, level with the nipples and below the axilla

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in many smooth muscles (Burnstock, 1970) are now generally believed to be the site of the low-resistance connections which give electrical coupling.

Most intestinal smooth muscle is spontaneously active even when neural influences are removed (Bulbring, 1955; Nonomura, Hotta and Onashi, 1966), but the mechanism of this automaticity is not known. A number of workers have modelled the electrical activity of the stomach and small intestine by a series of linked relaxation oscillators with varying intrinsic frequencies (Nelson and Becker, 1968; Sarna *et al.*, 1970; Brown *et al.*, 1971). The spontaneous electrical activity or basic electrical rhythm (b.e.r.) of the stomach is at a frequency of approximately 3 cycles/min and bears a 1:1 relationship to the mechanical contractions of the stomach when these are present. While the b.e.r. recorded at different sites in the stomach changes in shape or phase, the frequency is constant. As the whole of the stomach is therefore controlled by a single frequency of b.e.r., it seems reasonable that there should be reinforcing external current flow which will be detectable from surface electrodes.

Recordings from the human small intestine show a frequency plateau for the b.e.r. in the first and second parts of the duodenum, but a frequency gradient more distally in the small intestine (Daniel *et al.*, 1968; Duthie *et al.*, 1972). While it would seem likely in principle that the resulting current flow from the duodenum might give detectable external current flow, the frequency gradient for the rest of the small intestine should give cancellation in the components of external current flow.

The purpose of the work to be described was to discover the source of the electrical signals which can be recorded from surface electrodes. The possibility of obtaining electrode artefacts or mechanical artefacts from movement of the gut has been explored, and various methods of signal processing have been used. The subjects have all been normal controls, and we have found that consistent records of gastric electrical activity can be recorded for 90% of the time; in some cases, signals from more distal parts of the gut may be obtained.

Methods

(*a*) *Technical*

Electrodes were placed on the trunk as shown in Fig. 1, three pairs being over the 'gastroduodenal area' and the fourth pair placed across the chest and used to record respiration from an impedance pneumograph. Silver/silver-chloride electrodes (ES type EM 202) were used in all cases, and at least an hour was allowed to pass after attaching electrodes before recordings were started. The skin was prepared by abrasion with fine emery cloth and electrode jelly (ES electrode cream) was used. If recording was started within an hour of attaching electrodes there was often a large amount of electrode 'noise' and respiratory artefact.

The three electrode pairs were taken to differential amplifiers with the specification in Table 1.

Table 1

Differential input impedance: 20 MΩ
Frequency response (3 dB points): 0·016–1·0 Hz
Common-mode rejection ratio (50 Hz): 80 dB
Voltage gain (at 0·1 Hz): 40 dB
Noise referred to input: 10 μV p-p
(Source impedance: 10 kΩ)

The amplified signals were recorded on magnetic tape (SE 8/4 f.m. recorder) from which they could be replayed either onto an ultraviolet recorder or into a computer terminal for further analysis.

The impedance respirometer passed a current of 1 mA at 100 kHz between the electrodes placed across the chest and sensed the changes in impedance. While this method is open to a number of criticisms as a measure of lung volume, it does form a convenient means of recording respiration. The pneumograph output was also recorded on tape and used to identify or eliminate respiratory artefacts on the electrical recordings.

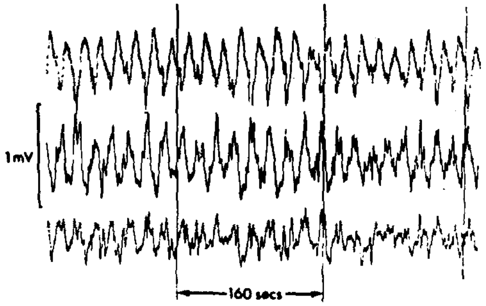

Fig. 2 Recording made from surface electrodes placed as in Fig. 1. The three traces correspond to the upper, middle and lower electrode pairs, respectively. There is an obvious rhythm at approximately 3 cycles/min in the upper and middle traces

(*b*) *Experimental*

Recordings have been made on 16 normal subjects both in the fasting state and immediately following a meal. The subjects had no known disorders of the g.i. tract and had an average age of 27 years (range 21–33 years). Electrodes were attached 60 min before the first recording session of 1½ hours. The fasted subjects were placed in a supine position and asked to remain relatively still during the recording session. At the end of this period a meal was given. The meal was not controlled as it was not intended to identify the response to specific gastric content.

