ELECTROGASTROGRAPHY

signal analytical aspects and interpretation

ELECTROGASTROGRAFIE

signaal analytische aspecten en interpretatie

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE GENEESKUNDE
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krips repro meppel

PROMOTOR: PROF. DR. G. VAN DEN BRINK

Aan mijn ouders,

waarvan mijn moeder helaas geen getuige meer kan zijn

Aan mijn dieren en dierbaren

VOORWOORD

Dit proefschrift werd bewerkt binnen de afdeling Medische Technologie van de Erasmus Universiteit Rotterdam. Velen hebben bijgedragen aan de totstandkoming ervan, waaronder in het bizonder staf en medewerkers van

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- de afdeling Interne Geneeskunde II;
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CONTENTS

1. INTRODUCTION AND OBJECTIVES OF THE STUDY

Electrogastrography is defined as the recording of the myoelectrical activity of the smooth muscles of the stomach by means of cutaneous electrodes attached to the abdominal skin. The recorded signal is called an electrogastrogram.

On October 14, 1921, Walter Alvarez attached two electrodes to the abdominal skin of a 'little woman' and connected the leads to a very sensitive string galvanometer. The abdominal skin was so thin that gastric peristalsis was easily visible. The repetition frequency of the sinusoidal configuration of the recorded potential variations, being 0.05 Hz, corresponded to the repetition frequency of the gastric waves passed by, proving the gastric origin of the electrical signal. Alvarez stated: 'The first human electrogastrograms are here presented' (Alvarez, 1922). However, he never succeeded in deriving electrogastrograms from other persons. All the same he may be considered to be the pioneer in the study of myoelectrical and mechanical behaviour of the stomach endowed with great prophetic gifts. Most of his observations predominantly made from recordings derived with electrodes attached to the serosal wall of the stomach in test animals (which he denoted also electrogastrograms) command great respect since in our eyes only primitive equipment was available.

From literature it seems that little progress has been made concerning the myoelectrical activity of the stomach until the sixties. About that time, when improvements in electronics made recordings much easier to perform, an enormous increase in interest in this topic occurred, resulting in a vast amount of publications. Many of the findings of Alvarez have been rediscovered by other investigators. The reason for this conspicuous interest arose from the growing notion that the myoelectrical activity of the stomach plays a dominant role in controlling gastric functions, more or less similar to the electric activity originating in the sino-atrial node does in the heart. It was felt to be reasonable at that time to expect that gastric motility disorders would be accompanied by a disturbance of the electrical activity and that the electrical activity would therefore be of a diagnostic significance.

It became clear that two types of electrical activity could be distinguished on the distal stomach: The always present, not contraction related, *electrical control activity,* normally propagated in aboral direction and the so-called *electrical response activity* which is only present when contractions occurred and that is locked to the electrical control activity.
In Chapter 2 we will give a more detailed description of the electrical activity and the related mechanical behaviour of the stomach. The understanding and interpretation of electrogastrographically derived signals did not occur hand in hand with the increasing knowledge of the intra- and extracellularly measured signal characteristics. As may become clear from the literature survey given in Chapter 3, many authors claimed diagnostic significance for the electrogastrogram but unfortunately 'these claims were reported with inadequate experimental detail and without a good statistical background' (Smallwood, 1976). As a consequence these claims were not convincing. Moreover, since most authors performed studies using only abdominal electrodes and reference signals were not derived simultaneously from the stomach itself, it has remained unclear for long what exactly is measured in electrogastrography.

The extracellularly measured myoelectrical activity of the stomach is a reflection of the intracellular electrical activity of the smooth muscle cells originating in ion shifts from the intracellular to the extracellular space and vice-versa, thereby regulating the contractile behaviour of the cells. Whereas extracellular recording techniques (with electrodes located in the immediate proximity of the cells) provides detailed information about the electrical activity of groups of cells, surface recording techniques will only provide global information about the electrical (and mechanical) activity of the stomach. Smout, Van der Schee and Grashuis (1980a) concluded from a comparative electrogastrographic study in the dog (i.e. also serosal electrodes and force transducers were implanted) that the repetition frequency of the electrical control activity constituted the dominant *frequency* in the electrogastrogram while the *amplitude* was related to the presence of the electrical response activity. Both, the sinusoidal configuration of the electrogastrogram and the electrical response activity related amplitude changes could be described with the aid of a model in which depolarization and repolari-

zation of the gastric muscle cells were represented as dipoles.
Furthermore, Smout (1980) described the characteristics of the recorded electrogastrograms in both dog and man and demonstrated the *potential* usefulness of electrogastrography in (clinical) practice. However, a prerequisite in order to achieve the ultimate goal of electrogastrography, namely the *actual* clinical usefulness whether as a screening method or as a reliable diagnostic tool, is the development of more sophisticated analyzing techniques leading to

1° an improvement of the fundamental knowledge of the relationship between the *waveform* of the cutaneously measured signal and the myoelectrical characteristics as measured with serosal electrodes, and

2° an accessible technique with which (clinical) relevant information can be extracted from the electrogastrogram.

In this thesis both these aspects are dealt with.
In Chapter 4 the major objective was to develop a digital filter method in order to remove various kinds of noise and disturbances from the cutaneous signal without distortion of the waveform, phase and amplitude of the *gastric component*. The waveform thus obtained lends itself to a better comparison with serosally derived waveforms.
A more detailed study dealing with waveform analysis (Volkers, Van der Schee and Grashuis, 1983) is given as an Appendix. In that study a coherent averaging technique is presented in order to answer the question whether surface electrodes located at well-defined positions on the abdominal wall could 'see' different electrical active parts of the stomach.
In both above mentiones studies the *dog* was used as an experimental animal.
In Chapter 5, being the main part of this thesis, the concept of running spectrum analysis is introduced into the field of electrogastrography. The major objectives were

1° to search for a fast and concise way of representing electrogastrographically obtained data, and

2° to investigate to what extent the myoelectrical characteristics as measured with serosal electrodes could be interpreted from the running spectrum.

In this chapter both, data obtained from the *dog* as well as from *man* are dealt with.

2. ELECTRICAL AND MECHANICAL ACTIVITY OF THE STOMACH

2.1 Introduction

The main physiological function of the stomach is to process food in such a way that, after the ingestion of a meal, small portions of chyme are gradually propelled into small bowel. Different parts of the stomach account for optimum regulation. The smooth muscles of the fundus and the proximal part of the corpus (see Fig.1) exhibit a relaxation after food intake accompanied by a decrease in tone.

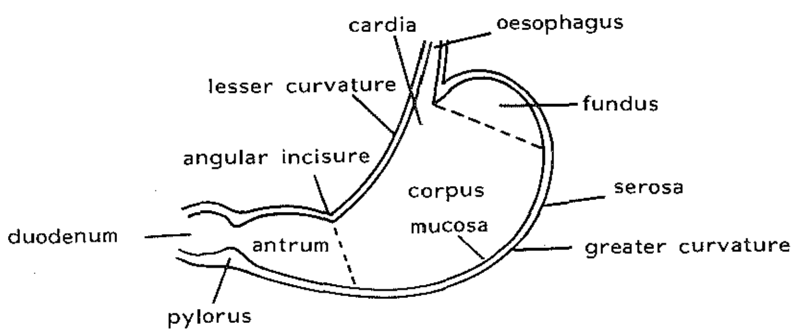

Fig.1. Macroscopic anatomy of the stomach.

This behaviour is essential for the temporary storage of a large meal. The relaxation phase is followed by a slow restoration of the tone. Tonic contractile activity moves the gastric contents to the distal part of the stomach where phasic contractions occur, propagating aborally to the pylorus. Small portions of the chyme are propelled into the duodenum, amongst others depending on the momentary diameter of the pyloric sphincter, while the bulk of the chyme is retropropelled in oral direction, thus accounting for mixing and grinding.
The underlying control mechanism, especially with respect to the distal part of the stomach, is of electrical nature. Although the proximal part is not completely electrically silent when measured with *intracellular* recording techniques (Morgan and Szurszewski, 1978; Morgan et al., 1980)

no electrical activity can be recorded by *extracellular* recording techniques.
The smooth muscle cells of the distal two-third of the stomach generate cyclic recurring change of electrical potentials, which can be picked up by extracellular electrodes.
Many names have been given to this *always present* periodic potential. In this thesis we will use the terms 'initial potential' (e.g. Daniel, 1965), 'control potential' (e.g. Sarna and Daniel, 1973) and 'electrical control activity' (ECA) (Sarna, 1975) which are commonly used and that are conform the terminology used in previous publications.
The ECA originates somewhere in the orad corpus as was demonstrated by transection experiments of the longitudinal and circular muscle layers of the stomach (Weber and Kohatsu, 1970; Kelly and Code, 1971). Thus, like the heart, the stomach may be considered to have a pacemaker from which the ECA is generated. However, a histologically identifiable group of pacemaker cells has never been described. According to Weber and Kohatsu (1970) the region on the greater curvature where a group of longitudinal smooth muscle fibers originates, can be considered to be the anatomical correlate of the pacemaker area.
The ECA sweeps distally through the longitudinal muscle fibers to the pylorus, where it vanishes (Kelly and Code, 1971).
In the dog the period between every generated ECA amounts to 10 to 12 seconds. The amplitude of the ECA (when measured monopolarly with extracellular electrodes) is in the order of 1 mV in the corpus and 3 mV in the antrum (Kelly et al., 1969). The propagation velocity increases towards the pylorus: from 0.1 - 0.2 cm/s to 1.5 - 4.0 cm/s in the distal antrum (Daniel and Irwin, 1968). Hence, *two or more ECA fronts are simultaneously present* on the stomach wall. In man the interval duration between successive ECA's is in the order of 20 seconds. The amplitudes show the same behaviour as those in the dog, but the propagation velocity differs: about 0.3 cm/s in the corpus and 1.0 cm/s in the antrum (Hinder and Kelly, 1977).
The gastric pacemaker, like the cardiac pacemaker, is present throughout life, but the gastric pacemaker, unlike the cardiac, *does not always have contractions associated with it.*
The ECA is followed by specific potential changes when contractions occur. They have become known under several alternative names. We will use the terms 'second potential' (Daniel, 1965), 'second component' (Papasova et

al., 1968) or 'electrical response activity' (ERA) (Sarna, 1975). Fast pulse like potential changes (spikes) may be superimposed on the ERA. In its spread over the stomach the *ECA determines the position, the direction and the propagation velocity of contractions*. Contractions may occur or extinguish at each level in the distal stomach.

The extracellularly recorded electrical activity is a reflection of the *intracellular activity* of the smooth muscle cells. The knowledge about intracellular electrical activity of gastric smooth muscle cells was obtained from *in vitro* studies on longitudinal and circular muscle strips, using microelectrodes inserted into the cell (e.g. El-Sharkawy et al., 1978), pressure and suction electrode techniques (e.g. Bortoff, 1967, 1975) and the sucrose-gap technique (Szurszewski, 1975).
No significant difference seems to exist between intracellular electrical characteristics of dog, cat and man (see Fig.2).

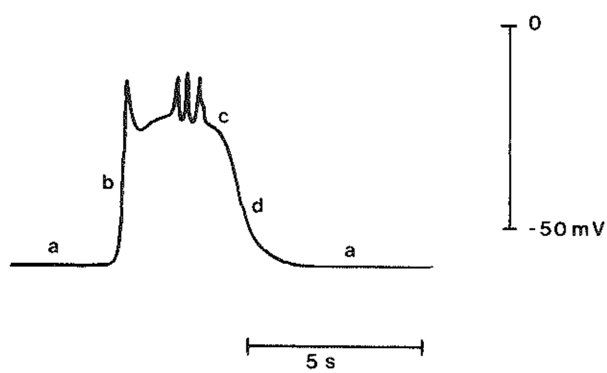

Fig.2. Configuration of the potential changes in gastric smooth muscle cells.
a: resting membrane potential
b: depolarization
c: plateau, which may or may not bear spikes
d: repolarization

The resting membrane potential (Fig.2,a) of the muscle cells involved is about -70 mV. The amplitude of the depolarization (b) in the corpus and in the antrum is in the order of 30 and 45 mV, respectively (El-Sharkawy et al., 1978). The depolarization rate also increases in aboral direction.

Values of 0.54 V/s in the corpus to 2.15 V/s in the pyloric region have been found.
In mechanically inactive tissue, the plateau (c) is completely absent (Daniel, 1975) or of small amplitude and duration (Szurszewski, 1975). Contractile activity appears to be associated with the formation of a plateau, while the transition between depolarization and plateau consists of a partial repolarization. Stronger contractions are associated with higher plateaus of longer duration and a higher velocity of repolarization (see Fig.3).

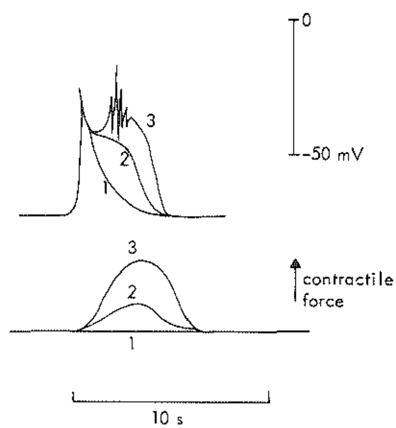

Fig.3. Intracellular electrical configurations of antral smooth muscle cells and the corresponding (qualitative) contractile behaviour (after Daniel, 1965; Papasova et al., 1968; Szurszewski, 1975).

Figure 4 shows the relation between intracellular electrical activity, extracellular electrical activity (monopolar) and contractile force as may occur in the distal canine antrum schematically.
For a detailed description of the characteristics of the myoelectric activity of the stomach and techniques of recording, both, from reported results in literature and from own investigations, the reader is referred to the thesis of Smout, 1980: 'Myoelectrical activity of the stomach; gastroelectromyography and electrogastrography'.

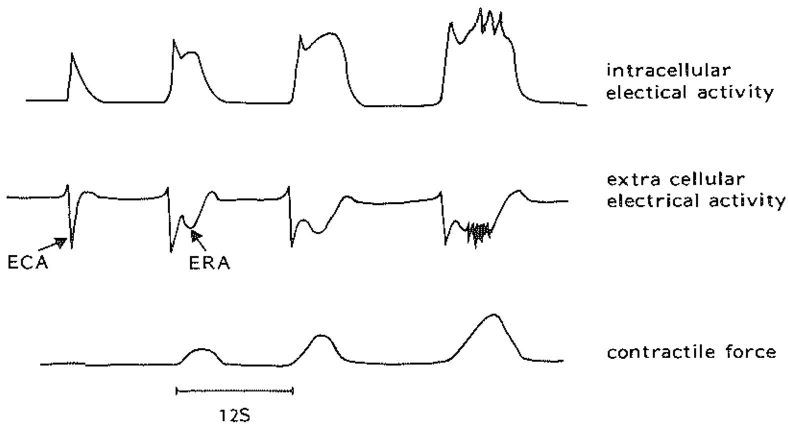

Fig.4. Schematically drawn relation between intracellular, extracellular and contractile activity respectively, occurring in the canine antrum.

2.1.1 Interdigestive activity

In the interdigestive state, the stomach is mechanically inactive most of the time. Only the ECA fronts are propagated aborally with constant interval times between the successive ECA's, as depicted in Fig.5.

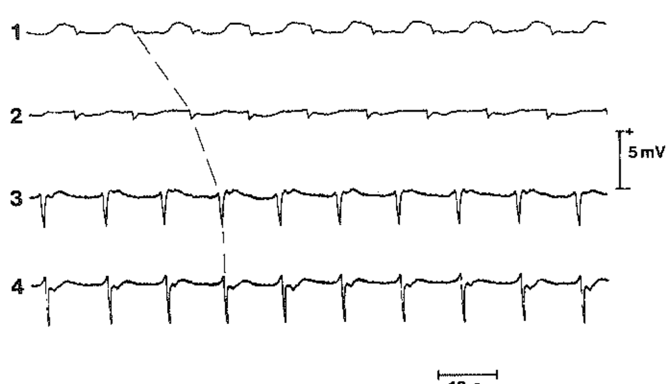

Fig.5. Monopolarly recorded canine serosal signals in the fasted state during the period of motor quiescence. Electrodes 1-4 located at 12, 7, 4 and 2 cm from the pylorus respectively (from Smout, 1980).

In 1969 Szurszewski found recurring fronts of intense spike activity in the small intestine of fasting dogs which migrated slowly down the entire small bowel (in about 1½ hours). When such a front reaches the terminal ileum, another one developed in the duodenum.
In 1975 Code and Marlett observed that the so-called interdigestive myoelectric complex (IDMEC) also occurs in the stomach (see Fig.6).

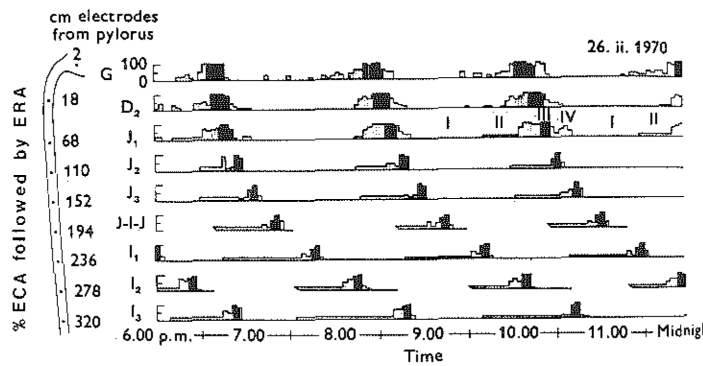

Fig.6. Three interdigestive myoelectric complexes. Roman numerals designate the phases described in the text. Black vertical bars represent the activity front. Note that the complexes migrate distally from the stomach and duodenum to the terminal ileum (from Code and Marlett, 1975).

They further divided the interdigestive pattern into four phases. During phase I there is no ERA or spike activity. Phase III represents the activity front and the phases II and IV are transition phases. Phase III lasts for about 12 minutes in the stomach.

The *motor correlate of the IDMEC* has been described by Itoh and co-workers (Itoh et al., 1977, 1978) using strain-gauge force transducers located all over the gastrointestinal tract.

Whereas Code and Marlett (1975) described the gastric activity front as characterized by the presence of maximum ERA with each control potential, our observations are in accordance with the description of the motor correlate of the activity front reported by Itoh et al. (1977); i.e. phase III in the antrum consists of *groups* of strong contractions being alternated by short periods with weak or absent contractions, as illustrated in Fig.7.

Fig.7. Electrical and mechanical activity of the canine stomach during the activity front of the interdigestive migrating complex. Bipolar electrodes 1-4 were located at the same positions as in Fig.5. Force transducer FT.A and FT.B were located opposite electrodes 2 and 4 respectively. C is a cutaneously derived signal and 4' was monopolarly derived from electrode 4.

As can also be observed in Fig.7 the occurrence of contractions are associated with a considerable variation in interval time between successive ECA's. Hence, gastric IDMEC, when present, could be recognized from the interval function, as demonstrated by Smout, Van der Schee and Grashuis (1979), who used an ERA-score as a measure for contractile strength (see Fig.8).

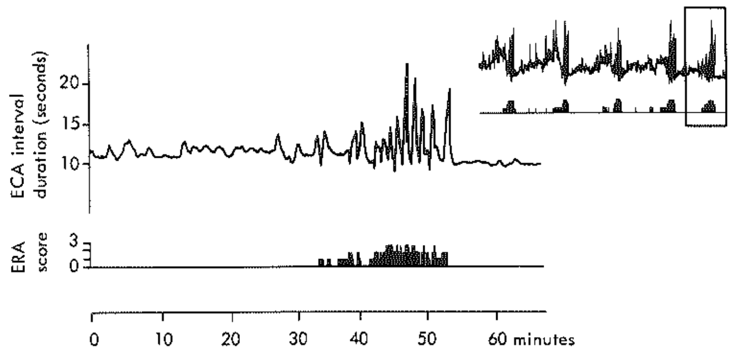

Fig.8. Interval function and plot of ERA scores showing an IDMEC cycle that is the last of 5 cycles shown in the inset (from Smout et al., 1979).

In fasting dogs we did not always observe gastric interdigestive migrating complexes (IMC's). Sometimes a so-called 'minute rhythm' was seen, characterized by a few consecutive strong contractions alternated with episodes of motor quiescence of 1 to 3 minutes of duration. Although such a behaviour may be attributed to gastrointestinal disorders (Carlson et al., 1972; Vantrappen et al., 1977b; Aeberhard and Bedi, 1977) we concluded that gastric IMC in general is not as stable as its intestinal counterpart (Smout et al., 1979).