The meal was completed within 30 min, after which time a further $1\frac{1}{2}$ h recording was made under the same conditions as the first session.

(*c*) *Analytic*

The electrical records contained 'noise' in addition to the wanted intestinal signals. In order to reduce these unwanted signals and also to identify 'conducted' waveforms, both Fourier analysis and correlation methods were used.

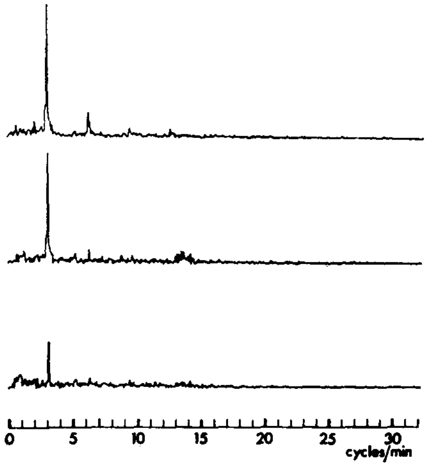

Fig. 3. Frequency analyses of the signals shown in Fig. 2. There is a large component at 3·15 cycles/min in all three channels

The Fourier analysis was made using a fast Fourier transform program on a system 4/40 computer. Records were digitised at 3·3 characters/s to an accuracy of 8 binary bits and analysed in 4K word blocks. This corresponds to block lengths of 20 min, giving four complete analyses for each $1\frac{1}{2}$ h recording session. The analysis was performed on all three electrical channels and also on the respiration records.

For some records the autocorrelation function was calculated in order to assess the periodicity of the data, and also the crosscorrelation function between channels in order to determine phase displacements. Both functions were produced by a hard-wired correlator (Biomac 1010) and displayed on an *xy* plotter.

Results

The electrical records contained a number of signals and 'noise' in addition to what was thought could be gastric electrical activity. However, a significant component at approximately 3 cycles/min (average 3·02 ± 0·21 cycles/min) was found in at least one channel for 88% of the analysed records.

Fig. 2 shows a record made from a fasting subject, and in this case a repetitive waveform with a 20 s period is visible in two of the three channels. The frequency analysis of this record (Fig. 3) shows clearly a large component at 3·15 cycles/min in all three channels. Before drawing any further conclusions the origin of the 3 cycles/min waveform needs to be established.

Four possibilities have been considered:

(*a*) the signals are an electrode artefact

(*b*) the potential changes do not arise from the stomach but from another 3 cycles/min oscillator

(*c*) the signals are the result of mechanical artefacts from the gut

(*d*) the potential changes arise from the b.e.r. of the stomach.

Taking these possibilities in turn:

If (*a*) were the case, it seems likely that electrode position would not be critical. In five recordings a pair of electrodes were placed on the arm and the potential changes recorded. The amplitudes of the signals from the arm were in all cases less than those from the gastric area, and in no cases were consistent frequency components obtained. A typical record is given in Fig. 4. It seems unlikely, therefore, that the potential changes recorded over the gastric–duodenal area are the result of electrode artefact.

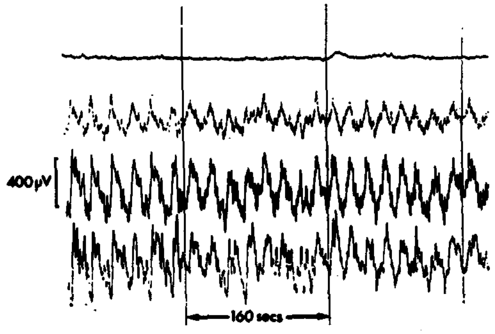

Fig. 4 The upper trace was recorded from electrodes placed 8 cm apart on the arm. No consistent activity can be seen. The lower three traces were recorded from electrodes on the trunk, and a 3 cycles/min rhythm is present in all three traces