Interdigestive motor activity in man has been studied mainly manometrically (e.g. Vantrappen et al., 1977a, 1977b; Lux et al., 1980). The IMC pattern resembles that described in dogs, although it seems to be somewhat less regular with regard to periodicity and the point of origin (Vantrappen et al., 1977b).
Functionally, the activity front may be considered to act as a gastrointestinal housekeeper sweeping the bowel periodically clean (Code and Schlegel, 1973; Mroz and Kelly, 1977). Bacterial overgrowth in the small intestine was reported (Vantrappen, 1977b) in cases where phase III of the IMC was not present in humans.

The underlying control mechanism of the IMC is not yet clear. A vast amount of publications appeared in recent years, regarding this phenomenon. They deal with hormonal, neurogenic and secretory aspects. These numerous investigations, which are still in progress, will not be dealt with in this thesis.

2.1.2 Postprandial activity

After the ingestion of a meal, a so-called fed pattern is induced and the IMC is disrupted, not only in the stomach but simultaneously in the entire small intestine. The duration of the disruption depends on the volume of food and on its physico-chemical composition (e.g. Ruckebusch and Bueno, 1976). The postprandial pattern is characterized by the occurrence of contractions of mediocre strength (compared with those of the activity front of the IMC), after each ECA (see Fig.9).

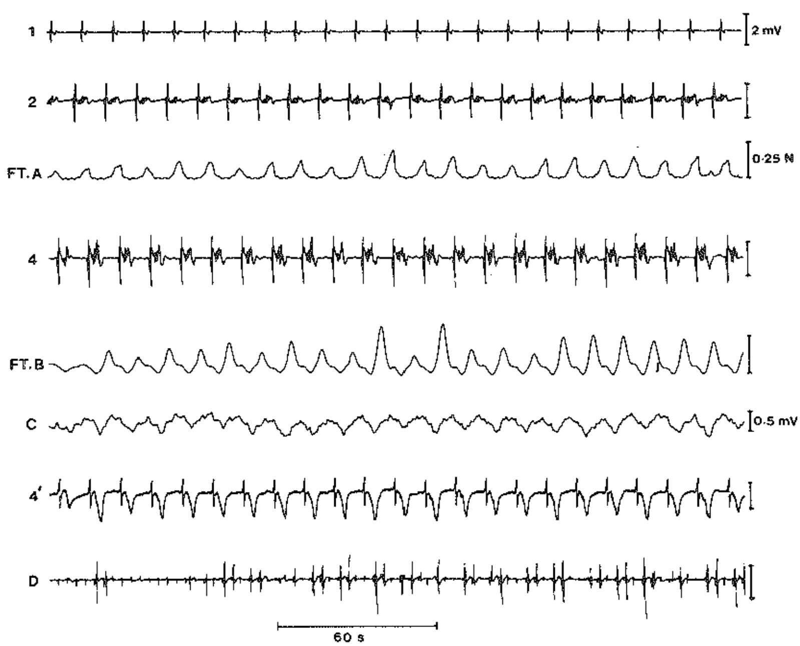

Fig.9. Electrical and mechanical activity of the canine stomach and electrical activity of the proximal duodenum during the postprandial state.
Electrodes and force transducers were located at the same positions as in Fig.7. C is the cutaneously recorded signal, 4' was monopolarly derived from electrode 4 and D shows the bipolarly recorded duodenal electrical activity at 2 cm from the pylorus.

Immediately after food intake, in man the repetition frequency of the ECA decreases significantly, followed after about 10 minutes by an increase in frequency to above the fasting value (Duthie et al., 1971). In contrast with man, in dog a decrease in ECA frequency was observed. It remained stable during the entire postprandial state (Smout et al., 1979).
Whereas gastric emptying of liquids is predominantly controlled by tonic contractions of the proximal part of the stomach, the phasic aborally propagated antral contractions account for emptying of solid meals (Kelly, 1980).

3. ELECTROGASTROGRAPHY

3.1 Introduction

As is the case for many internal electrically active organs in the body, electrical potential changes generated by the stomach can be picked up with the aid of surface electrodes attached to the skin.
Analogously to terms like electrocardiography and electroencephalography the term 'electrogastrography' has been designated to the method of recording gastric electrical activity from cutaneous electrodes. Although in literature sometimes 'electrogastrography' is used for serosal and/or mucosal recordings of gastric potentials (e.g. Alvarez, 1922; You et al., 1980b), the term 'gastroelectromyography' is much more suitable in such cases, in our opinion.

In this thesis the abbreviation 'EGG' will refer to both, *electrogastrography* and the signal recorded with it, called *electrogastrogram*.
With regard to the amplitude of the generated potentials the stomach is the most electrically active internal organ next to the heart. It may therefore be considered to be remarkable that surface recordings have not yet been introduced to routinely practical application.
In the next section the lines along which our insight in the EGG has progressed in the course of years towards a method that brings possible (clinical) usefulness within reach, will be traced. In section 3.3 the electrogastrographic *recording techniques* as used in our studies will be described.

3.2 Literature survey

In this survey we confine ourselves to discuss only those publications in which on recording from the skin has been reported.

Since Alvarez (1922) reported on the first (human) electrogastrogram, no papers dealing with electrogastrography could be traced until 1953. In that year Ingram and Richards described an electrometer amplifier and recorder with a response time of 2 seconds, which they used to measure the luminal potential in the stomach (i.e. potential differences between gastric lumen and the fore-arm in man) as well as 'skin/skin' potentials. They made 216 recordings in 148 subjects, 45 of which were surface recordings. Analysis was performed by visual inspection. Results of the skin/skin potentials were not provided but summarized in a rather cryptic sentence: 'Movement of the wakeful patient was obviously a factor, for a skin/skin tracing from a sleeping subject became completely flat....'

In 1957, Davis et al., attached two EEG electrodes to the abdomen (in humans) as well as one on the abdomen and one to 'the dorsal surface of the right arm'. These authors considered the latter electrode configuration to be monopolar. They found potential variations with a frequency of about 3 cycles per minute and amplitudes in the order of 100 - 500 mV. The movement of the stomach was detected after swallowing a steel ball (1/4 inch in diameter) and using a mine detector. They made a careful study of the possible artefacts and concluded: 'There is little doubt that we show (...) an electrical aspect of the ordinary gastric or enteric contractions of three to four per minute'. They were primarily interested in the response to psychological stimuli and pursued this interest in a further paper (Davis et al., 1959) in which they used chlorided silver discs as surface electrodes.

Tiemann and Reichertz (1959a, 1959b) published data concerning the 'Elektro-Intestinogramm'. In these papers they provided some data about electrogastrographic explorations in humans, obtained by using one active (EEG) electrode on the abdomen and an 'indifferent' electrode on the right leg. The time constant of the amplifiers used in that study was 1 second. Considering the fact that this time constant corresponds with a 3 dB cut-off frequency of the high-pass filter of about 0.15 Hz (9 cpm), it is surprising that the authors found a frequency of 3 cpm and an amplitude in the order of 0.2 - 0.5 mV. Moreover, they paid much attention to the waveform of the recordings and stated that various types of waveforms were characteristic for gastrointestinal 'affections'. However, clear descriptions of these waveforms were not given.

In 1962 Sobakin et al. introduced a one channel electrogastrograph, constructed according to well-thought-out specifications. The bandwidth of the amplifier was 0.05 - 0.2 Hz. They used one electrode in the epigastric region and one on the right leg. The authors stated that they used the electrogastrogram for the 'registration of the peristaltic action during digestion'. Recordings were made on healthy volunteers and in patients with various gastric disorders. All subjects were given a meal consisting of barium, white bread and sweet tea. The best signals were obtained between thirty minutes and two hours after ingestion of the meal. In the healthy subjects a frequency of 3.0 ± 0.3 cpm, with an average amplitude of 0.25 mV was found on the basis of visual inspection of the recordings. Because Alvarez (1922) was capable to record only an electrogastrogram from a 'thin, little woman', the authors emphasized their success in recording an electrogastrogram from a woman which was of 'average height, but weighted 96 kg', and concluded that the 'equipment we have developed permits the recording of electrical oscillations of the stomach from the surface of the body, not only of normal subjects but also of ill persons with a hypertrophic layer of fat'.

Summarizing their findings in pathology: in patients with gastric ulcer, with the ulcer located in the small curvature, normal activity was seen. In patients with pyloric stenosis the amplitude of the gastric waves was increased to twice that of normal and in patients with gastric carcinoma, waves with a highly variable rhythm and low amplitude were observed. Unfortunately, the material was presented without a statistical justification of their final conclusions: 'clinical approbation of the electrogastrographic method and equipment discussed here has shown it to be completely suitable for objective pathophysiological studies of the displacements of the motor system of the stomach during digestion'. All the same the Russian group may be considered to be the first one to have gone deeply into the problems associated with the *technique* of surface recording.

Russel and Stern (1967) advocated the method of EGG developed by Davis et al. (1957, 1959) in a chapter on electrogastrography, contributed to 'a Manual of Psychophysiological Methods'. They gave a survey of various methods for studying gastric motility, including electrogastrography. Regarding the recording equipment, the authors considered the capability of 'registering DC-potentials' as a necessity to record the EGG. They also described an experiment in the dog, in which intraluminal, serosal and cutaneous electrical signals of the stomach were recorded simultaneously. An electrode on the skin surface of the animals' back served as the reference for all recordings. The authors stated that 'as expected, a significant positive correlation was obtained between the gastric activity of the three sites', although the companying figure, showing the

three signals, does not support this statement at all.
Most interesting is the publication of Nelsen and Kohatsu in 1968 in which they reported on gastroelectromyography and electrogastrography in dog and man. To our knowledge they were the first authors to relate the EGG directly to the electrical activity of the stomach instead of to gastric motility. Furthermore, they discerned the noisy character of cutaneous recordings, especially in the fasting state, and observed sinusoidal signals, varying slowly in frequency. To account for these properties of the EGG they used sophisticated analyzing techniques. Autocorrelation techniques were applied to extract the periodicity of the signal. The paper contains a figure that shows the response of feeding on the gastric frequency in man (a frequency dip followed by a frequency rise), completely determined from cutaneous signals. In order to deal with the occurring slowly varying frequencies and the poor signal-to-noise ratio of the EGG, they used a tracking filter (phase-lock technique) implemented on two TR20 analogue computers for retrieval of the electrogastrogram. They considered this, for that time advanced, technique superior to narrow band-pass filtering that usually was being used. The phase-lock technique was previously introduced by Nelsen in 1967. He stated that 'animal experiments (...) point to its (the electrogastrograms) potential usefulness as a specific diagnostic tool in certain human disorders (e.g. emptying disorders)' and that the method 'permits the retrieval of the electrogastrogram from the vast majority of patients without resort to surgical implantation'.
In both publications (Nelsen, 1967; Nelsen and Kohatsu, 1968) the same figure was provided, concerning the comparison of simultaneously measured serosal electrical activity, cutaneous activity and the phase-lock filtered version of the cutaneous signal. Although relatively limited experimental data was given, the authors concluded that they 'believe that the present recordings from cutaneous electrodes are of sufficient quality to undertake a study of gastric disease with sufficient numbers of patients to permit classification and establishment of diagnostic criteria'. Unfortunately, this optimistic conclusion has not been followed by the publication of the results of the clinical trial that they suggested.
Since 1967, Martin, Thillier, Martin and co-workers (Tours, France) have published a number of papers on the use of surface recording from the whole of the gastrointestinal tract. Most of these publications dealt

with studies in man, were mainly descriptive and contained about the same information. They used the term 'electrosplanchnography' for abdominal leads and 'electrogastroenterography' (EGEG) for limb leads (Martin and Thillier, 1971a, 1971b, 1972). The time constant of the high-pass filter used in 1967 (Martin, Thouvenot and Touron) was either 0.7 or 1.5 seconds, which is obviously too low to record reliable 3 cpm activity. In a later paper Martin and Thillier (1971a) reported on bipolar surface electrode recordings with a time constant of 3 seconds (corresponding to a 3 dB cut-off frequency of 3 cpm of the high-pass filter). The cut-off frequency of the low-pass filter has not been mentioned in any publication by the French group. They claimed an excellent correlation between motor activities of the alimentary canal and radiocinematography, but gave no details of either the instrumentation or the results. The authors had the opinion that signals recorded from the skin reflect the contractile activities and that absence of visually recognizable waves implies absence of contractile activity. However, experimental confirmation was not provided. It was not before 1978, that Drieux et al. performed a study on the relation between electrogastrographical and gastroelectromyographical signals and intra gastric pressure (in the guinea-pig). They found that rhythmic distentions of the antrum induced a synchronous modulation of the electrogastroenterogram, the magnitude of which was correlated with the amplitude of the distention. They stated that 'These results suggest that the origin of EGEG is essentially the movements of the stomach', but were unable to elucidate the underlying mechanism. The French group claimed that the methods of electrosplanchnography and electrogastroenterography are of great diagnostic importance (Martin et al., 1970; Martin et al., 1972; Combe et al., 1972) but convincing evidence supporting this claim was not provided. Studies which make a more realistic impression, and which were performed in collaboration with Tonkovic (Yugoslavia), were reported a few years later (Thouvenot et al., 1973; Tonkovic et al., 1975; Tonkovic et al., 1976). In healthy volunteers a gastric frequency of 2.7 to 3.6 cpm was found and the peak-to-peak amplitude of the gastric waves was 180 - 450 μV. Signals were recorded on magnetic tape for subsequent computer analysis (Thouvenot et al., 1973). They stated that amplitude criteria for interdigestive and postprandial states could be defined but that 'this study cannot as yet be a basis for a diagnostic conclusion because too many parameters have not yet been conquered, and many are still unknown'.

Tonkovic et al. (1975) used an array of electrodes covering the area between the sternum and the pubis, and recorded (from man) the signals on a 7-track FM tape recorder. The records were digitized and the autocorrelation function was Fourier transformed to obtain the power spectrum. They made use of a Hamming window in order to reduce the obscuring effect of respiration and the ECG. Nevertheless it is not to understand why the use of windowing should have the above mentioned effect. Several records were obtained from 8 subjects and analyzed. The authors stated that 'an analysis of the power spectra shows that it is possible to determine typical frequency bands for the different organs' activities. This allows us, using suitable filtering, to identify their activities even in the absence of visual recognition of typical waveforms'. The paper published in 1976 (Tonkovic et al.) did not add more information.

In 1973 Schulz et al. reported on the effect of metaclopramide on the gastric waves. They used the recording technique of the French group, but the recordings were analyzed by visual inspection. Intravenous administration of metaclopramide resulted in an increase of amplitude and frequency of the gastric waves. In 1976 Schulz et al. pursued their interest in the effect of drugs, using the same technique and confirmed their previous finding: metaclopramide increased the frequency of the gastric waves from 3.36 ± 0.2 to 5.45 ± 0.3 cpm. Atropine decreased the frequency from 3.51 ± 0.2 to 2.93 ± 0.2 cpm. The authors considered electrogastrography as 'pharmacological function test' a valuable method providing diagnostic information.

In 1973 Nechiporuk et al. recommended electrogastrography as 'an additional, objective diagnostic and prognostic test' in acute pancreatitis, since, in all 47 patients with acute pancreatitis studied, they found a significant decrease of the EGG, which they interpreted as 'suppression of the motor function'.

In 1974 Stevens and Worrall published a comparative electrogastrographic study in the cat. Signals were derived from one abdominal electrode with respect to a reference electrode on the left hind leg, and were compared with signals obtained from an extraluminal force transducer attached to the stomach. Besides visual inspection, they used auto- and crosscorrelation techniques as well as Fourier transformation of the autocorrelation function. A periodical component with a frequency of 3.76 to 4.54 was found (in agreement with the repetition frequency of gastric ECA in the cat, being about 4 cpm). Significant correlations between the cutaneous signal and the contraction signal were found. The authors stated that 'The present report is not intended to demonstrate that the mechanical and electrical records of the active stomach are exact mirror images of each other' and 'one can find segments of record where slow wave electrical activity appears to occur in the presence of a quiet mechanical record.' The authors were primarily interested in gastric psychophysiological research and referred to the publication of Russell and Stern (1967) extensively.

In 1975 Brown et al. (Sheffield, England) reported on surface recording in 16 healthy subjects. Three pairs of electrodes were placed over the gastro duodenal area. In a few cases mucosal electric activity and intra gastric pressure were measured simultaneously. They used auto- and cross-correlation techniques to reveal the periodicity of the signals and the common periodicity of the cutaneous signal and the mucosal signal, respectively. In addition they used Fourier analysis to compute the amplitude spectrum of the EGG's. In 88% of the signal fragments analyzed, a significant component of approximately 3 cpm (average 3.02 ± 0.21 cpm) was found. The authors paid particularly attention to the origin of this component and concluded that the electrical control activity of the stomach has to be considered as the source. After food intake, they found an amplitude increase of the gastric component of the order of a factor 2.5 which they attributed to a decreased distance of the electrodes to the distended stomach. In 9 out of 32 recordings, made in the fasted state, they found a frequency component of 10 to 12 cpm. They considered this component to originate from duodenal electrical activity.

Several studies were published by the Sheffield group, predominantly dealing with sophisticated methods of analysis of electrogastrographic signals (Smallwood et al., 1975; Smallwood, 1976, 1978a, 1978b; Linkens, 1977; Linkens and Datardina, 1978). Apart from autocorrelation and crosscorrelation techniques used, Linkens (1977) reviewed briefly 5 methods of frequency analysis, i.e. fast Fourier transforms, fast Walsh transforms, autoregressive modeling, phase-lock loop techniques and raster scanning. Smallwood (1976) dealt with fast Fourier transforms and phase-lock loop techniques. The latter technique, in principle adopted from Nelsen (1967), was modified using advanced integrated micro-electronic circuitry. The results of this technique were published in 1978 (Smallwood 1978a, 1978b). The percentage of the recording time for which the loop was locked for more than 3.2 minutes was 41% before a meal and 47% after the meal. Smallwood (1976) presented also results on measurements on patients before and after truncal vagatomy plus pyloroplasty. A significant increase in mean gastric frequencies was reported (from 3.15 ± 0.24 to 3.44 ± 0.27 cpm). Using 10 minute stretches of time signal (recorded from healthy volunteers) on which fast Fourier transform was performed, he found a similar postprandial frequency pattern as reported earlier by Nelsen and Kohatsu (1968).

Sobakin and Privalov published a multichannel surface recording technique in 1976. They applied 8 electrodes to 'the anterior abdominal wall in the projection of the cardia, fundus, body and also the antral and pyloric parts of the stomach'. A reference electrode was attached to the right leg. From all signals, derived from 20 healthy subjects, the autocorrelation function was calculated. Measurements were carried out after ingestion of a test meal. The mean gastric postprandial frequency was 3.0 ± 0.1 cpm and a 'high degree of correlation was found between the phasic electrical processes in different parts of the stomach'. During the first 15 minutes after the test meal (bread and tea) the amplitudes of the signals from electrodes above the cardia, fundus and corpus were higher than those from electrodes above the distal stomach (0.26 ± 0.01 mV and 0.23 ± 0.02 mV respectively). Later on an inverse amplitude ratio was observed. The authors interpreted these findings as follows: 'shortly after the beginning of digestion the strength of the peristaltic wave spreading from cardia towards the pyloric sphincter has a tendency to diminish (...). During evacuation of the chyme from the stomach peristalsis of the pyloro-antral part increases, and this is characterized by an increase in its electrical activity'. However, evidence to support this interpretation was not provided.

Walker and Sandman (1977) and Walker et al. (1978) were primarily interested in psychological effects on abdominal skin potentials. They used 'mildly stressful stimuli' such as the solving of anagrams and arithmic problems. They made a distinction between a tonic component of the EGG and a phasic component. They claimed the former to be discriminative between duodenal ulcer patients and healthy subjects. However, throughout their publications, they completely ignore the relation of the recorded potentials with gastric function. As a result these studies do not show any correspondence to the rest of electrogastrographic literature.

Smout et al. (1980a) attempted to answer the question 'what is measured in electrogastrography'. They concluded from a comparative study in conscious dogs (i.e. force transducers and serosal electrodes were implanted and records were made simultaneously with cutaneous electrodes) that the fundamental frequency of the EGG (in dog about 0.08 Hz) is constituted by the repetition frequency of gastric ECA and that the amplitude of the EGG is related to the electrical response activity (ERA). This conclusion was based upon the following observations: firstly, that an EGG signal can also be recognized during motor quiescence, and secondly, that amplitude of the EGG signal increases with the occurrence of ERA, not only postprandially, but also in the fasted state. The authors provided for a theoretical, fundamental basis by means of a model which describes the surface signal as resulting from field potentials generated by slowly propagating depolarization and repolarization dipole fronts. These fronts originate from the *intra cellular activity* of the gastric smooth muscle cells. Furthermore these authors demonstrated that regular tachygastrias and the duodenal frequency (≈ 0.30 Hz) in dogs could be extracted from the EGG using fast Fourier transformation (Smout 1980a, 1980b). Also the interdigestive complex could be recognized from the EGG after analogue band-pass filtering (Smout et al., 1980b). They concluded that 'the method of EGG provides for information about the mean frequency of gastric (and duodenal) electrical control activity and, furthermore, provides information about the postprandial and interdigestive myoelectrical patterns in the stomach of the conscious dog'. In the thesis of Smout (1980) electrogastrographic explorations in humans were described. Six abdominal, recessed types of normal ECG electrodes were attached over the epigastric region with a mutual spacing of 6 cm. The reference electrode was placed at the right ankle. The frequency response of the recording amplifiers was 0.012 - 0.46 Hz (the same as used in the studies in dogs). The mean gastric frequency in the fasting state was 2.89 ± 0.17 cpm (17 healthy volunteers), the mean postprandial frequency was 3.01 ± 0.25 cpm. He also described the characteristic gastric frequency response after ingestion of a test meal, earlier reported by Smallwood (1976) and Nelsen and Kohatsu (1968). In the power spectra studies, peaks at the duodenal frequency (11 - 12 cpm) were very rare, such in contrast to the findings in dog. An electrogastrographic study dealing with the interdigestive complex in humans was not performed. An example was given of a probable occurrence of a tachygastria in a patient, one day after ileostomy.

It is concluded that the first electrogastrogram recorded by Alvarez in 1921, may be considered a tour de force which was not repeated until the 1950's. Since that time attempts have been made to record electrogastrographic signals, predominantly from humans, without using reference signals from the stomach itself. Most authors assumed that the EGG reflects the motor activity of the stomach. It should be noticed that especially those authors claimed diagnostic significance for the method of EGG, sometimes to an extreme extent. Authors, aware of the possible gastric myoelectric origin of the EGG and using advanced analyzing methods, were more reserved in their conclusions.

3.3 Electrogastrographic recording techniques used in our studies

In electrogastrography, like in any other 'EXG' technique, surface electrodes must be attached to the skin. The signals picked up by the electrodes must be amplified and can be filtered in order to reduce or eliminate disturbing frequencies.

So far, the EGG technique seems simple. Since the fundamental gastric frequency of the signal is very low, namely equal to the repetition frequency of gastric ECA (0.08 Hz in the dog and 0.05 Hz in man) and since both, electrode noise and electrode impedance increase with decreasing frequency (Geddes, 1972) we considered it necessary, however, to investigate which kind of electrode would be most suitable for electrogastrographic purposes. Attention has been paid to:

- the noise produced by identical pairs of ECG electrodes;
- the total impedance (consisting of a capacitive and a resistive component) between these electrodes;
- the total impedance, both with and without abrasion of the skin, of the electrode-electrolyte-skin-body-skin-electrolyte-electrode transitions.

In addition, the sensitivity of the applied technique to (mainly motion) artefacts was investigated; the band width of the recording system to be used was chosen and finally the optimum electrode leads were selected.

The results of those studies have been described by Smout (1980) and will be summarized here.

From potential differences measured between pairs of identical electrodes it was concluded that commercially available ECG electrodes, particularly the pregelled Ag/AgCl electrodes (Hewlett Packard 14245A; Harco, type 155;

3M, Red Dot 2256) had a sufficiently low noise level; whereas the EGG signal varies between 250 - 500 μV, the average noise level was about 2.5 μV. Below 10 Hz the electrode impedance appeared to be frequency independent, being in the order of 200 Ω (the surface of electrodes was 52 mm^2; the impedance was measured with a current source of 10 μA).
This value is low compared to the total impedance of a pair of electrodes attached to both sides of the human leg. This impedance is approximately 100 kΩ, while thorough abrasion of the skin may reduce this impedance by about a factor 10. Similar values were found in the dog.
The measured values were considered acceptable, since the input impedances of the amplifiers used were 27 kΩ (Van Gogh-ie.bb) and 100 MΩ (own manufacture), respectively.

The mentioned types of electrodes are all recessed, i.e. around the metal of the electrode a small basin filled with a gel-containing sponge is present. The use of these recessed types of electrodes strongly minimizes motion artefacts as was demonstrated by severe rubbing of the electrodes under measurement conditions.

The choice of the band widths of the amplifiers was determined by the following requirements:

1) the fundamental frequency of the EGG should be minimally attenuated;
2) DC electrode potentials and electrode drift must be avoided;
3) the duodenal frequency component (≈ 0.30 Hz) nearly always present in the EGG's derived from *dogs*, and tachygastrias, being a rapid succession of control potentials (repetition frequency in *dog* ≈ 0.20 Hz, in man ≈ 0.15 Hz) should be minimally attenuated;
4) simultaneous recording of the electrocardiogram has to be avoided as much as possible.

The choice of cut-off-frequencies of about 0.010 Hz and 0.50 Hz for the high- and low-pass filters respectively (6 dB/octave) were concluded to be adequate.

The five main types of leads, as used in electrocardiography were tested too.
The signals, bipolarly obtained from electrodes placed at the epigastric region appeared to be superior in terms of signal-to-noise ratio as com-

pared to extremity leads, either bipolarly derived or monopolarly with respect to a 'central terminal'. However, if the configuration of the signals is to be studied the need for monopolarly derived signals is a prerequisite (see Chapter 4). We therefore decided to record not only bipolar, but monopolar abdominal signals as well. The reference electrode needed for the latter was placed on the right hind leg in the dog and on the right ankle in man.

Because the quality of the recorded signals appears to vary from subject to subject and even within subjects, an 'optimum' electrode position cannot be defined. Therefore we used routinely a few leads and selected the 'best' signal, either from direct monopolar or bipolar recordings or after electronic subtraction, on the basis of visual inspection.
The signal obtained in this way was used for further analysis.

4. WAVEFORM ANALYSIS

4.1 Introduction

A prerequisite for a better understanding of the accomplishment of the EGG is a thorough knowledge of the relation between the electrical signals at its source and the resulting *waveform* as measured with surface electrodes. As is apparent from literature, little attention has been paid to this fundamental aspect. The finding that the second potential contributes to the amplitude of the EGG and the theoretical foundation of it in terms of travelling dipoles (Smout et al., 1980a) may be considered a valuable contribution in explaining what is being measured in electrogastrography, however, no attempt has ever been made to look in more detail at the EGG waveform itself, to our knowledge.

The study of the above mentioned relationship is seriously hampered by the generally poor quality of the cutaneous signal. Bipolarly recorded signals are of better quality because, in particular, most of the occurring motion artefacts are eliminated. A disadvantage of bipolar signals, however, is that it cannot be concluded which potential variations occur at which electrode.

If the configuration of the EGG is to be analyzed with respect to serosally derived signals, a clean monopolarly recorded signal has to be available too.

Since conventional (analogue) band-pass filtering, in the region beyond the gastric frequency indeed improves the signal-to-noise ratio, the phase and the waveform are affected in an undesirable way. Therefore we attempted to implement a digital adaptive filter which improves the signal-to-noise ratio of monopolarly derived EGG's (from dogs) with a minimum distortion of the waveform constituted by *gastric* electrical activity.

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4.2 Adaptive filtering of canine electrogastrographic signals. Part 1: system design

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Abstract—*The study of the relation between gastric myo-electrical activities recorded from serosal and cutaneous electrodes is hindered by the poor quality of the cutaneous signal. This hindrance could be minimised by suitable filtering of the signal. Since it is not yet clear which aspects of the cutaneous signal constitute valuable information, the filter process should not affect phase, amplitude, frequency and waveform of the gastric component, while noise components should be suppressed strongly. The system design of a modified adaptive filter that meets these requirements is described. The filter was implemented on a digital Nova 2 minicomputer. The filter performance is described and tested.*

Keywords—*Adaptive filtering, Electrogastrography*

1 Introduction

THE method of recording gastric electrical activity from surface electrodes is called electrogastrography. The electrogastrographic signal has often been described as sinusoidal and has a dominant frequency equal to the frequency of the gastric electrical control activity (e.c.a.) (BROWN *et al.*, 1975), i.e. about 0·05 Hz in man and 0·08 Hz in dog. Recently SMOUT *et al.* (1980*a*) concluded from a study in the dog that both e.c.a. and, if present, electrical response activity (e.r.a.), the latter being related with phasic contractions, are reflected in the cutaneous signal.

In general the monopolarly recorded cutaneous signals (potential differences between exploring electrodes on the abdomen and an indifferent electrode, e.g. on the leg) are of poor quality due to a number of factors. Noise originating from the electrode-skin interface introduces low-frequency components (< 0·03 Hz). Pulse-shaped motion artefacts disturb the signals nearly over the entire frequency range recorded (0·01–0·5 Hz). Respiration artefacts affect the range between 0·2 and 0·3 Hz, and when one is only interested in the gastric component of the signal, contributions from other organs, e.g. the duodenum (frequency about 0·3 Hz), can also be considered artefacts. Bipolarly recorded cutaneous signals (potential differences between adjacent electrodes on the abdomen) are of better quality because most of the motion artefacts and respiration artefacts are cancelled out. But, these signals do not permit detailed study of phase and waveform, in relation to the electrical signals recorded from the serosa. In the case of monopolarly recorded signals poor quality often hinders a good interpretation of the time signal.

In most cases the gastric frequency component can be extracted from the signal by means of Fourier analysis (THOUVENOT *et al.*, 1973; LINKENS and CANNELL, 1974; BROWN *et al.*, 1975; SMALLWOOD *et al.*, 1975; SMOUT *et al.*, 1980*a*, 1980*b*), while other methods of analysis, i.e. auto-regressive modelling (LINKENS and DATARDINA, 1978) and phaselock techniques (SMALLWOOD, 1978*a*, 1978*b*), have also been applied with success.

Our aim was to develop a specialised filter technique to improve the signal-to-noise ratio of the electrogastrographic signal. We define the signal-to-noise ratio of the electrogastrographic signal as the ratio between the power in a small frequency band (0·01 Hz) around the gastric frequency component, and the power in the remainder of the spectrum. It is obvious that conventional bandpass filtering improves the signal-to-noise ratio but affects the phase and waveform. Moreover, this kind of filtering demonstrates undesired lasting decay phenomena. Our filter should obey the following requirements:

(1) The filter must be capable of following the time-varying properties of the gastric component.

(2) Waveform, phase and amplitude of the gastric component should be affected as little as possible.

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*) See footnote, page 38.

(3) No lasting decay phenomena may occur in response to pulse shaped motion artefacts.

A digital filter method which meets these requirements is the adaptive filter technique described by WIDROW (1966), WIDROW *et al.*, (1967) and WIDROW *et al.*, (1975). Little or no previous knowledge of the signal to be filtered is needed, because the filter optimises itself. As will be discussed, a modification of the adaptive filter technique is needed for use in electrogastrography. The design of this modified filter will be described in this part of the paper.

2 Fundamentals of adaptive filtering

The principle of adaptive filtering is shown in Fig. 1. The notation used is after WIDROW *et al.* (1975). The primary signal d consists of a (gastric) signal component s and a noise component n_0. The reference

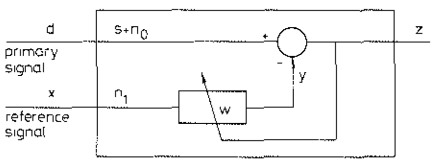

Fig. 1 *Block diagram of the adaptive filter. Input d consists of the signal components s and the noise components n_0. Input x consists of noise components n_1. 'Error' signal y is subtracted from d. The weighting vector W is adjusted by the output signal z*

signal x consists of the noise n_1. It is assumed that n_0 and n_1 are correlated in some (unknown) way, but are not correlated with s. The filter transfer function creates a signal y which can be considered as an error signal. After subtraction of y from d the output signal z is obtained. The adaptive character is realised by adjusting W to the time-varying signal properties, according to some algorithm. In the ideal case y equals n_0. The output z is:

$$z = s + n_0 - y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

squaring gives

$$z^2 = s^2 + 2s \cdot (n_0 - y) + (n_0 - y)^2 \quad . \quad . \quad . \quad . \quad (2)$$

Taking expectation values at both sides and realising that s is uncorrelated with n_0 and y, one gets

$$E(z^2) = E(s^2) + E((n_0 - y)^2) \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Only those signal components in the primary signal should be suppressed that are correlated with the reference signal. The minimalisation of the output power can now be used as an optimalisation criterion, because the signal power $E(s^2)$ is not affected when the output signal power $E(z^2)$ is minimised:

$$\min E(z^2) = E(s^2) + \min E((n_0 - y)^2) \quad . \quad . \quad . \quad (4)$$

After j samples, spaced T_s s, the output signal y can be written in digital form:

$$y_j = \sum_{n=j-(M-1)}^{j} x_n w_{(j-n)j} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where

w_{ij} is the value of the i-th weighting factor after j samples,

M is the total number of weighting factors and

x_n is the value of the reference signal after n samples.

The process can be realised by using a so-called tapped delay line (Fig. 2). It can be proven (WIDROW *et al.*, 1975) that the optimum weighting factors are given by the Widrow–Hoff LMS algorithm:

$$w_{ij+1} = w_{ij} + 2\mu x_{j-i} z_j \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where μ represents a feedback parameter.

After each sample each of the weighting factors is adjusted with the value $2\mu x_{j-i} z_j$. Starting with arbitrary weighting factors the algorithm will converge in the mean. The convergence speed is dependent on the value of μ. When the optimum condition is reached, w_i will be constant in the mean because the mean value of the product $2\mu x_{j-i} z_j$ equals zero. However, the instantaneous value causes w_i to fluctuate around the optimum value with an amplitude controlled by the factor μ (weighting vector noise). Therefore, choosing the value of μ one must compromise between convergence speed and accuracy. The algorithm will remain stable if the parameter μ obeys:

$$0 < \mu < \frac{1}{\sum_{i=0}^{M-1} x_{j-i}^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

(WIDROW *et al.*, 1975; KENTIE, 1980).

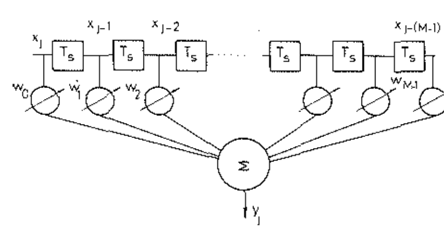

Fig. 2 *Tapped delay line, showing the construction of signal y from the reference signal. w_0 through w_{M-1} are the M weighting factors.*

3 Choice of filter parameters

Before application of the filter the total number of weighting factors and the sample frequency must be chosen. According to the sample theorem the sample frequency must be greater than or equal to twice the highest signal frequency component. The total length of the delay line has to be such that it contains two independent samples from the component with the lowest frequency. If the sample theorem is just met the minimum number of weighting factors M' can be found from

$$M' = \tfrac{1}{2}T_{max}/T_s = f_{max}/f_{min} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where T_{max} is the period time of the signal with the lowest frequency. In case of electrogastrographic signals, $f_{max} = 0{\cdot}5$ Hz and $f_{min} = 0{\cdot}01$ Hz. Thus, the sample frequency is 1 Hz. From eqn. 8 it follows the total number of weighting factors is 50.

Because it is possible that certain noise components arrive at the primary input before they do the reference input, a time delay of 25 s is implemented in the primary signal circuit. In this way a pseudo not-causal filter is constituted.

4 Modified adaptive filter

In electrogastrographic practice it appeared to be impossible to obtain a reference signal completely devoid of gastric activity, while the electrode-skin noise in the reference and primary signal appeared to be uncorrelated. So the adaptive filter described above cannot be used for electrogastrographic signals recorded from different electrodes. It appeared to be possible, however, to extract the reference signal from the primary signal of one and the same electrode by using a band reject filter which suppresses the gastric component (see Fig. 3). For this purpose we used an analogue Butterworth filter with cut-off frequencies at 0·05 and 0·15 Hz and an attenuation of 24 dB/octave. This configuration will be called the modified adaptive filter. WIDROW *et al.* (1975) prove that in the z-domain the optimum value of the weighting vector is

$$W_j = \begin{pmatrix} w_{0j} \\ \vdots \\ w_{M-1j} \end{pmatrix}, \text{ holds:} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$W(z)_{opt} = S_{xd}(z)/S_{xx}(z) \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where

$S_{xd}(z)$ is the crosspower spectrum of the reference and input signal and

$S_{xx}(z)$ is the power spectrum of the reference signal.

This equation is the z-transformed representation of the Wiener–Hopf equation (BODE and SHANNON, 1950).

Because, with the modified adaptive filter the relation between the primary signal and the reference signal is fixed, the transfer function of the modified adaptive filter can be established.

Let $S_{dd}(z)$ be the power spectrum of the input signal and let $H(z)$ be the transfer characteristic of the band reject filter. Then follows

$$S_{xx}(z) = H(z)H(z^{-1}) \cdot S_{dd}(z). \quad . \quad . \quad . \quad (11)$$

and, realising that d is the input signal and x the output signal of the band reject filter:

$$S_{xd}(z) = H(z^{-1})S_{dd}(z) \quad . \quad . \quad . \quad . \quad . \quad (12)$$

This leads, together with eqn. 10 to

$$W(z)_{opt} = 1/H(z) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

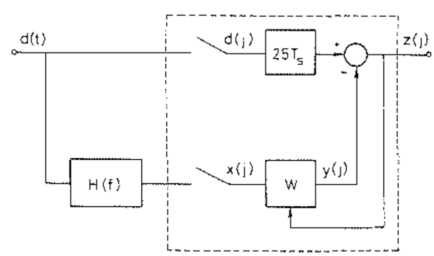

Fig. 3 *Block diagram of the modified adaptive filter with $H(f)$ being the transfer function of the band reject filter*

The transfer function of the modified adaptive filter is now

$$F(z) = 1 - H(z)W(z) = 0 \quad . \quad . \quad . \quad . \quad (14)$$

This result could be expected, since the reference signal is completely correlated with the primary signal. However, this optimum transfer is constituted after many samples, i.e. adaptation cycles. It will be shown that the filter is useful in the time interval before this state is achieved.

It can be proven (WIDROW *et al.*, 1967; KENTIE, 1980) that each weighting factor w_{ij} converges to its optimum value according to

$$w_{ij} - w_{iopt} = A_{io}(1 - 2\mu\overline{x^2})^j \quad . \quad . \quad . \quad . \quad (15)$$

where

j is the number of adaptation cycles,

A_{io} is the difference between w_{io} and w_{iopt}, and

$\overline{x^2}$ is the mean power of the reference signal.

From the last equation it follows that the convergence speed is determined by the value of $2\mu\overline{x^2}$.

Transforming the weighting vector to the z-domain one gets

$$W(z)_j - W(z)_{opt} = (1-2\mu X(z))^j A_0(z) \quad (16)$$

where

$X(z)$ is the power spectrum of the reference signal, and

$W(z)_j$ is the transfer function of W after j cycles.

For the modified adaptive filter, choosing $w_{io} = 0$, thus $W(z)_0 = 0$, it follows with eqn. 13

$$A_0(z) = 1/H(z) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

and from eqns. 16, 17 and 14 the transfer function of the modified adaptive filter is obtained, as a function of j, being

$$F(z)_j = (1-2\mu X(z))^j \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

From this expression it can be seen that high-power frequency components of the reference signal are suppressed faster than components with less power. As a consequence, some time after initiation of the adaptation process, unwanted signals and noise will be strongly suppressed, while the gastric component, attenuated by the band reject filter, will not.

5 Performance of the modified adaptive filter

As derived in paragraph four, the filter is not allowed to adapt until w_{opt} is reached. Therefore we determine the power transfer function as a function of j. From this result a suitable j can be chosen to filter electrogastrographic signals. The modified adaptive filter was enabled to adapt to one and the same signal during varying numbers of adaptation cycles. The filter has been programmed on a digital Nova 2 minicomputer. After j adaptation cycles has passed the weighting factors were fixed. Then the power transfer function was determined. The value of $\mu\overline{x^2}$ was taken $3{\cdot}5 \times 10^{-2}$, being an appreciable compromise between convergence speed and accuracy. The electrogastrographic signal used is shown in Fig. 4, together with corresponding power spectra. The peak at 0·08 Hz is the gastric component and the peak at 0·28 Hz is of duodenal origin. The recorded frequency band is 0·01–0·5 Hz, so the sampling rate was set at 1 Hz.