The second possibility, that a 20s-period oscillation is generated elsewhere than in the stomach, is more difficult to refute as there are many sources of electrical potential in the body that have not been investigated. The low frequency of the components recorded makes it most unlikely that any striated muscles are responsible. Surface electromyograms have shown components ranging from 10 Hz to 5 kHz (Brown, 1969). Even respiratory patterns are

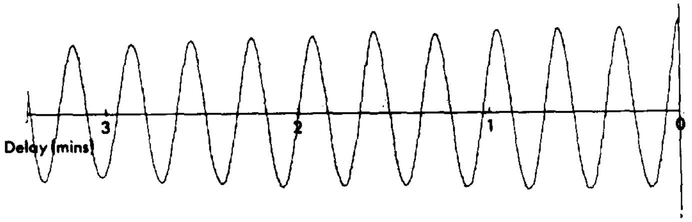

Fig. 5 The autocorrelation function plotted against time delay for the upper trace of Fig. 2

at a higher frequency than the recorded waveforms, and simultaneous respiration records have shown that the results are not respiratory artefacts. The most likely alternative source of 20 s-period signals is smooth muscle. Various frequencies have been reported from the length of the gut. While discrepancies exist in the literature Table 2 is representative of reported human recordings.

Table 2

Site	Frequency of b.e.r. cycles/min	Workers
Stomach	3	Alvarez and Mahoney (1922)
Duodenum	11·7	Bass *et al.* (1961) and Christensen *et al* (1964)
Ileum	6·5–9·3	Waterfall *et al.* (1972)
Transverse colon	8·4–10·6	Couturier *et al.* (1969)
Sigmoid colon	6–9 and 3	Taylor (1973)
Anal canal	1·4 and 16	Wankling *et al.* (1968)

Whilst some 3 cycles/min activity has been found in the colon, it has only been found for approximately 5% of recording time. It appears that the stomach is the only source of regular 3 cycles/min activity in the gut although there is a paucity of data in many cases. Vascular smooth muscle is another possible source of slowly changing electrical signals; however, the relatively small volume of muscle and its wide distribution make this an unlikely case.

The conclusion is therefore that there are no obvious alternative sources of 3 cycles/min activity to the stomach.

Possibility (*c*), that the mechanical activity of the stomach is giving rise to artefacts, is not consistent with the regularity of the recorded activity. While there is a 1:1 relation between the b.e.r. of the stomach and mechanical activity when this is present (Monges *et al.*, 1969), the mechanical activity is not present all the time. Calculation of the auto-correlation function for the electrical records illustrated in Fig. 3 shows that the activity is consistent (Fig. 5). If there were 'missed beats', the autocorrelation function would decay more rapidly to zero. Further evidence against possibility (*c*) is given by the recordings made before and after a meal. The mechanical activity would be expected to

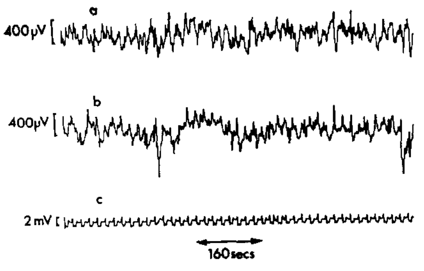

Fig. 6 Electrical recordings made from (a) and (b) surface electrodes placed as for the upper and lower pairs of Fig. 1; (c) a mucosal suction electrode. No gastric pressure waves were present during this recording. Both mucosal and surface recordings contain a 3 cycles/min rhythm

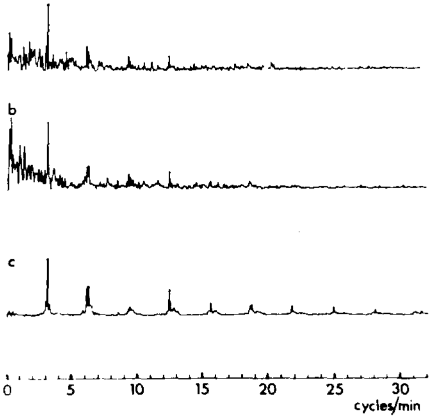

Fig. 7 Frequency analyses of traces (a), (b) and (c) of Fig. 6. A large fundamental at 3 cycles/min is present in all three analyses