According to eqn. 18 the transfer function of the filter is strongly influenced by the power spectrum of the reference signal (Fig. 4, x). Fig. 5 shows the power transfer function with j as parameter signal components being strongly represented in the reference signal (low-frequency noise and duodenum) are attenuated most rapidly ($j = 50$). With increasing j the dips became broader and deeper. The choice of j

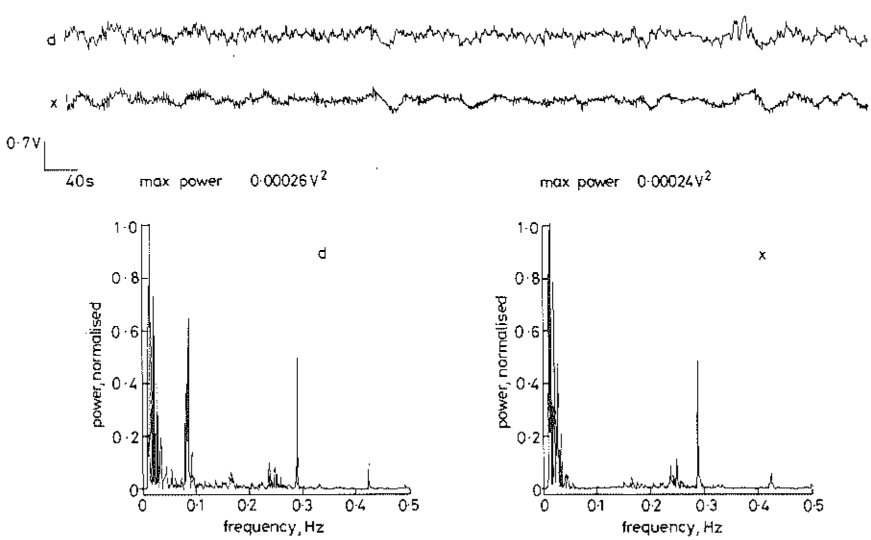

Fig. 4 *The test signal used for the modified adaptive filter. upper trace: primary signal d; lower trace: reference signal x extracted from the primary signal by the band reject filter; left: normalised power spectrum of the primary signal (1,024 samples); and right: normalised power spectrum of the reference signal*

determines the amount of suppression of unwanted frequency components.

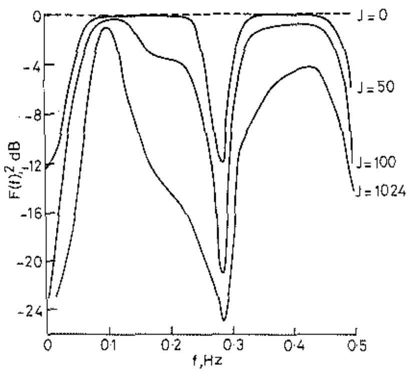

Fig. 5 *Power transfer function of the modified adaptive filter as a function of the number of adaptation cycles j*

After ending the adaptation process 1024 samples were filtered. From the power spectra of input and output signal the signal-to-noise ratio was determined as defined. The result is shown in Fig. 6. An initial rapid increase of the signal-to-noise ratio is followed by a part with slow increase, while the suppression of the gastric component increases slowly with increasing j.

6 Discussion

The properties of the electrogastrographic signal hinder an optimum filter procedure with the aid of conventional filter techniques. An appropriate filter appears to be the modified adaptive filter described in this paper. The reference signal is obtained from the primary signal using a band reject filter. In the ideal case the filter suppresses the noise components and lets through the gastric component. In view of the requirements mentioned in paragraph 1 the following remarks can be made:

(*a*) Due to the adaptive character of the filter the time varying properties of the gastric component are followed as far as this component is within the frequency band of the band reject filter.

(*b*) In the ideal case the filter constitutes a linear phase characteristic with a (built-in) time delay of 25 times T_s. Because the filter operates with the weighting vector converging to W_{opt}, the linear phase characteristic is approximated during the adaptation process. The waveform and amplitude of the gastric component are affected by the filter, but a suitable choice of the number of adaptation cycles j minimises this drawback.

(*c*) Because of the (overall) small power contents of pulse shaped artefacts the filter will not adapt to these parts of the signal. Therefore, these artefacts are hardly affected and lasting decay phenomena are limited to a minimum.

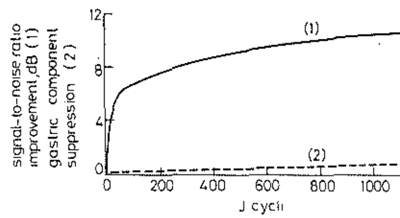

Fig. 6 *Signal-to-noise ratio improvement and gastric component attenuation (dotted line) as a function of j*

From theory it follows that the transfer function becomes zero with increasing time. Therefore, only relatively short signal stretches should be filtered or the weighting vector should be fixed after a number of adaptation cycles.

In Part 2 (VAN DER SCHEE *et al.*, 1981) the application of the modified adaptive filter on electrogastrographic signals will be described and data concerning the signal-to-noise ratio improvement will be presented.

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4.3 Adaptive filtering of canine electrogastrographic signals. Part 2: filter performance

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Abstract—*The modified adaptive filter method described in Part 1 was applied to 16 stretches of (cutaneous) electrogastrographic signal of 17·07 min duration. A signal-to-noise ratio improvement of about 8 dB was achieved. The most characteristic feature of the filter method appeared to be that waveform and phase of the gastric component of the electrogastrographic signal are preserved. It is concluded that the use of the modified adaptive filter forms a valuable tool in the study of the electrogastrographic signal.*

Keywords—*Adaptive filtering, Electrogastrography*

1 Introduction

WITHIN the study of the relationship between myoelectrical activities recorded from serosal and cutaneous electrodes it is of great importance to establish the waveform and time relationship of the cutaneous signals with respect to those of the serosal signal.

This study is hindered by the poor quality of the cutaneous signal. This hindrance could be minimised by suitable filtering of the signal. In the first part of this paper the design of an adaptive filter, meeting the requirements for adequate filtering of electrogastrographic signals, was described (KENTIE *et al.*, 1981).

In this part of the paper the application of the modified adaptive filter to these signals will be described.

2 Methods

2.1 *Methods of recording*

Recordings were made with two healthy conscious dogs (beagles) in which bipolar serosal electrodes, as described previously (SMOUT *et al.*, 1980*a*), were implanted at sites on the stomach and duodenum, shown in Fig. 1*a*. Before each recording session two disposable e.c.g. electrodes (14245A Hewlett Packard) were placed on the shaved skin of the abdomen, at the sites shown in Fig. 1*b*. A third (reference) electrode was placed on the right hind leg. The potential differences between abdominal electrodes and the leg electrode were recorded. Likewise monopolar signals were recorded from serosal electrodes. Connections were such that an upward deflection indicated that the exploring electrode was positive with respect to the reference electrode.

Recordings were made on paper (Van Gogh EP-8b) as well as on magnetic tape (Racal Store 14). For serosal electrical signals the highpass and lowpass filters (6 dB/octave) were set at 0·012 and 15 Hz, respectively, for cutaneous signals at 0·012 and 0·46 Hz. Recordings were made both in the interdigestive state (after more than 20 h fasting) and

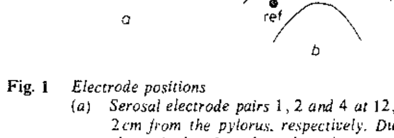

Fig. 1 *Electrode positions*
(*a*) *Serosal electrode pairs* 1, 2 *and* 4 *at* 12, 7 *and* 2 *cm from the pylorus, respectively. Duodenal electrode d at* 3 *cm from the pylorus*
(*b*) *Abdominal surface electrodes R and L*, 8 *cm apart on a transverse line midway between the lower end of the body of the sternum and the lowest point of the costal arch, and reference electrode on the right hind leg*

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in the postprandial state.

Analysis of the cutaneous signals was performed by visual examination of the original chart recordings and by spectral analysis of stretches of 1024 s (17·07 min) duration, using a fast Fourier transform algorithm implemented on a Nova 2 minicomputer.

2.2 *Methods of adaptive filtering*

From the theory in Part 1 it follows that the transfer function of the modified adaptive filter becomes zero with increasing time. Therefore the filter can only be applied to electrogastrographic signals in two ways:

(*a*) In a continuously adaptive mode, using signal blocks of limited duration. In our case a duration of 17·07 min.

(*b*) With fixed weighting factors. By keeping the weighting factors constant after a number of adaptation cycles, an optimally adjusted fixed filter can be constituted.

With the adaptive filter programmed on a Nova 2 digital computer, both filter methods were applied to 16 signal blocks of 17·07 min duration. The signal-to-noise ratio, defined as the ratio between the power in a frequency band of 0·01 Hz around the gastric frequency component and the power in the remainder of the spectrum, varied from −13 dB to −3 dB. For real-time filtering the lower and upper cutoff frequencies of the bandreject filter (24 dB/octave) were set at 0·05 and 0·15 Hz, respectively, and the sample frequency at 1 Hz. To speed up analysis the signals were filtered at 4 times real time, involving only adjustment of the sample frequency and the cutoff frequencies of the analogue band reject filter.

The signal-to-noise ratio improvement and the suppression of the fundamental gastric frequency were determined from the power spectra of input and output signal. These parameters together with qualitative visual analysis of the filtered signals were used as a criterion for the suitability of the filter.

3 Results

3.1 *Continuously adaptive filtering*

As mentioned in Part 1, each of the weighting factors w_{ij} will converge in the mean to its optimum value according to

$$w_{ij} - w_{i\,opt} = A_{io}(1 - 2\mu\overline{x^2})^j \quad . \quad . \quad . \quad . \quad . \quad (1)$$

As can be seen, the filter adjustment with maximum signal-to-noise ratio improvement is governed by the value of $\mu\overline{x^2}$ ($\overline{x^2}$ being the mean power of the reference signal), since this value determines the convergence speed of the filter. Small values hardly lead to noise suppression within a reasonable time, and large values cause relatively fast suppression of the gastric frequency component and increasing weighting vector noise.

For each signal stretch the optimum value of $\mu\overline{x^2}$ was established before the actual filtering process started. Table 1 presents the mean value and standard deviation of $\mu\overline{x^2_{opt}}$, signal-to-noise ratio improvement and gastric frequency suppression of the 16 signal stretches.

The filter was found not to be very sensitive for deviations in $\mu\overline{x^2}$ (see Fig. 2). The value $3{\cdot}5 \times 10^{-2}$ appeared to be a practical one. Fig. 3 gives an example of the filter performance. The Figure illustrates that unwanted noise such as low-frequency noise and duodenal electrical activity (frequency about 0·30 Hz) are strongly suppressed by the filter. The signal-to-noise ratio of the output signal z equals 2·1 dB, indicating that about 40% of the power was distributed over other frequency components than the gastric component, predominantly in the higher frequency range.

As can be concluded from the filter transfer function resulting from this signal (Part 1) the second and third harmonic of the gastric component are attenuated about 10 dB and 18 dB, respectively, and therefore can not be seen in the normalised power spectrum of signal z. However, these (attenuated) harmonics still contribute to the waveform of signal z.

3.2 *Filtering with fixed weighting factors*

The adaptation process was stopped when a compromise between signal-to-noise ratio improvement and gastric frequency suppression was reached. Taking for $\mu\overline{x^2}$ the value of $3{\cdot}5 \times 10^{-2}$, and accepting a maximum suppression of the gastric frequency of 10%, this optimum was found to be reached after about 600 adaptation cycles (i.e. 10 min real time). Therefore, the 17·07 min signal stretches were filtered using the weighting factors found after 600 adaptation cycles.

Table 2 summarises the results of this procedure applied to the 16 signal stretches. Fig. 4 shows the filter

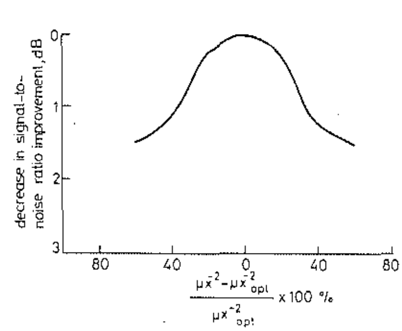

Fig. 2 *Variation of signal-to-noise ratio improvement with varying values of* $\mu\overline{x^2}$

performance applied to the same signal stretches as shown in Fig. 3.

Fig. 5 illustrates the relations between the filtered cutaneous signal R and the electrical activity recorded monopolarly from serosal electrode 4.

The lower trace shows a conventional bandpass-filtered version of the signal, using a Butterworth filter (cutoff frequencies 0·05 and 0·15 Hz, 24 dB/octave).

Table 1. Mean value and standard deviation of $\overline{\mu x^2_{opt}}$, signal-to-noise ratio improvement and gastric component suppression in 16 signal stretches of 1024 s duration, continuously adaptively filtered

$\overline{\mu x^2_{opt}}$	signal-to-noise ratio improvement	gastric component suppression
	dB	%
$3{\cdot}5 \times 10^{-2} \pm 1{\cdot}5 \times 10^{-2}$	7·7 ± 1·8	13·0 ± 9·2

Table 2. Mean value and standard deviation of signal-to-noise ratio improvement and gastric component suppression in 16 signal stretches filtered with fixed weighting factors. Same signal stretches as Table 1

signal-to-noise ratio improvement	gastric component suppression
dB	%
8·2 ± 1·1	8·5 ± 6·5

4 Discussion

It can be concluded that the modified adaptive filter, used in the constantly adaptive mode, is suitable for filtering electrogastrographic signals. The adaptive properties enable the filter to follow shifts in gastric frequency (within the frequency range of the band reject filter). However, during the initial phase of the filtering process the noise components are hardly suppressed, while after some time the gastric

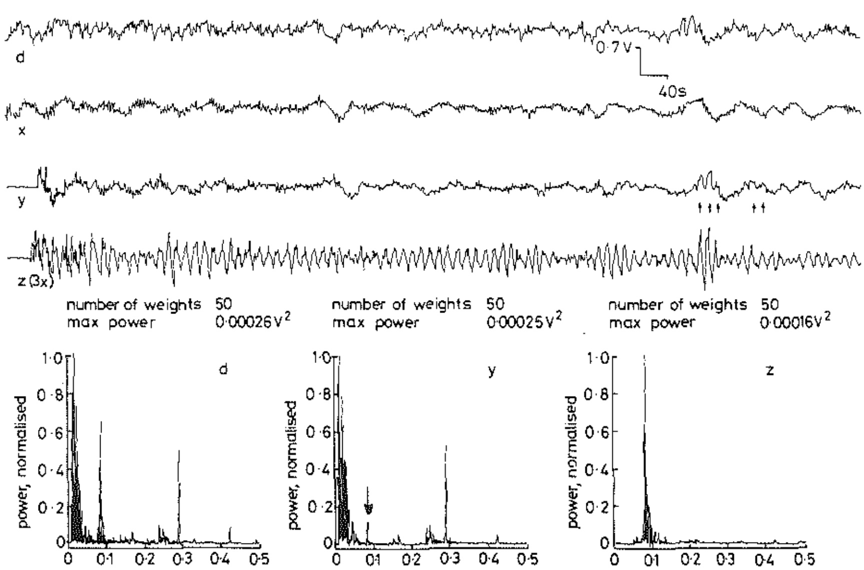

Fig. 3 *Continuously, adaptively filtered input signal d, reference signal x, error signal y and output signal z, with corresponding power spectra (1024 time samples) of signals d, y and z (cutaneous signal R, dog 2). Output signal z is amplified three times in comparison with the other time signals. Signals y and z were not time shifted to correct for the filter time delay. Note the noisy character of time signal z during the initial phase of the filter process and appearance of a gastric component in signal y (during the last phase) and spectrum y, as indicated by the arrows (compare the same signal in Fig. 4)*

component shows up in the error signal. Moreover, weighting vector noise, inherent to the adaptive process, is added to the output signal. As a consequence, only short signal stretches can be filtered.

When the filter is used with fixed weighting factors, the filter has constant properties and no weighting vector noise is added, resulting in a slightly better signal-to-noise ratio improvement. The transfer

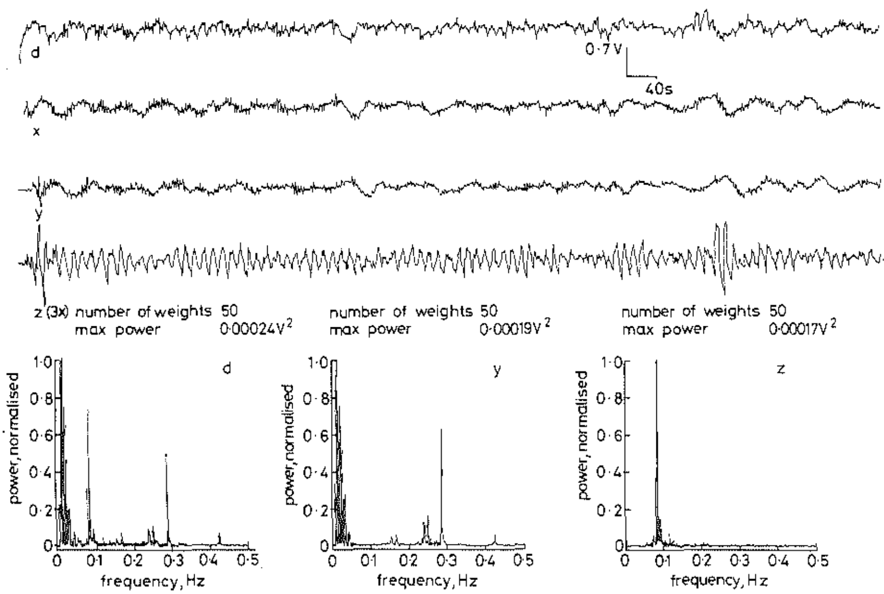

Fig. 4 *Same signal fragment as shown in Fig. 3, but now filtered with fixed weighting factors, as described in the text*

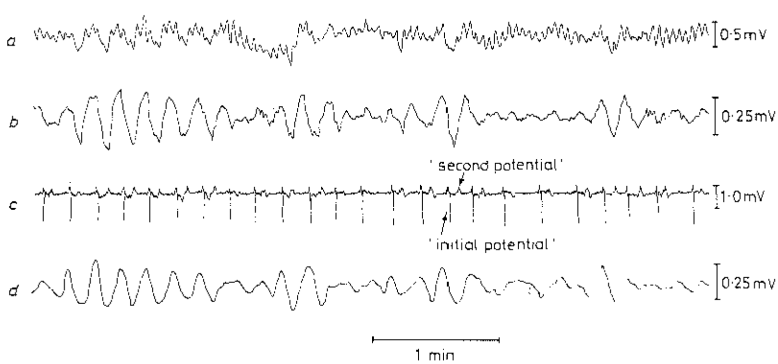

Fig. 5 *(a) Cutaneous signal R, (b) its adaptively filtered version (fixed weighting factors), (c) the corresponding signal recorded monopolarly from serosal electrode 4 and (d) the bandpass-filtered version of signal R*
The second trace is shifted to the left over 25 s to correct for the filter delay time. The fourth trace is time shifted in order to correct for the delay time of the Butterworth filter of the mean gastric frequency (0·08 Hz). As in this example, a coincidence of the negative deflection of the adaptively filtered cutaneous signal R with the 'second potentials' in the serosal signal (electrode 4) was often observed

function of the filter is now determined by the mean properties of the signal, where it is assumed that all signal properties are sufficiently represented in the first 600 samples. Because of the nearly linear phase characteristic, the limited gastric frequency suppression and the attenuation of only 5 dB ($j = 600$) of the second harmonic, the waveform is affected to a minimum. This makes the described filter technique suitable for the study of time and waveform relationships with respect to recorded signals from the serosa. For instance, in Fig. 5 episodes of high amplituded filtered cutaneous signals can be recognised, known to be related with phasic contractions (SMOUT *et al.*, 1980*b*). In the serosal recording these contractions are reflected in the 'second potentials', phase-locked to the omnipresent 'initial potentials' (DANIEL, 1965). (The initial potential is considered to be the extracellular manifestation of the intracellular depolarisation, whereas the second potential represents the intracellular repolarisation.) It can be seen in Fig. 5 that the minimum of the large negative deflections of the filtered signal R coincides with the second potentials in the serosal signal recorded from electrode 4. A detailed discussion of this phenomenon in terms of de- and repolarisation fronts and the significance of this observation is beyond the scope of this paper. However, it is important to mention that an observation like this could never have been made from a conventionally bandpass-filtered signal, nor from the original cutaneous signal. It is therefore concluded that the modified filter method described in Part 1 forms a valuable tool in the study of electrogastrographic signals.

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*) Mr. M.A.Kentie was studying at the department of Electronics of the Delft University of Technology, under supervision of Prof.Dr. J. Davidse and Ir. Ch.D. van Maaren. In his last study-year he was working at the department of Medical Technology of the Erasmus University Rotterdam, during which period he completed his doctoral report, under the guidance of Dr.Ir. J.L. Grashuis and Ir. E.J. van der Schee.

4.4 Additional observations and discussion

In the previous section we concluded that the presented filter method might provide for signals enabling analysis of the *configuration* of EGG's, both, in mutual connection and with respect to serosal signals. To investigate how this worked out in practice we applied adaptive filtering to a total of 25 hours of monopolarly recorded cutaneous signals, recorded during the interdigestive state as well as during the postprandial state. A remarkable difference in result was observed between these two states.
In all cases an improvement of the signal-to-noise ratio of about 8 dB was obtained, in agreement with the expected value (page 36).
Figure 10 shows a representative example of the unfiltered and filtered versions of EGG's, derived from various electrode positions depicted in the same figure, together with serosally recorded signals (monopolar electrodes 2 and 4; see Fig.1, page 34). The signals were recorded during phase III of the IMC (section 2.1.1). As can be seen in this figure the configuration of the filtered waveforms appeared to be highly variable, so, unfortunately no definite answer could be found concerning consistent time relations and waveforms of the cutaneous signal, neither mutually, nor with respect to serosally recorded signals. A similar pattern was observed in the interdigestive state during the periods of motor quiescence, be it with smaller amplitudes. The poor results obtained during the activity front can be understood by the fact that a highly variable power content of the recorded EGG is spread over a frequency range from the normal gastric frequency down to lower frequencies, as will be demonstrated in section 5.4. As a consequence, a considerable amount of this 'power' is not compensated for by the reference signal of the filter, leading to distortion of the filter output. It may thus be concluded that adaptively filtered cutaneous signals, obtained during the activity front of the IMC are not suitable for detailed waveform analysis. The factors to which the disappointing results obtained during periods of motor quiescence of the IMC have to be attributed are yet unknown.
The filtered signals, recorded during the postprandial state, especially those derived from the standard leads (electrodes R and L), showed most frequently a more consistent behaviour (see Fig.11).
The most conspicuous property of the cutaneous signals in this figure is the approximately opposite polarity of the R and L signals and, as a consequence, about the doubled amplitude in R-L.

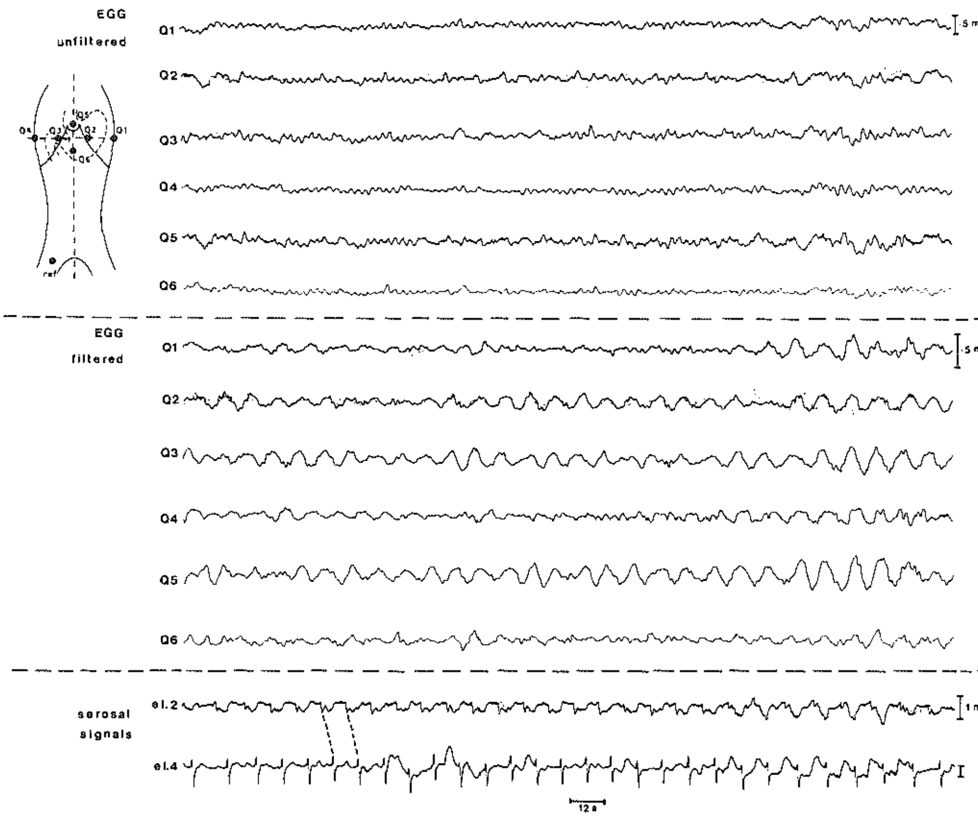

Fig.10. Direct EGG recordings from the electrode positions shown in the left figure, adaptive filtered version of these signals (with fixed weighting factors after 600 adaptive cycles), and serosal signals from electrodes 2 and 4 respectively.

If we assume that the leads R and L mainly 'see' the electrical activity of the distal antrum and when the configurations of R and L are compared with the time moments of depolarization and repolarization as also indicated in Figure 11 (serosal electrode 4), the following observations can be made:

- the negative deflections in R coincide with the moments of repolarization (second component in electrode 4);
- the negative deflections in L coincide approximately with the moments of depolarization.

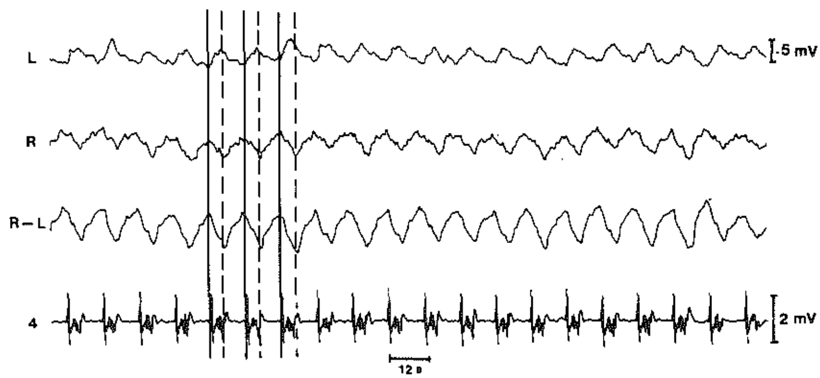

Fig.11. Adaptively filtered cutaneous signal L and R, the bipolar signal R-L (obtained by electronic subtraction), in relation to the moments of de- and repolarization of the terminal antrum: solid and broken lines respectively; serosal electrode 4.

It is therefore very unlikely that the opposite polarities of R and L are caused by the fact that every de- and repolarization front first travels underneath one electrode and then, half a cycle duration later, underneath the other, for, in that case the times of de- and repolarization should have coincided with 'zero crossings' (i.e. midway the slopes) in the cutaneous signals.

An alternative qualitative description of the observed signal difference may be based on the assumption that electrodes R and L see opposite sides of the fronts (see Fig.12).

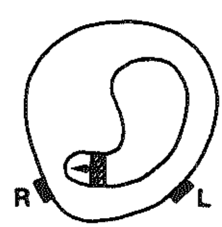

Fig.12. Schematic cross-section through the abdomen of the dog at the level of electrodes R and L. R and L see opposite sides of a de- and repolarization front that transverses the antrum.

When a depolarization front approaches a remote electrode R, the potential at R becomes more and more positive, until the pylorus is reached. The opposite potential changes are expected to occur when a repolarization front approaches electrode R (see Fig.13).

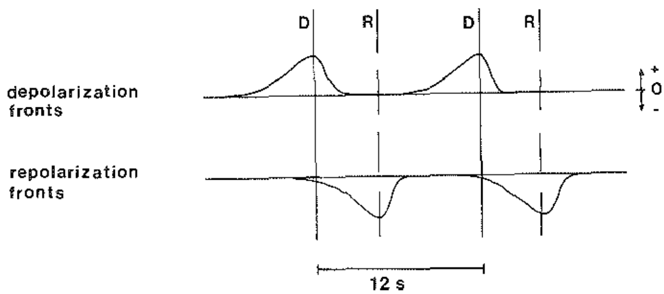

Fig.13. Potential changes expected to occur at electrode R when depolarization fronts or repolarization fronts travel over the antrum.
D = moment of depolarization of the terminal antrum.
R = moment of repolarization.

Potential changes are expected to occur at electrode L that are approximately the inverse of the changes at electrode R.
In the bipolar signal R-L, deflections of the same polarity as in R, but of approximately doubled amplitude can therefore be expected. This simple qualitative approach may, therefore, describe the characteristics as seen in figure 11. The same configurations and relations as shown in that figure, however, should be present too during the occurrence of contractions in the interdigestive state. As demonstrated, the aid of the adaptive filter method failed to reveal such kind of relationship.

Many of our recordings seem to confirm the first assumption, namely that the leads R and L mainly see the electrical activity of the antrum; the findings in section 5.6. appeared to be in agreement with this assumption. However, other recordings indicated that the activity of more proximal parts of the stomach might also be reflected in the EGG (e.g. during minute rhythms; section 5.4, page 72 and section 5.5). Therefore we decided to search for other techniques which enable more detailed waveform analysis of EGG signals. Regarding the properties of the time signals involved, it is obvious that only techniques based on a statistical approach would be promising. In developing such a technique we have chosen an averaging procedure in which the control potentials, derived from one location on the serosa, served as a trigger pulse for consecutive averaging of corresponding EGG stretches. The objectives of this study (Volkers, Van der Schee and Grashuis, 1983) were 'first, to investigate whether use of a suitable averaging technique would allow meaningful waveforms to be derived. from the crude EGG recording, secondly, to study whether these waveforms depend on the position of the cutaneous electrodes and thirdly, to determine whether the waveforms thus obtained could be correlated with the contractile activity of the stomach wall'. In that study it was concluded that, among other things, indeed differently positioned surface electrodes 'see' different electrical active parts of the stomach, but in all electrodes the electrical activity of the terminal antrum was reflected, particularly in electrode R. Moreover, during the activity front of the IMC a consistent relation was found between the cutaneous electrodes R and L. and serosal electrode 4, similar to that depicted in figure 11. Therefore it seems reasonable to conclude that the assumption that electrodes R and L see approximately opposite sides of de- and repolarization fronts travelling over the distal antrum and the qualitative description based on it are valid. For more detail with respect to EGG waveform analysis, the reader is referred to the above mentioned article that has been given as an Appendix on page 129: A.C.W. Volkers, E.J. van der Schee and J.L. Grashuis (1983), 'Electrogastrography in the dog: waveform analysis by a coherent averaging technique'.

Finally, we may comment that in case of *retrograde* antral conduction the negative deflection in R (and R-L) may be expected to coincide with the *depolarization* fronts (control potentials). However, we never observed retrograde conduction with a repetition frequency of about 0.08 Hz in normal physiological circumstances. Instead, in a few cases we observed long lasting tachygastrias, being rapid successions of control potentials originating in the distal antrum and propagating in oral direction (Smout,1980; Smout et al., 1980b; Van der Schee et al., 1982). The repetition frequency of those tachygastrias is in the order of 0.25 Hz. Since these signals are potentially useful to confirm the above mentioned prediction, future studies have to give decisive answers.

5. SPECTRAL ANALYSIS

5.1 Introduction

Abnormal myoelectrical activity seems to be characterized predominantly by disturbances and sudden alterations of the repetition frequency of gastric ECA. Both, these so-called gastric arrhythmias and tachygastrias have frequently been observed during our own measurements (in the dog) as well as reported in literature (e.g. Code and Marlett, 1974; Gullikson et al., 1980). Also in man they appear to occur (Telander et al., 1978; Stoddard et al., 1981), while You et al. (1980b, 1981) reported a relation between human gastric dysrhythmias and unexplained nausea and vomiting.
Since the fundamental frequency of the cutaneous signal is constituted by the repetition frequency of the ECA and since it is relatively easy to extract this frequency from rather noisy signals, we focussed our attention to spectral analysis of the EGG: it may be expected that the *frequency content* or, to be more specific, the *power spectrum* of the EGG may serve as a valuable quantity for practical purposes.
Over more than ten new techniques dealing with the estimation of the power spectrum have been developed in the last two decades. For a comprehensive review of those methods and discussion about their pros and cons the reader is referred to Kay and Marple (1981).
In our study we used a well-known classical method, based on Fourier analysis.
Blackman and Tukey published in 1959 their famous monograph on spectral analysis, in which they described the Fourier transformation of the autocorrelation function to obtain the power spectrum. This approach was the most popular spectral estimation technique until the introduction of the fast Fourier transform (FFT) algorithm in 1965, credited to Cooley and Tukey. The power spectrum is obtained as the squared magnitude of the output values from an FFT, performed on the data set. Our choice was made on the basis of the following considerations:

1) the method is most computationally efficient;
2) the output (after squaring) is directly proportional to the power of the signal;

3) regarding the 'accessibility' requirement, many *hardware* FFT equipment is commercially available nowadays, and,
4) anticipating on future developments, the costs of an FFT stand-alone system, which is suitable for bedside use, is expected to decrease considerably, due to rapid improvements in micro-electronics and computer technology.

Applying the FFT to relatively long record stretches, information about the mean frequency content within that stretch, is being obtained, but time information is being lost. Running Spectrum Analysis (RSA), however, yields both time and frequency information, since in time overlapping spectra are considered.
The objective of applying RSA was to provide for a method with which varying frequencies, lasting for relatively short periods, could be visualized in an interpretable way.
Both, our attempt to minimize the disadvantages inherent to the use of fast Fourier transformation and the concept of running spectrum analysis, will be outlined in the next section.
The main objectives of all studies performed and presented in this chapter were:
1) to search for a fast and concise way of representing electrogastrographically obtained data, and
2) to investigate to what extent the gastric myoelectrical characteristics could be interpreted from the running spectrum.

5.2 Method used in our study

5.2.1 Computational procedure

We will first describe the general computational procedure. A fast Fourier transform (FFT) algorithm, implemented on a Nova 2 digital computer, was used to obtain the power spectrum of the derived time signals. The FFT algorithm calculates the Fourier coefficients, representing the strength of the frequency of various sinusoids present in the time signal. Squaring these coefficients gives values proportional to the power magnitude of the sinusoids. The magnitude of a particular power peak in a spectrum depends on the amplitude of that particular frequency and on the number of cycles of that frequency component within the signal stretch to be analyzed. When either one or both quantities increase, the power magnitude will increase.

A computer program was developed which treated real time signals, consisting of 2M real-valued numbers as M complex numbers (complex in the mathematical sense), according to the algorithm of Cooley et al. (1970) and adopted from Pederson (1980). This procedure saves computer memory space and computing time. During the analogue-to-digital conversion, the sample frequency must be greater than or equal to two times the highest frequency being present in the analogue signal, according to the well-known *theorem of Shannon*. This requires preprocessing of the time signal, e.g. adequate band-pass filtering.

When an FFT program is operated on N points of time data, N Fourier coefficients are obtained. Since the time signal is real, an even spectrum is obtained, i.e. the spectrum is symmetrical about the origin (or about the Nyquist frequency, the latter being half the sample frequency; see Fig. 14,d).

Hence, the total power is obtained by adding the corresponding squared positive and negative Fourier coefficients and as a result $\frac{1}{2}N+1$ spectral data points represent the power content completely.

The use of RSA implies that the obtained spectra overlap in time. During processing each successively computed spectrum is displayed on a screen (Tektronix 4010) together with a spectrum number, the value of the frequency component with the highest power magnitude and the value, in computational units, of that magnitude. The time signal to be analyzed is replayed on a chart recorder and a pulse train is echoed from the computer by a digital-to-analogue converter. The distance between positive going flanks of the pulses indicates the time shift of the computed spectra. In this way the time signal corresponding to a particular spectrum can be exactly established. From the display a suitable scaling factor can be chosen to produce a pseudo-three-dimensional representation. The time signals and display are as illustrated in figure 2 of section 5.3, page 61. After completion of the processing each computed spectrum can be separately analyzed in detail by choosing the desired spectrum number. The drawing-program facilitates different points of view, e.g. if frequency components are hidden from others, the picture can be rotated and inspected from an other angle. In order to facilitate the recognition of frequency *patterns* more easily, a program was developed that provides a 'grey-scale' plot of the spectra: each point in the (f, t) plane is represented by a picture element (pixel), the blackness of which is proportional to the magnitude of the power. Pseudo-3D-displays and grey-scale plots were made on a Versatec 1100 A printer-plotter.

5.2.2 Theoretical background

For a thorough mathematical treatment of digital signal processing, both, in general sense and with respect to Fourier analysis, appropriate textbooks on this subject are recommended to consult (e.g. Rabiner and Gold, 1975; Oppenheim and Schafer, 1975). After the introduction of the FFT an extensive amount of publications and textbooks, focussed on this particular subject saw the light. For a clear, illustrative treatment of the FFT and its properties we refer to Brigham (1974) and Rendall and Tech (1977), and for a more fundamental approach, concerning Fourier transforms of continuous and sampled functions, to Papoulis (1962). In the remainder of this section we will confine ourselves to handle briefly those properties of the FFT which are of major importance for our method.

The general Fourier transform-pair is given by:

$$G(f) = \int_{-\infty}^{\infty} g(t)\ \exp(-j2\pi ft)dt \qquad (1)$$

and

$$g(t) = \int_{-\infty}^{\infty} G(f)\ \exp(j2\pi ft)df \qquad (2)$$

where $g(t)$ is a continuous function of time, and

$G(f)$ is a continuous function of frequency.

If firstly, a sampled data sequence is available from only a finite time window over $n = 0$ to $n = N-1$, and secondly, the transform is discretized also for N values by taking samples at the frequencies $f = k\Delta f$ for $k = 0,1...N-1$, where $\Delta f = 1/T = 1/N\Delta t$, then one can develop the familiar *Discrete* Fourier transform (DFT) (e.g. Brigham, 1974):

$$\begin{aligned} G(k) &= 1/N \sum_{n=0}^{N-1} g(n)\ \exp(-j2\pi k\Delta f n\Delta t) = \\ &= 1/N \sum_{n=0}^{N-1} g(n)\ \exp(-j\ \frac{2\pi kn}{N}) \end{aligned} \qquad (3)$$

and the inverse transform:

$$g(n) = \sum_{k=0}^{N-1} G(k)\ \exp(j\ \frac{2\pi kn}{N}) \qquad (4)$$

Both, equation (3) and (4) are cyclic with period N. Thus using (3) we have forced a periodic extension to both, the discretized data and the discretized transform values, even though the original continuous (not sampled) data may not have been periodic. Figure 14 illustrates the various forms of the Fourier transforms. Note that for convenience sake the time and frequency functions in (3) and (4) have not been made symmetrical about the origin, but because of the periodicity of each, the second half also represents the negative half period to the left of the origin (Fig.14).

It is obvious that the DFT is much better adapted to digital computations. Moreover, the FFT algorithm reduces the computation time by a factor $N/\log_2 N$ in comparison with conventional DFT, which for the case of $N = 1024$ is more than 100.

The power of the assumed periodic signal is defined as:

$$\text{power} = |G(k)|^2 \qquad (5)$$

A few comments have to be made about the dimensions of the various spectra. For those forms where the *spectrum* is a *continuous* function of frequency (Fig.14,a and c) the spectral components have the dimensions of *spectral density*. In particular, the amplitude squared spectrum typically has the dimensions of either energy per unit frequency (energy spectral density) or of power spectral density, after division by the time interval in which the data are available. It must be integrated over a finite bandwidth in order to obtain the energy or the power. Dealing with *discretized* spectra, a thorough mathematical treatment with the use of Dirac delta functions is required to describe them in terms of power density (Papoulis, 1962). Therefore it is more common to represent discretized spectra as *power spectra,* scaled directly in power units, conform equation (5). Since we compute the power according to (5), the plots we generate are scaled in power units.