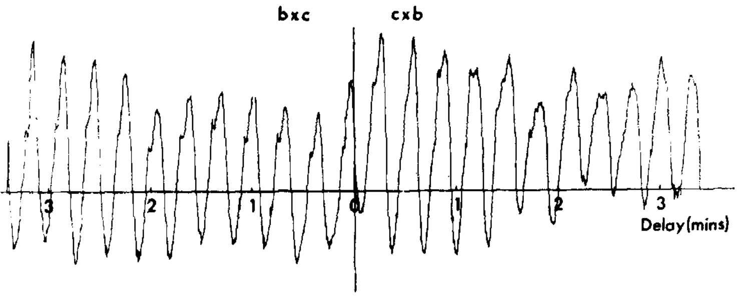

Fig. 8 The crosscorrelation function plotted against time delay for simultaneous mucosal and cutaneous electrode recordings. The subject was the same as for Figs. 6 and 7

increase after the meal (KWONG, 1972). While the surface electrical recordings we have made show an increase in amplitude of the 3 cycle/min component by 150%, the number of occasions on which the activity is recorded is not changed significantly by the meal. The increase in amplitude could arise from the closer proximity of the electrodes to the distended stomach.

Evidence to support the fourth possibility, that the electrical recordings have their origin in the stomach, was obtained by making simultaneous recordings from the surface and from mucosal suction electrodes attached to a naso-gastric tube. The mucosal recordings were made in the manner described by KWONG (1972). Fig. 6 shows simultaneous recordings, Fig. 7 the corresponding frequency analysis and Fig. 8 the corresponding crosscorrelation function. There is excellent correlation between the two waveforms. The probe from which the mucosal recording was made also contained a fine open-ended tube which was used to record gastric motility. Electrical activity at 3 cycles/min was recorded from the surface electrodes even when there was no mechanical activity recorded. This provides further evidence that what is being recorded is the gastric b.e.r. and not a movement artefact.

In 9 of the 32 recordings, consistent activity was found at a frequency between 10 and 12 cycles/min (average 10·8 cycles/min) during some part of the $1\frac{1}{2}$ h recording. This activity was found almost exclusively in the records made in the fasting state. While the activity is near respiratory frequencies and respiratory artefacts were often obtained, simultaneous monitoring of respiration enabled the waveforms to be separated (Fig. 9). The higher-frequency activity did not appear preferentially at any one recording electrode site.

Discussion

The results presented show that electrical recordings from cutaneous electrodes of gastric b.e.r. can be obtained with a high success rate if the means are available for a frequency analysis of the records. While our present recording success is high, initial experiments gave disappointing results. Choice of electrodes, careful skin preparation and the time for which electrodes were attached were found to be important. At the very low frequencies involved, amplifier frequency response and low noise also contribute greatly to the ease of recording. The overall success rate was 88%, although in any one subject the percentage might be considerably less. This success rate compares quite favourably with other electrophysiological measurements which are used as diagnostic tools. However, the amount of information which can be extracted from the recordings is limited. While an electrocardiograph can be recorded and diagnostic value attached to the waveforms as well as the frequency, only the amplitude, repetition frequency and regularity of the gastric b.e.r. can be determined from the cutaneous

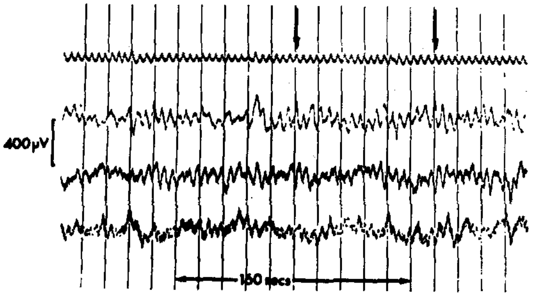

Fig. 9 The lower three traces show recordings from electrodes placed as in Fig. 1 in a fasting subject. The upper trace is an impedance pneumogram. Activity at approximately 10 cycles/min is visible in two of the electrical recordings and is not a respiratory artefact. Between the arrows there are 20 respiratory cycles but only 17 cycles of the electrical rhythm

recording. Nonetheless, there is an unexploited potential for the use of this method which can be applied with no trauma to the patient.

The source of the signals with frequencies between 10 and 12 cycles/min, which were recorded from many subjects, is less certain than the 3 cycles/min rhythms. The waveforms were certainly not a respiratory artefact and they did not originate in the skin electrodes. The most likely source is some part of the smooth muscle of the gut, but simultaneous records from mucosal and cutaneous electrodes, such as were obtained for the gastric b.e.r., are needed to establish the source with certainty. Electrical rhythms at 10 to 12 cycles/min have been found in both the small and large intestines by a number of workers, and our cutaneous electrode sites were such that the signals could result from either position. The most likely source would be at a point of frequency plateau so that external currents would be reinforcing rather than cancelling. The fact that nearly all our recordings of higher-frequency activity were made in the fasting state could well be explained by the changed position of the gut with respect to the recording electrodes after a meal. The recorded gastric b.e.r. was very much increased in amplitude after a meal, and is consistent with the distended stomach being close to the cutaneous electrodes after the meal and hence displacing the small and large bowel. The relatively small percentage of recording time for which higher-frequency activity was found can be explained either as an absence of signals at source or by nonoptimal position of cutaneous electrodes. While there is evidence that electrical activity from parts of both the small and large bowel is not present for 100% of the time, there is a need for cutaneous recordings from many electrode sites before a firm conclusion can be reached.

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Potentiels électriques du muscle intestinal lisse, enregistrés à l'aide d'électrodes superficielles

Sommaire—Des mesures électriques â partir d'électrodes cutanées appliquées sur le tronc, ont été enregistrées dans le but d'établir la source des changements de potentiel lents pouvant être observés. On a fait des enregistrements cutanés sur 16 sujets normaux â jeun et après un repas, et dans certains cas, des enregistrements simultanés on été entrepris sur des électrodes reliées à l'extrèmité d'une sonde nasogastrique et aspirées contre la paroi stomacale. On a entrepris des analyses de corrélation de fréquence afin d'assister à l'interprétation des changements de potentiel.

On a trouvé une composante significàtive de la fréquence á environ 3 cycles par minute dans 88% des bandes d'enregistrement analysées. On démontre que ceci est le rythme électrique de base de l'estomac. Dans un nombre moins élevé d'enregistrements (28%) on a trouvé une composante significative de la fréquence à 10 à 12 cycles par minute. On n'a pas découvert la source de ces rythmes, mais il est possible qu'ils possible qu'ils proviennent soit du gros intestin, soit de l'intestin grêle.

Durch auf der Haut angebrachte Elektroden aufgezeichnete elektrische Potentiale der glatten Darmmuskulatur

Zusammenfassung—Durch auf der Bauchhaut angebrachte Elektroden wurden elektrische Werte aufgezeichnet, um die Ursache für die langsamen Änderungen des potentials zu finden, die sichtbar wird. An 16 normalen Personen wurden Hautaufzeichnungen nach Fasten und Nahrungsaufnahme vergonommen. In manchen Fällen wurden gleichzeitig Aufzeichnungen von Elektroden am Ende der Rachenspeiseröhre vorgenommen, die von der Magenwand angesogen wurden. Zur Interpretation der Potentialänderungen wurden Frequenz- und Korrelations-analysen verwendet.

Bei 88% der Aufzeichnungen wurden bedeutende Frequenzelemente bei ca. 3 Schwingungen/min (im Durchschnitt 3,02 ± 0,21 /min.) bei Analyse festgestellt. Es wird demonstriert, dass dieses der basische elektrische Rhythmus das Magens ist. Bei einem kleineren Teil der Aufzeichnungen (28%) wurde ein bedeutendes Frequenzelement bie 10–12 Schwingungen/min. festgestellt. Die Ursache für diese Rhythmen wurde noch nicht bewiesen. Sie liegt jedoch wahrscheinlich im Dünn- oder Dickdarm.