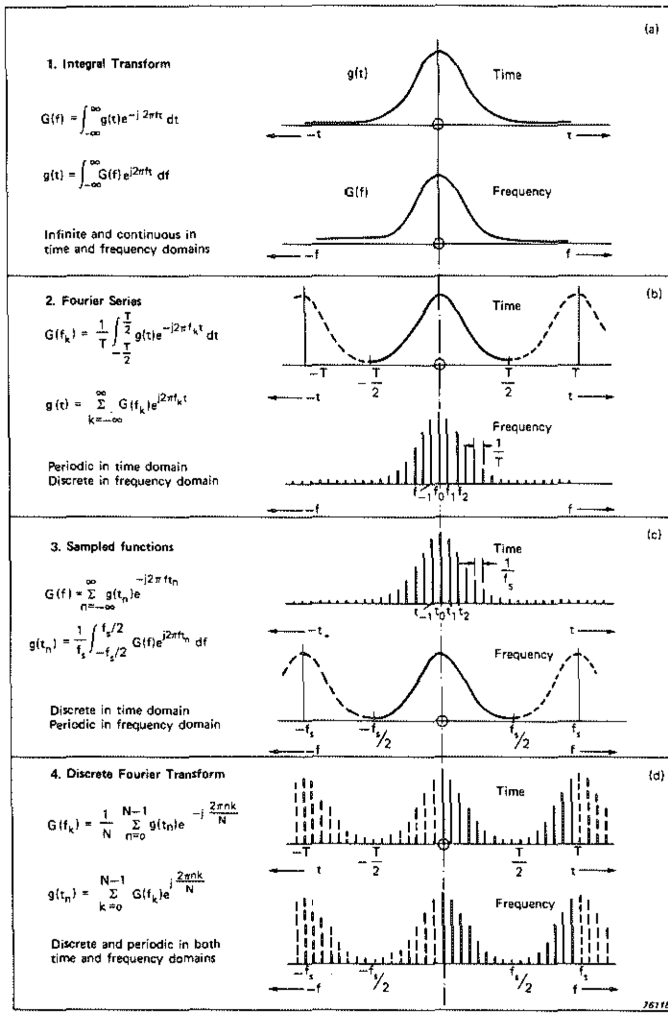

Fig.14. Various forms of the Fourier transform; f_s is the sample frequency (from Rendall and Tech, 1977).

As mentioned, the FFT is computationally most efficient. The main disadvantage of the method, however, is the limited ability to distinguish spectral components of two or more signals.

When a record with a duration of T seconds that consists of N values that are equidistantly sampled with intervals of Δt seconds is transformed (thus $T = N \cdot \Delta t$) the frequency spacing in hertz equals the reciprocal value of T, being $1/N\Delta t$. As a consequence, applying FFT to relatively short during time periods, ambiguities may occur, as illustrated in figure 15,a. To minimize this drawback zero padding may be applied: i.e. a sequence of sampled data is successively filled up with zeroes before the transformation is performed. In essence, zero padding has to be considered as an *interpolation* process in the *frequency domain*, as illustrated in figure 15 too. Zero padding is useful for:

1) smoothing the appearance of the spectrum via interpolation,
2) resolving potential ambiguities, and
3) reducing the 'quantization' error in the accuracy of estimating the frequencies of spectral peaks.

A second limitation of the FFT is due to the implicit rectangular windowing of the data. In the frequency domain each computed spectral data point is convolved with the Fourier transform of the time window, the latter being the well-known sinc function ((sin x)/x). If an integral number of periods of a particular sinusoid fits exactly in the time window T, the FFT computes the exact amplitude of that sinusoid. In general, sinusoids present in the time signal do not fit in the time window. As a consequence, the convolving process manifests itself as 'leakage' in the spectral domain, i.e. energy (or power) in the main lobe of a spectral component 'leaks' into the side lobes, obscuring and distorting other spectral components that are present. Application of tapered data windows can reduce the sidelobe leakage, *but always at the expense of broadening of the main lobe*.

The use of a Hamming window may be considered a reasonable compromise between leakage reduction and mainlobe width (e.g. Blackman and Tukey, 1968; Noll, 1967; Pederson, 1980).

The Hamming window function is expressed as:

$$H(n) = 0.54 - 0.46 \cos\left(\frac{2\pi n}{N}\right) \qquad n = 0,1....,N-1$$

If the original data sequence is $g(n)$, $n = 0, 1...,N-1$ a new sequence is formed by $g'(n) = g(n).H(n)$.

Then the FFT is applied to the sequence $g'(n)$.

Figure 16 compares the spectra of the rectangular window and the Hamming window. We used the Hamming window throughout this study.

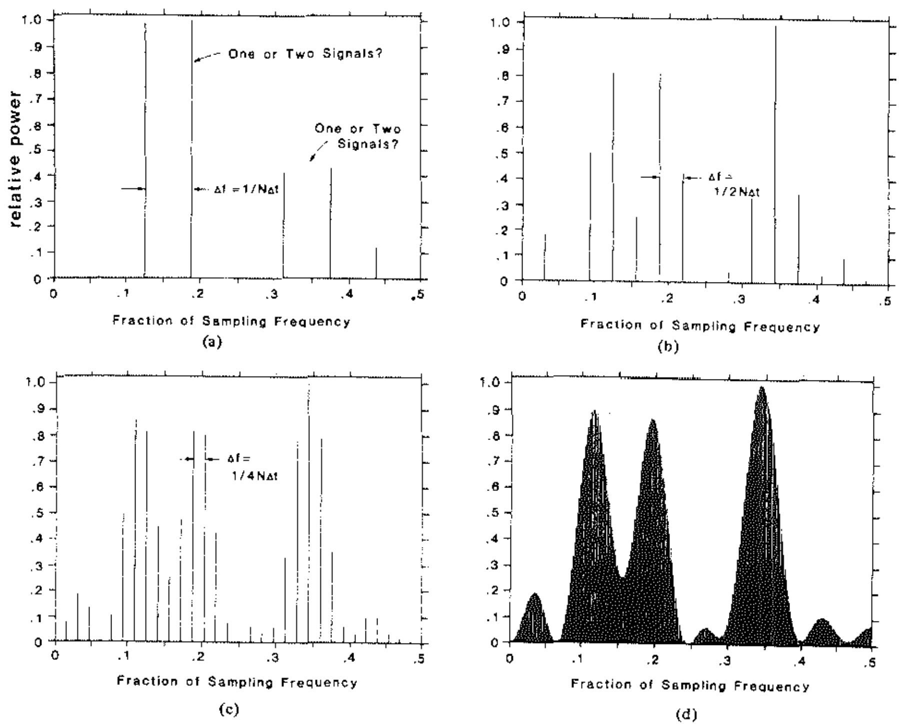

Fig.15. Consequences of zero padding. All spectra were calculated using the same 16 samples of a process consisting of three sinusoids of fractional sampling frequencies 0.1335, 0.1875 and 0.3375 respectively.

(a) No zero padding; ambiguities are present.
(b) Double padding; ambiguities resolved.
(c) Quadruple padding; smoothed spectrum seen.
(d) 32-times padding; envelope is approximation to continuous Fourier transform.

(From Kay and Marple, 1981)

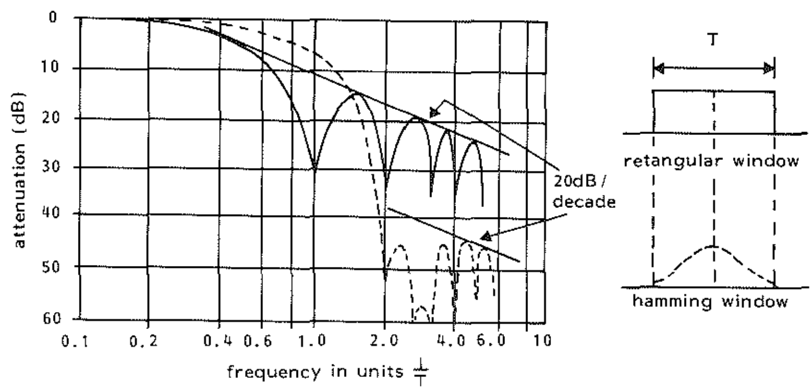

Fig.16. Comparison of the spectra of the rectangular window and the Hamming window (after Rendall and Tech, 1977).

5.2.3 Running Spectrum Analysis

In principle the procedure of running spectrum analysis is simple: every ΔT seconds a spectrum is computed from the preceding T seconds of signal and each spectrum is displayed in an appropriate way. However, the concept of RSA requires some further discussion, since it is not obvious beforehand under which circumstances adequate information can be obtained, using this procedure. To investigate the concept in more detail we modulated a basis frequency (being 0.25 times the sample frequency) with a periodic function as shown in figure 17.

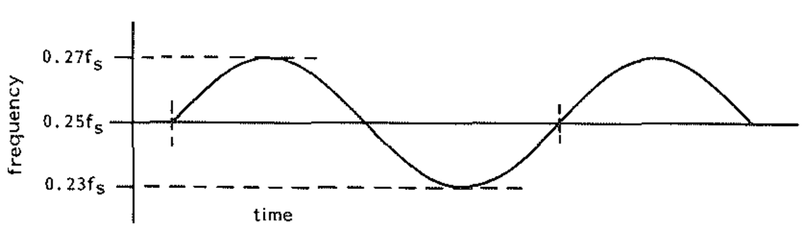

Fig.17. Frequency modulation with a sinusoid.
Basis frequency is 0.25 times the sample frequency (f_s).

If firstly, contiguous spectra are computed with a record length of T seconds (so no overlap is applied) and, secondly, the period of the modulation frequency (modulator) equals the time window length T, the modulator may be considered to be 'sampled' once a time in each period. As a result each spectrum has the same frequency content as the previous one (see Fig.18,A). Obviously we have to account for the sampling theorem of Shannon, where each 'sample' now consists of T seconds of data. *That means that each period of the modulator has to be 'sampled' at least two times,* as depicted in figure 18,B (as a matter of fact Fig.18,A illustrates 'undersampling'). Since still the nature of the modulation cannot be established from this figure, four (or more) samples give better information (Fig.18,C). If overlap is used, *interpolation* occurs, providing for a more interpretable display as demonstrated in the figures 19,A, B and C (overlap 75%, i.e. $\Delta T = \frac{1}{4}T$; Fig.18,A through C corresponds with Fig.19,A through C).

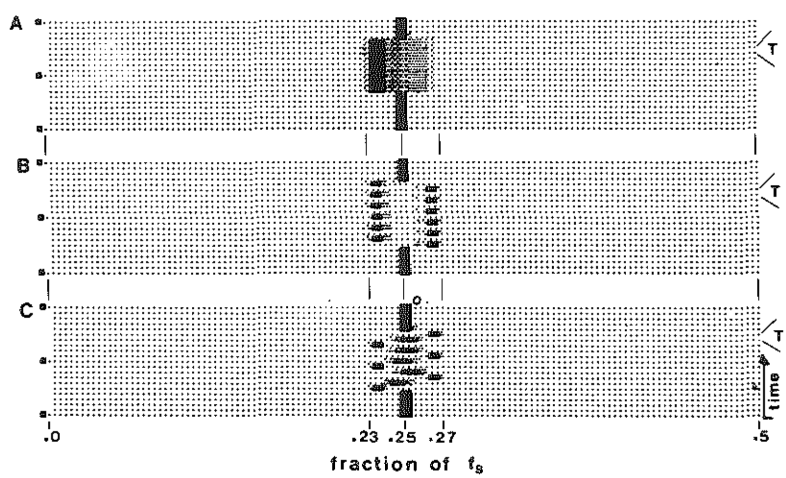

Fig.18. Running spectrum display (without overlap) of a time signal described by the characteristics of figure 17. The period of the sinusoid equals T, (A), 2 times T, (B), and approximately 4 times T, (C), respectively, where T is the length of the time window.

In this connection it is important to recall that we routinely used the Hamming window. Because of the tapered ends of the window the frequency content of the time signal which coincides with the mid-portion of the window, dominates the spectrum.

The 'effective' width is in the order of $\frac{1}{2}$T.

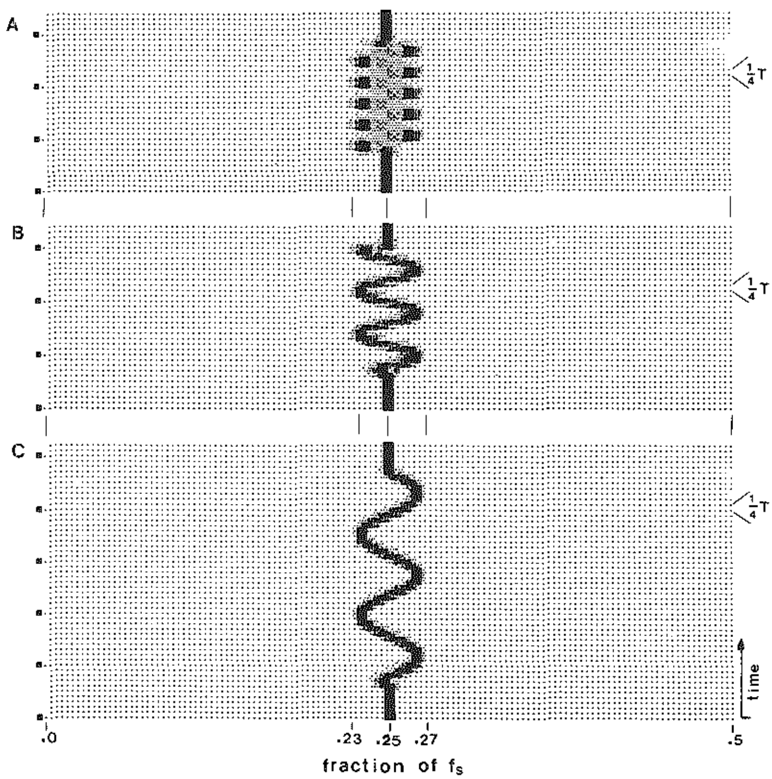

Fig.19. Runningspectrum display of the previously described time signal. Overlap: 75%. Interpolation occurs. A, B and C correspond with figure 17,A, B and C respectively.

Figure 20 illustrates the interpolation process related to the figures 18,C and 19,C and reveals that frequency changes which can be resolved by RSA are in the order of ΔT seconds.

In figure 21,A and B the time relations between the computed spectra, the time signal and the echoed pulse train, are illustrated in more detail than in figure 2 , page 61.

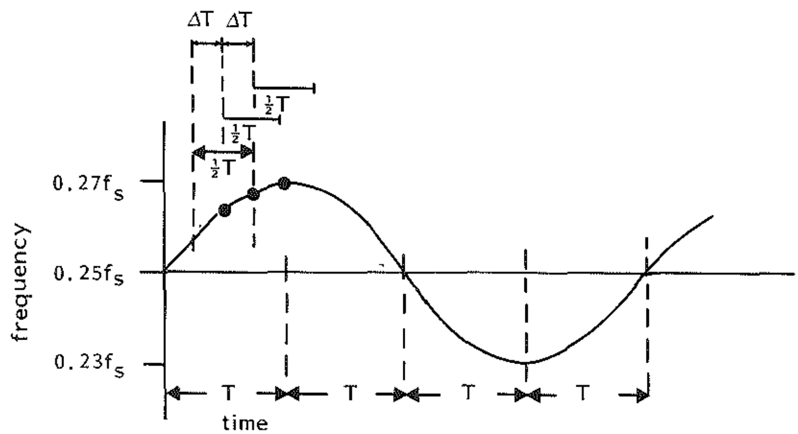

Fig.20. Running spectrum analysis applied to a frequency modulated signal. Period of modulator equals 4 times the length of the time window. Effective width of the window is ½T and ΔT is ¼T. Interpolation of frequency content occurs. Compare figures 18,C and 19,C.

5.2.4 Standard procedure for EGG signals

Referring to our standard recording technique of EGG signals the signals were preprocessed by analogue band-pass filtering using a Butterworth filter (24 dB/octave). The cut-off frequency of the high-pass filter was set at 0.01 Hz to remove possible DC-components (e.g. introduced by the electronics of the taperecorder and/or the amplifier which is used before the signal is fed into the computer). The cut-off frequency of the low-pass filter was set at 0.5 Hz, and the sample frequency of the AD-converter at 1 Hz, thus avoiding aliasing. All values are real-time, however, in practice the signals were replayed from the tape with a speed up to 16 times real time, which requires adjustment of the filter settings and sample frequency accordingly.
A time window of 256 seconds (256 samples) was found to be suitable in electrogastrographic practice, corresponding to a frequency spacing of 1/256 = 0.0039 Hz (0.234 cycles per minute). After applying FFT, 129 discrete spectral power values are obtained, equidistantly spaced over the frequency interval 0 -0.5 Hz. Using running spectrum analysis, most frequently an overlap of 75% was chosen. In the grey-scale representation, the resolution of which is determined by 16 distinct levels, 128 power

values were plotted, since the value of the DC-component usually equals zero. However, to check for that, in every ten spectra additionally one data point was plotted, together with the actual size of one pixel.

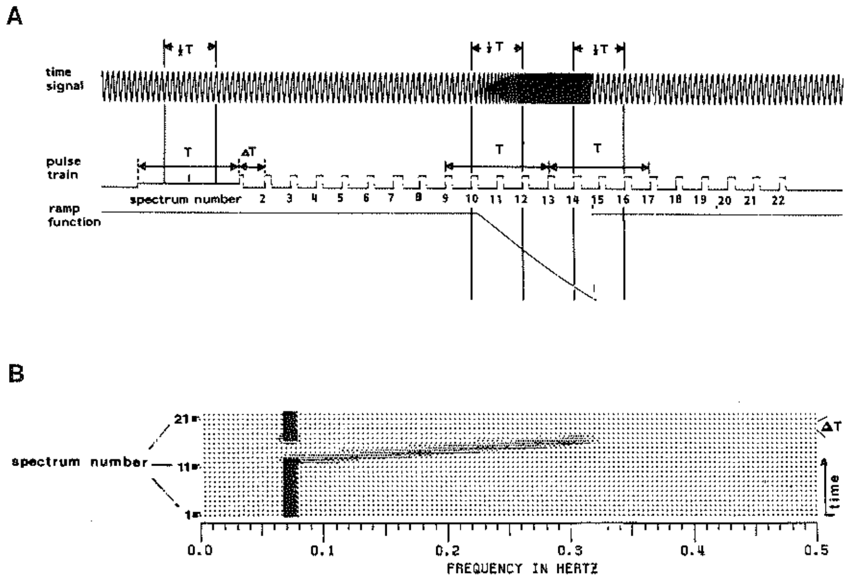

Fig.21. A frequency of 0.07 Hz modulated with a ramp function.
A. Time signals.
B. Running spectrum; $T = 256$ s, $\Delta T = 64$ s.
Upgoing flanks of the pulses indicate the time shifts. Note that spectrum number 13 is dominated by the power content of the time signal between number 10 and 12, i.e. the start of the ramp. Note also that the duration of the ramp is approximately 4 times ΔT, which can be estimated from both the time signal and the running spectrum.

Motility of the Digestive Tract, edited by M. Wienbeck, Raven Press, New York © 1982.

5.3 Application of Running Spectrum Analysis to Electrogastrographic Signals Recorded from Dog and Man

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The recording of gastric electrical activity from surface electrodes is called Electrogastrography (EGG). The electrogastrographic signal has a dominant frequency equal to the mean repetition frequency of the electrical control activity (ECA) of the stomach, i.e. about 0.050 Hz (3 cpm) in man and about 0.085 (5 cpm) in dog.

Recently Smout et al. (13) concluded from a study in the dog that both ECA and -if present- electrical response activity (ERA) are reflected in the electrogastrogram, the latter being related to phasic contractions.

In general, monopolar recordings (potential differences between an exploring electrode on the abdomen and an indifferent electrode, e.g. on the leg) are of poor quality. Bipolar recordings (potential differences between adjacent electrodes) are of better quality because most of the motion and respiration artefacts are cancelled out. Even then, direct visual interpretation of EGG signals is very difficult. Therefore various methods of analysis have been applied to EGG signals, such as auto-regressive modelling (5), phase-lock techniques (8, 9), adaptive filtering (3,17) and, most frequently, Fourier analysis (2,4,10,13,14,16).

Using Fourier analysis of 17.07 min stretches of EGG signal, Smout et al. (14) showed that the specific myoelectrical characteristics of the postprandial and interdigestive states in the canine stomach, could be recognized from the electrogastrogram. However, although spectral (Fourier) analysis of relatively long stretches of EGG signal provides information about the mean frequency content, time information is lost. Running Spectrum (RS) analysis, which provides overlapping power spectra displayed as a function of time, offers the advantage of yielding both time and frequency information.

The object of this study was to evaluate the usefulness of RS analysis of EGG signals recorded from dog and man.

METHODS

Recording

Recordings were obtained from four healthy conscious dogs, and also from seventeen healthy human volunteers ranging in age from 16 to 37 years.

In the dogs gastric myoelectrical, gastric contractile and cutaneous electrical activities were recorded simultaneously from the electrodes and force transducers at the sites shown in Fig.1A and 1B. In dog 4 an additional bipolar electrode was implanted on the serosal surface of the duodenum, at a distance of 3 cm from the pylorus.

In man cutaneous electrical activity was recorded from electrodes (14245A, Hewlett Packard) at the sites shown in Fig.1C.

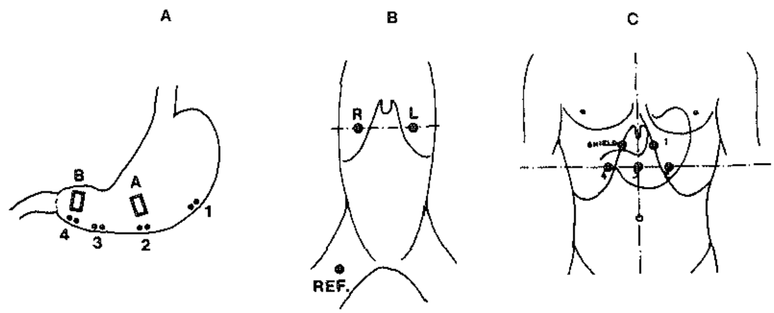

FIG. 1, A. Bipolar serosal electrodes (Ag-AgCl) 1,2,3 and 4 implanted at 12, 7, 4 and 2 cm from the pylorus respectively. A and B implanted strain gauge force transducers.
B. Abdominal surface electrodes R and L, 8 cm apart, and reference electrode on right hind leg.
C. Surface electrodes 2, 3 and 4 situated on Addison's line (transpyloric line). Distance between electrodes 6 cm. Reference electrode on right ankle.

With each dog recording sessions were carried out in both the postprandial state and the interdigestive state.

From all human subjects fasting activity (after an overnight fast) was recorded during a 35 minute period. Subsequently, a test meal, consisting of 250 ml of yoghurt with 20 g of sugar, was given, while recording was continued. Recording was terminated 55 minutes after the start of food intake. Subjects lay quietly in a supine position during the entire recording session. Respiratory movements were recorded by means of a force transducer attached to the chest.

All recordings were made on paper (Van Gogh EP-8b) as well as on magnetic tape (Racal Store 14). For monopolar serosal recordings the high- and lowpass filters (6 dB/octave) were set at 0.012 and 15 Hz respectively, for bipolar serosal recordings at 0.5 and 15 Hz and for cutaneous recordings, both monopolar and bipolar, at 0.012 and 0.46 Hz.

In man all bipolar and monopolar EGG signals (10 possible combinations) were visually inspected in order to establish the 'cleanest' signal, i.e. the one most devoid of artefacts, to be used for further analysis.

Signal Analysis

A fast Fourier transform algorithm, implemented on a NOVA 2 digital computer, was used to obtain the power spectra of the time signals. In our standard recording procedure the highest frequency is about 0.5 Hz. Therefore, before being fed into the computer, the signals were bandpass-filtered with a Butterworth filter (24 dB/octave) with cut-off frequencies set at 0.01 and 0.5 Hz, while, in order to avoid aliasing, the sample frequency was set to 1 Hz.

Running spectra were obtained as follows. The time signal was fed into the computer, either on line or from tape, at a speed up to 16 times real time. Every ΔT seconds a power spectrum was computed from the preceding T seconds of signal, to which a Hamming window was applied (1,6) in order to reduce leakage. In this way overlapping spectra were obtained (See Fig.2). Using e.g. ΔT = 64 s and T = 256 s, an overlap of 75% results, while the 128 computed spectral data points give a frequency resolution of 0.0039 Hz (0.234 cpm).

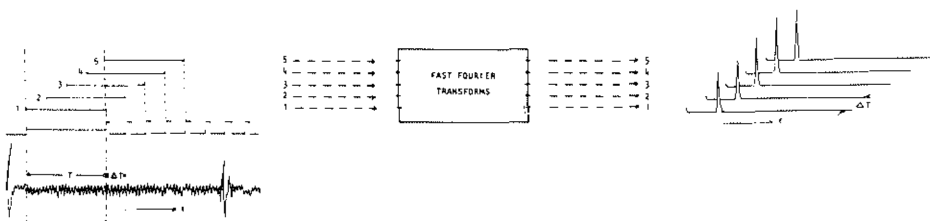

FIG. 2, Principle of Running Spectrum analysis.

During processing each computed spectrum was drawn on a Tektronix 4010 display terminal, together with its spectrum number. After completion of the processing each spectrum could be analyzed in detail by choosing the corresponding spectrum number.

Computer programs enable different graphical representations of the running spectra. In Fig.2, the first 5 spectra are displayed as a pseudo-3-dimensional (3-D) representation. Such a display can be rotated in order to change the viewing angle. The generation time for a display of this kind with some 100 spectra is about 20 minutes. The data can also be displayed as a grey-scale plot: each point in the (f,t)-plane is represented by a picture element (pixel), the blackness of which is proportional to the magnitude of the power. The 'grey' resolution is bounded by 16 distinct grey levels. This kind of display especially facilitates the recognition of frequency *patterns*. The generation time for this type of plot is about 1 minute. All drawings were made on a Versatec 1100A printer-plotter.

RESULTS

Dog

RS analysis was applied to EGG signals with a total duration of about 80 hours; 15 hours during the postprandial state, 55 hours during the fasted state and about 10 hours during pharmacological manipulation. A total of 20 interdigestive migrating complexes (IMC's) was analyzed. In two dogs antral tachygastrias occasionally occurred. One of these dogs (dog 4) never showed IMC-cycles in the fasted state, 'minute patterns' (14) or continuous weak contractions were observed instead.

Fig.3 shows the result of applying RS analysis to a typical postprandial EGG signal in the dog. Gastric and duodenal components (at 0.095 and 0.31 Hz) show little variation in frequency and amplitude.

RS analysis was applied not only to the cutaneous signal but in some cases also to the simultaneously recorded antral and duodenal myoelectrical signals.

This procedure clearly demonstrated the presence of gastric and duodenal frequencies in the cutaneous signal. Brief episodes of tachygastria were easily recognized. See Fig.4 and Fig.5.

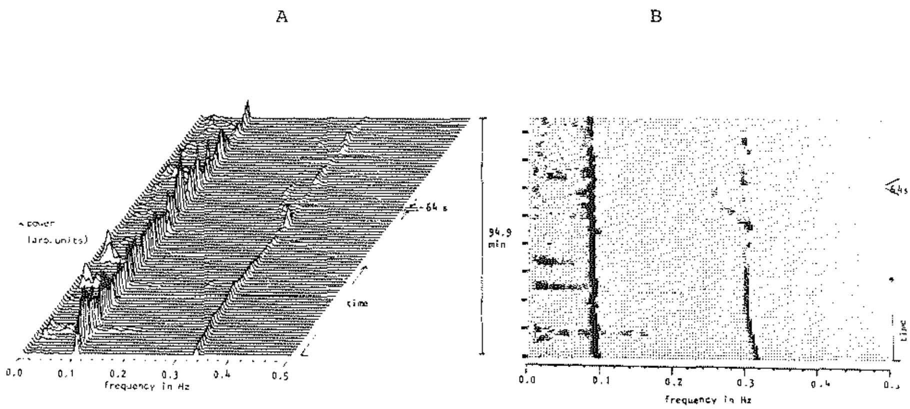

FIG.3, Running Spectrum display of 94.9 min of postprandial recording. Cutaneous signal R-L. Overlap 75%. Dog 2. A. Pseudo 3-D display. B. Grey-scale plot.

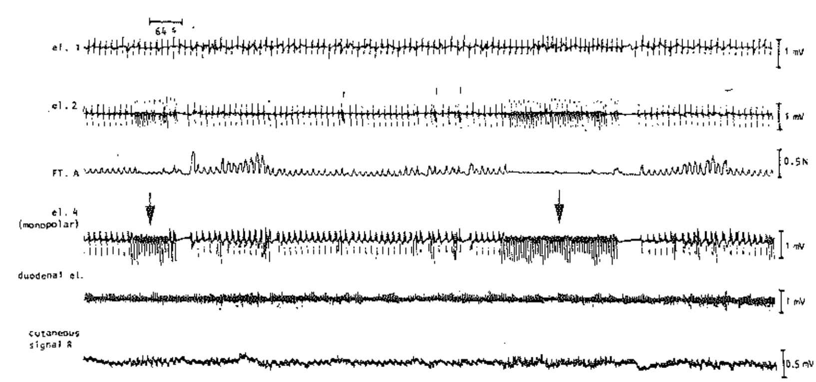

FIG.4, Electrical and mechanical activity recorded from dog 4. Fasted state. Arrows indicate episodes of tachygastria.

As we reported earlier (14), the activity front of the IMC manifests itself by the appearance of low frequency components in the electrogastrogram. Using RS analysis, these fronts are characterized as shown in

Fig.6. The figure also reveals clearly the increase in duodenal frequency which is related to the activity front (15). Although all the IMC-complexes which were analyzed showed the characteristics described, it was sometimes difficult to distinguish between IMC and motion artefacts. However, it appeared that motion artefacts contained more high-frequency components than IMC's, thereby facilitating the distinction.

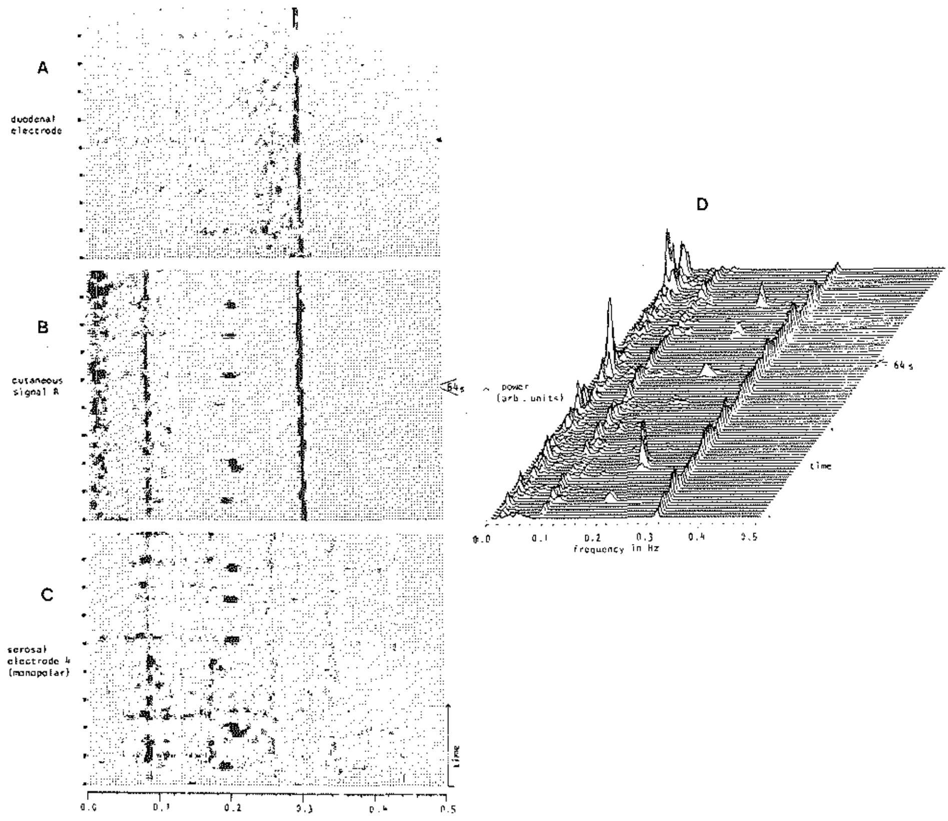

FIG.5, A. B. and C. Grey-scale plots of RS analysis applied to 99.2 minutes of simultaneously recorded duodenal, cutaneous (electrode R) and antral (electrode 4) electrical signals, respectively. All signals low-pass filtered at 0.5 Hz before processing. Overlap: 75%. Fasted state. Dog 4. D. Pseudo 3-D display of the processed cutaneous signal R.

Gastric frequency at 0.085 Hz, tachygastrias at about 0.21 Hz and duodenal frequency at 0.32 Hz (note the 4 higher harmonics in Fig.C). First 22.5 minutes of the time signals are shown in Fig.4.

In dog 3 pharmacological experiments were carried out in order to induce changes in the gastric frequency and the pattern of contractile activity. A persistent regular antral tachygastria at a frequency of about

0.22 Hz (13.2 cpm) was terminated within 30 seconds after i.v. injection of 50 mg of lidocaine. The administration of 20 mg of domperidone, p.o., was followed within 17 minutes by an increase in the amplitude of contractions and a decrease in frequency (Fig.7).

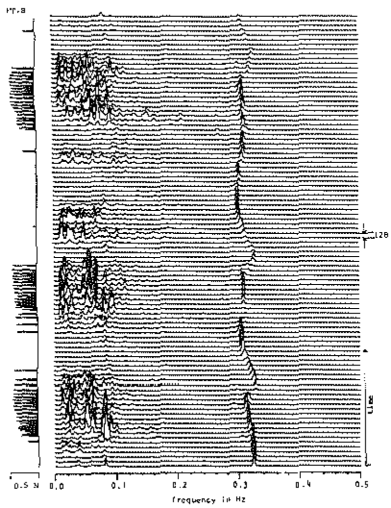

FIG.6, Pseudo 3-D display of 3.52 hours of EGG recording. Overlap: 75%. Fasted state. Dog 3. 3 IMC-cycles are recognized. At the left the gastric motor pattern as recorded with force transducer B is shown.

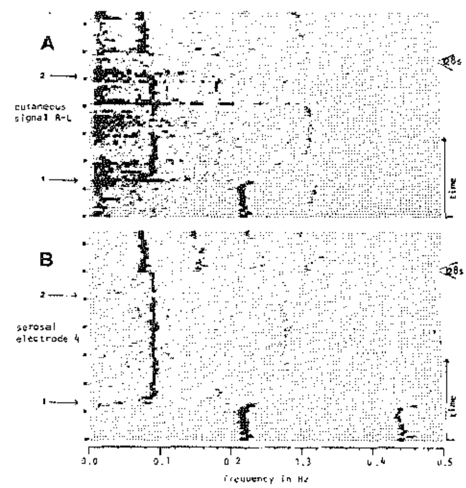

FIG.7, Grey-scale plot of 162.1 min of simultaneously recorded cutaneous signal R-L (A) and antral myoelectrical activity from el.4 (B). Overlap: 50%. Fasted state. Dog 3. 1: Administration of 50 mg of lidocaine, i.v.. 2: Administration of 20 mg of domperidone, p.o..

Man

In general, visual examination of the recorded EGG's revealed that in most subjects the bipolar signal obtained from electrode 1 minus 4 was suitable for RS analysis; in a few cases other bipolar or monopolar signals were analyzed. Nevertheless, in two subjects mean gastric frequencies, before and after food intake, could not be established because of excessive motion artefacts. The remaining 15 subjects showed a mean gastric frequency ± 1 S.E.M. of 0.048 ± 0.003 Hz (2.88 ± 0.18 cpm) in the fasted state, and 0.050 ± 0.004 Hz (3.00 ± 0.24 cpm) during the postprandial state.

In 5 subjects examination of the gastric response immediately after ingestion of the test meal was rendered impossible by motion artefacts associated with food intake. From the remaining 10 subjects the total of 90 minutes of recording could be used.

Fig.8 shows an example of the human electrogastrographic signal and the corresponding pseudo 3-D dimensional RS display and grey-scale plot.

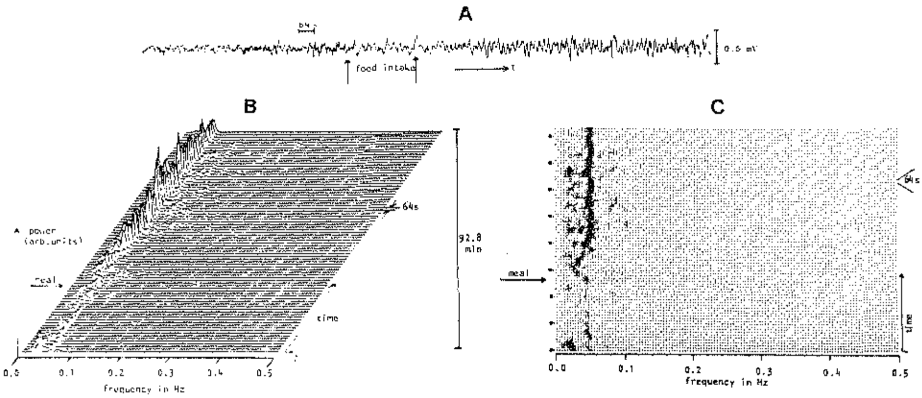

FIG.8, Example of human electrogastrogram, monopolar recording from cutaneous electrode 1 and its running spectrum. Signal stretch (A) is part of the 92.8 min of the time signal from which the pseudo 3-D display (B) and the grey-scale plot (C) were calculated. Note the frequency decrease and amplitude increase following the ingestion of the test meal.

During the interdigestive phase, a pattern of relatively low power magnitude at about 0.05 Hz (3 cpm) was observed. After food intake (average time of food intake was 3.7 ± 1.2 minutes) the power magnitude increased by a factor of about 5 (corresponding to an increase in the amplitude of the time signal by a factor of about $\sqrt{5}$), while a well-defined frequency dip as shown in Fig.8C, always occurred. The characteristics of this frequency dip were quantitatively analyzed, using the grey-scale plots and detailed analysis of the individual spectra obtained from 10 subjects. The results are graphically presented in Fig.9 and summarized in Table 1. (The meanings of the various parameters are indicated in Fig.9.)

TABLE 1. Characteristics of the gastric frequency response after the test meal in man (n = 10).

$f_{fasting}$ ± 1 S.D.	f_{min} ± 1 S.D.	f_{max} ± 1 S.D.
0.048 ± 0.003 Hz (2.88 ± 0.18 cpm)	0.039 ± 0.002 Hz (2.34 ± 0.12 cpm)	0.054 ± 0.006 Hz (3.24 ± 0.36 cpm)

t_{min} ± 1 S.D.	t_d ± 1 S.D.	t_{max} ± 1 S.D.
2.5 ± 0.5 min	12.1 ± 3.1 min	22.4 ± 2.6 min

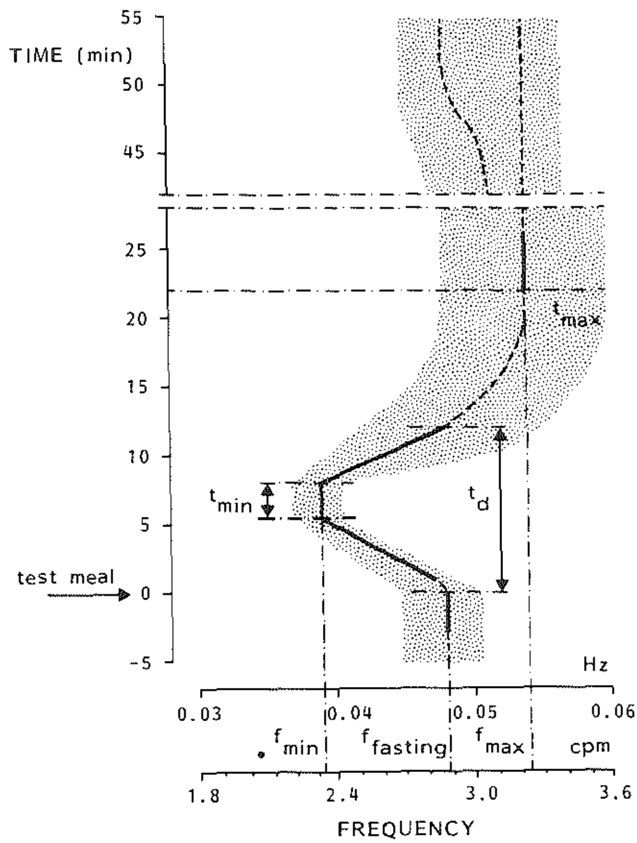

FIG.9, Characteristics of the gastric frequency variations in relation to the test meal in man. Dotted area indicates the standard deviation.

The following additional remarks can be made:

- The average frequency decrease amounted to 18.8 ± 5.9%.
- The standard deviation (S.D.) of the parameters describing the frequency dip was remarkably small.
- Following the dip some overshoot in frequency occurred.
- After the maximum frequency was reached, 60% of the volunteers maintained that frequency during the remaining recording period. 40% showed a slow decrease to the value before food intake.

During the analysis of the electrogastrograms frequencies near 0.17 Hz (10 cpm) were never observed in any of the volunteers, indicating that electrical activity from the small or large bowel was not recorded by the electrodes.

DISCUSSION

This study demonstrates that RS analysis offers a fast and concise representation of electrogastrographical data in both the time and frequency domains. The method especially allows the recognition and quantitative analysis of gastric (and duodenal) frequency patterns, relatively uninfluenced by the appearance of short-lasting motion artefacts.

The recognition and quantification of contractile activity is more difficult because the relation between EGG-amplitude and contractile force is not very strong (13). However, when contractions occur at irregular intervals, as for example during the activity front of the IMC, RS analysis permits detection by the appearance of low frequency components. Our recent -unpublished- experiences with simulated serosal and cutaneous electrical waveforms (based on dipole theory) indicate that these low frequencies are related to the prolonged ECA intervals that have been shown to occur during the activity front (12).

In man, a frequency decrease immediately following a meal was found (electrogastrographically) by Smallwood (7) and Smout (11). The first author found a decrease of about 9% and the second author a decrease of about 4% (but this last value appeared not to be significant). Our study revealed a decrease of about 18%. This discrepancy can be easily understood when it is realized that these authors used Fourier analysis of long non-overlapping signal stretches (10.39 minutes and 8.53 minutes duration) leading to a considerable underestimation.

A striking difference between the human and canine EGG recordings is that in man there is a complete absence of intestinal activity, while in the dog 100% of the EGG's contained a duodenal frequency component. Brown et al. (2) reported that in 9 out of 32 human EGG recordings of 1½ hours duration a frequency component between 10 and 12 cpm occasionally occurred. They assumed that this component originated from the intestine. Although we cannot explain the discrepancy between their findings and ours, it is clear that in practice the presence of intestinal activity in human electrogastrograms is very rare.

Recently, You et al. (18) studied gastric electrical activity in patients suffering from unexplained nausea, bloating and vomiting by means of a peroral electrode. In 9 out of 14 subjects abnormal myoelectric activity was found, described as repeatedly occurring episodes of tachygastria and tachy-arrhythmia of short duration. In view of our results in the dog it might be expected that, in cases like these, EGG combined with RS analysis offers an important non-invasive diagnostic tool.

We conclude that RS analysis offers the possibility of extracting both qualitative and quantitative information from the electrogastrogram. It can be considered as a significant improvement in the analysis of the EGG, which brings electrogastrography one step closer to (clinical) application.

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5.4

Contraction-related, low-frequency components in canine electrogastrographic signals

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VAN DER SCHEE, E. J., AND J. L. GRASHUIS. *Contraction-related, low-frequency components in canine electrogastrographic signals.* Am. J. Physiol. 245 (Gastrointest. Liver Physiol. 8): G470–G475, 1983.—Interdigestive gastric contraction-related phenomena were studied in four healthy conscious dogs by running-spectrum analysis of signals derived from the abdominal surface. When groups of contractions occur irregularly spaced in time, low frequencies (in the range below 0.085 Hz) show up in the power spectra of the electrogastrograms. It has been hypothetized that prolonged electrical control activity (ECA) intervals shown to coincide with irregular contractions are related in some way to these low frequencies. This hypothesis was investigated in detail. Whereas a certain degree of correlation was demonstrated between ECA interval variations, contractile activity, and the presence of low frequencies in the spectra obtained from electrogastrograms recorded during interdigestive migrating complexes, a more pronounced correlation between these phenomena was found during "minute rhythms." It was concluded that the presence of lower frequencies ranging from the normal gastric one to about 0.01 Hz in the running-spectrum representation of electrogastrograms recorded in fasting dogs is indicative of strong antral contractions and that the mechanism through which this is brought about involves prolongation of ECA intervals associated with these contractions.

running-spectrum analysis of electrogastrograms; electrical control activity interval duration; interdigestive migrating complex; minute rhythm; interdigestive gastric contractile activity

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GASTRIC ELECTRICAL ACTIVITY in the form of slowly varying electrical potentials can be determined from cutaneous electrodes applied to the external abdominal surface. In analogy with electrocardiography and electroencephalography, the recording of this electrical activity is called electrogastrography and might provide a noninvasive method for obtaining information about gastric motility. The electrogastrographic signals can be considered a summation of time-shifted waveforms generated by the electrical control activity (ECA) and, if present, the contraction-related electrical response activity (ERA) travelling along the stomach (12). As a consequence the electrogastrogram (EGG) has a dominant frequency equal to the mean repetition frequency of the ECA, i.e., about 0.050 Hz in humans and about 0.085 Hz in dogs.

Because of the relatively poor signal-to-noise ratio of the EGG, direct visual interpretation of the cutaneous signal is often very difficult. Various analytical methods have therefore been applied to electrogastrographical data either in the time domain (6, 17) or, most frequently, in the frequency domain (1, 7, 12, 13, 16).

We recently introduced running-spectrum (RS) analysis into the field of electrogastrography, offering a fast and concise representation of recorded cutaneous data (18). This method uses Fourier analysis to provide overlapping power spectra as a function of time, thus permitting the extraction of quantitative frequency information over the course of time. The extraction of other information from the spectra, particularly the possible occurrence of contractile activity, is hampered by a lack of knowledge of the way in which contraction-related mechanisms affect the frequency contents of the associated cutaneous signals. Since the EGG reflects the myoelectric activity of the stomach, it provides only indirect information regarding the contractile activity of that organ.

We described the gastric frequency component in the EGG power spectra of dogs and humans during the postprandial phase (where each ECA is followed by ERA) as having a significantly higher-power magnitude compared with this magnitude during motor quiescence in the interdigestive phase. The postprandial frequency component showed little variation in frequency and amplitude. The significant increase in power magnitude occurred immediately after food intake (13, 18). In the interdigestive phase different motor patterns exist. During the activity front (phase III) of the interdigestive migrating complex (IMC) groups of strong contractions alternate with short periods (0.5–1.0 min) of motor quiescence or very weak contractions, whereas during phase II of the IMC an irregular pattern of contractile activity with a periodicity of 1–3 min is observed (3, 5, 10, 11, 19). A similar pattern has been described by other authors in the absence of IMCs (9, 13) or during periods of inadequate fasting (15). We will designate the fasting motor patterns not identical to phase III of the IMC as "minute rhythms."

Smout et al. (12) demonstrated that the presence of ERA manifests itself in the EGG by an increase in amplitude but that the relation between EGG amplitude and contractile force is not very close. In previous papers we described the appearance of ultra-low-frequency components ($<$0.03 Hz) in the EGG during the activity front of the IMC (13) and demonstrated (18) the appearance of low-frequency components in the power spectra obtained from the recorded EGG ranging from the gastric frequency down to the chosen high-pass filter cutoff frequency (about 0.01 Hz) during phases II and III of the IMC. These observations suggest that low-frequency components of EGG power spectra may correspond to the occurrence of phasic contractions of the stomach irregularly spaced in time. The appearance of these frequencies cannot be ascribed to an increase in EGG amplitude. If only amplitude increase were involved, the power magnitude at the gastric frequency would also increase or frequency components would show up symmetrical around the gastric frequency when regularly spaced repetitive groups of contractions occur (amplitude modulation). It was hypothetized (13, 18) that the low-frequency components described above are related to the prolonged ECA intervals that have been shown to coincide with irregular contractions (4, 8, 11). This assumption, however, was never investigated in detail. The objectives of the present study were first to establish the relation between ECA interval variations during the interdigestive phase in dog and its reflection in the (running) power spectrum obtained from the corresponding electrogastrographic signal and second to investigate to what extent this reflection may be indicative of the presence of contractile activity.

METHODS

Recordings were obtained from four healthy conscious dogs (beagles) weighing between 10 and 14 kg. Electrodes and extraluminal strain-gauge force transducers were sutured to the serosal surface of the stomach under general anesthesia (induction with thiopental sodium, maintenance with nitrous oxide and enflurane) and using a sterile operating technique. The serosal electrodes consisted of two silver-silver chloride conical tips, 3 mm long, 0.2-mm base diameter, mounted 2 mm apart in a small plate. The electrode wires were connected to a multipin connector implanted in the animal's neck. For cutaneous recording disposable silver-silver chloride electrocardiogram electrodes (14245 A, Hewlett-Packard) were used. Before placement of these electrodes some electrolyte paste (Redux paste, Hewlett-Packard) was rubbed on the shaved skin.

Gastric myoelectric, gastric contractile, and cutaneous electrical activities were recorded simultaneously from the electrodes and force transducers at the sites shown in Fig. 1, *A* and *B*. During the recording sessions, lasting from 1 to 16 h (after a fast of at least 18 h), the dogs were standing in a canvas support mounted in a rack. When not subjected to fasting, the dogs were fed ad libitum with dry food (Canex). Weekly recording sessions were carried out on *dogs 1* and *2* for at least 2 mo and biweekly sessions on *dogs 3* and *4* for more than a year. All monopolar recordings were made with respect to the reference electrode attached to the right hindleg. The recordings were made on paper (Van Gogh EP-8b) and stored on magnetic tape (Racal store 14). For monopolar serosal recordings the high-pass and low-pass filters (6 dB/octave) were set to 0.012 and 15 Hz, respectively; for bipolar serosal recordings to 0.5 and 15 Hz; and for cutaneous recordings, both monopolar and bipolar, to 0.012 and 0.46 Hz.

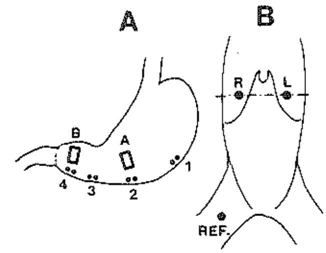

FIG. 1. *A*: serosal electrode pairs 1, 2, 3, and 4 implanted 12, 7, 4, and 2 cm from pylorus, respectively. Strain-gauge force transducers A and B were implanted opposite electrodes 2 and 4. *B*: abdominal surface electrodes R and L are 8 cm apart on a transverse line midway between distal ends of body of sternum and costal arch and reference electrode on right hindleg.

In this study only the bipolar cutaneous signal R-L will be considered (either from direct recording or through electronic subtraction), since this signal contained the fewest motion artifacts.

A fast Fourier-transform algorithm, implemented on a NOVA-2 digital computer, was used to obtain the power spectra of the EGG. The signals, replayed from magnetic tape at speed of up to 16 times real time, were preprocessed by bandpass filtering using an analog Butterworth filter (24 dB/octave) with (real-time) cutoff frequencies set at 0.01 and 0.5 Hz to remove possible DC components and to avoid aliasing. Then, they were digitized (sampling rate, 1 Hz) and fed into the computer.

Every 64 s a power spectrum was computed from the preceding 256 s of signal, to which a hamming window was applied in order to reduce leakage. This procedure generates a series of overlapping spectra that we plotted in two different ways, using pseudo-three-dimensional and gray-scale plots. In the latter case each point in the frequency-time plane is represented by a picture element (pixel), the blackness of which is proportional to the magnitude of the power. The "gray" resolution is bounded by 16 distinct gray levels. This kind of display especially makes easy the recognition of frequency patterns.

To facilitate the interpretation of the obtained spectra in relation to myoelectric, cutaneous electrical, and contractile activity, we developed a program permitting simultaneous digitizing and subsequent processing of up to eight time signals. This program made it possible to carry out *1*) measurement of intervals between consecutive ECA peaks recorded from electrodes at different levels of the stomach (interval functions), *2*) measurement of contraction amplitudes as recorded by the force transducers, *3*) measurement of intervals between consecutive maxima in the (sinusoidal) EGG (after smoothing by bandpass filtering between 0.05 and 0.10 Hz, 24 dB/octave), *4*) measurement of magnitude of these EGG maxima, and *5*) digital storage of ultra-low-pass-filtered versions of the EGG. Results were plotted with preservation of proper time relationships. All drawings and plots were made on a Versatec 1100A printer-plotter.

RESULTS

About 150 h of recording were made on fasting dogs. In total 21 IMC cycles were recorded. One of the dogs (*dog 4*) never showed IMCs but continuous minute rhythms instead. These latter rhythms were also observed in *dogs 2* and *3* in about 30% of the fasting recordings. During about 5% of the recording time, the cutaneous signal contained excessive noise due to motion artifacts lasting for more than 15 min when the animal became restless after recording sessions of more than 5 h of duration. These periods, including one IMC cycle, were discarded from analysis.

The cutaneous signals of the remaining 20 IMCs were subjected to spectral analysis. An example of such an analysis, presented as a pseudo-three-dimensional display, is shown in Fig. 2. The gastric frequency component during the period of motor quiescence (≈0.082 Hz) has a relatively low-power magnitude. The activity fronts are characterized by groups of high-power, low-frequency components.

All IMC complexes analyzed exhibited the characteristics shown and could be distinguished from relatively short-during motion artifacts because motion artifacts also disturb the spectrum in the higher-frequency components (i.e., above the gastric frequency) (18). Figure 3 clearly demonstrates a relation between ECA interval duration, contractile activity, and the presence of high-power low frequencies in the running spectrum during the activity front. However, this relation is not perfect. On the one hand peaks in the ECA interval function do not always coincide with contractions or with the appearance of low frequencies in the spectrum, whereas on the other the high-power low frequencies generally seem to correlate better with prolonged ECA intervals than with contractions.

Figure 4 illustrates the types of signals obtained from serosal electrodes, force transducers, and cutaneous elec-

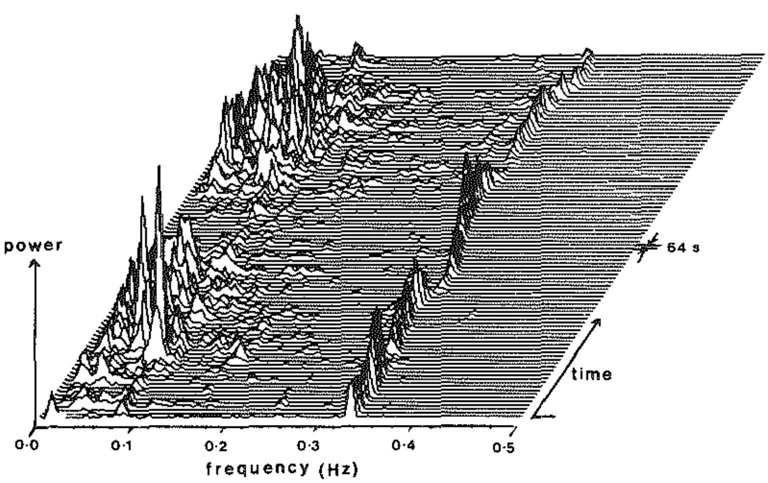

FIG. 2. Pseudo-three-dimensional plot of running power spectrum obtained from 107.7 min of recorded cutaneous signal (R-L). Two activity fronts of interdigestive migrating complex are recognized. Gastric frequency during motor quiescence is about 0.082 Hz. Frequency at about 0.320 Hz is of duodenal origin. Power is in arbitrary units. From *dog 3*. Note activity front-related increase in duodenal frequency (14).

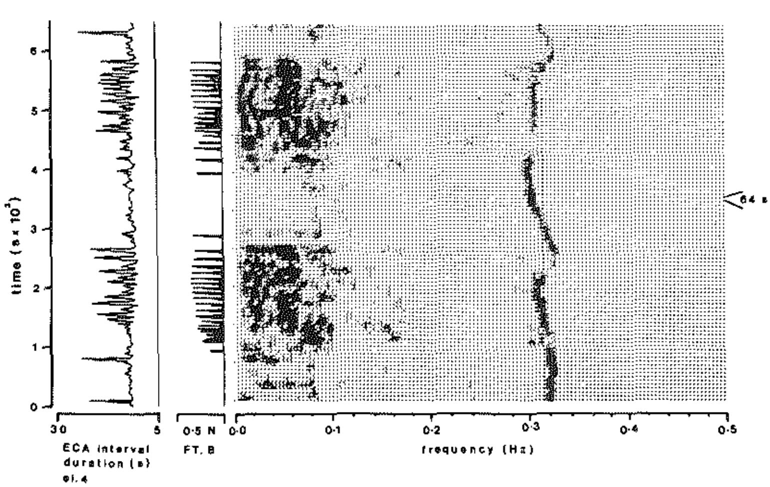

FIG. 3. Electrical control activity (ECA) interval function (electrode 4) and gastric motor activity as measured by force transducer B, together with a gray-scale plot of spectral data of Fig. 2.

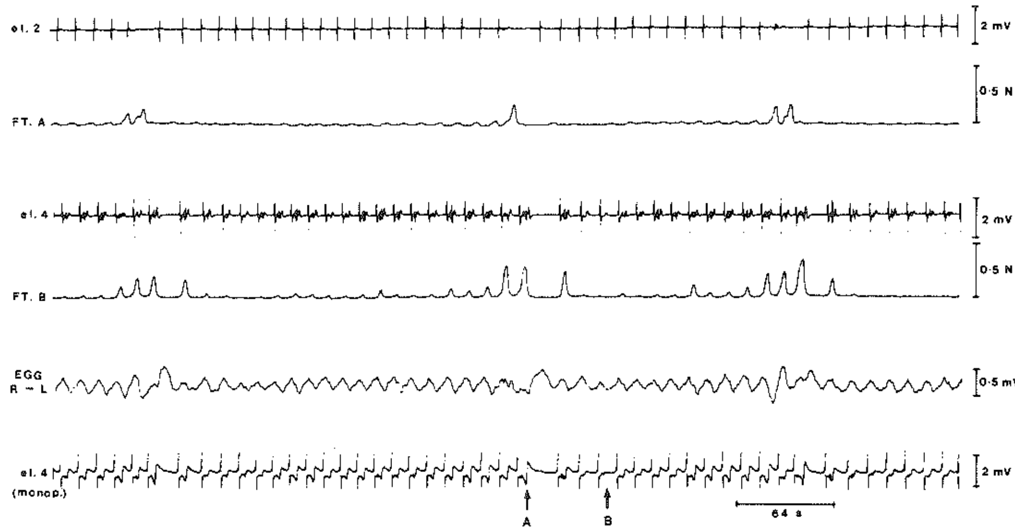

FIG. 4. Recording of gastric myoelectric and mechanical activity (bipolar serosal electrodes 2 and 4, force transducers A and B) and corresponding cutaneous signal (R-L). Bottom signal was derived monopolarly from electrode 4 with respect to reference electrode. *Arrows*: maximum second potential (*A*) and absence of of second potential (*B*), respectively.

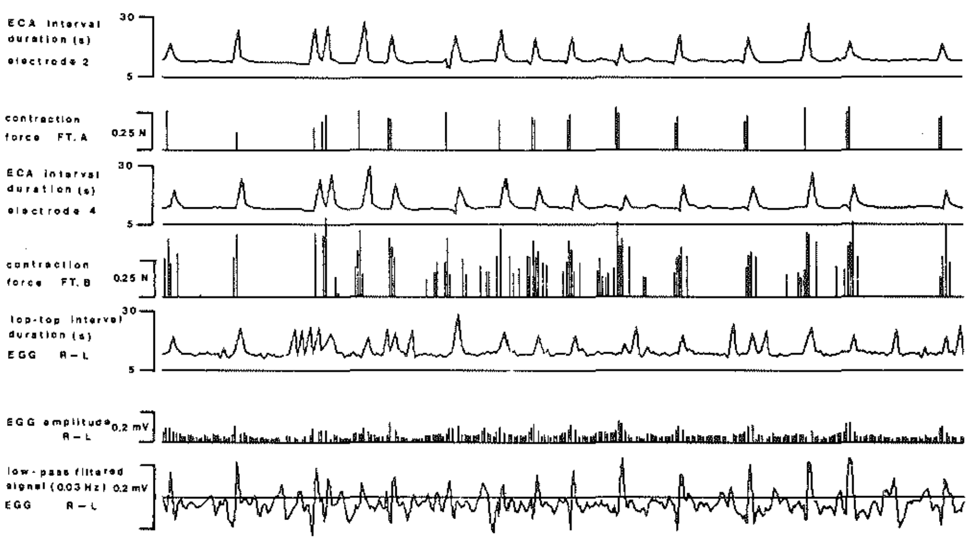

FIG. 5. Plots of interval functions and contraction force at different levels in stomach together with the electrogastrogram (EGG) interval function, EGG amplitude, and an ultra-low-pass-filtered version of EGG (0.03 Hz, 24 dB/octave). All signals were processed simultaneously. Minute rhythm. From *dog 4*.

trodes during the minute rhythms. The bottom trace presents the monopolar recorded signal from electrode 4, showing the amplitude variations of the ERA or second potentials (2) running parallel to the variations in contraction force and, less clearly, to the EGG amplitude, a finding demonstrated earlier and quantified by Smout et al. (12). Considerable changes in EGG waveforms occur at the moment relatively strong contractions show up accompanied by a prolonged ECA interval.

It can be seen from Fig. 5 that each peak in the interval functions measured from the serosal electrodes is present in the "interval function" of the EGG. However, the latter exhibits quite a few peaks that are not present in the ECA interval functions. This is partly due to the

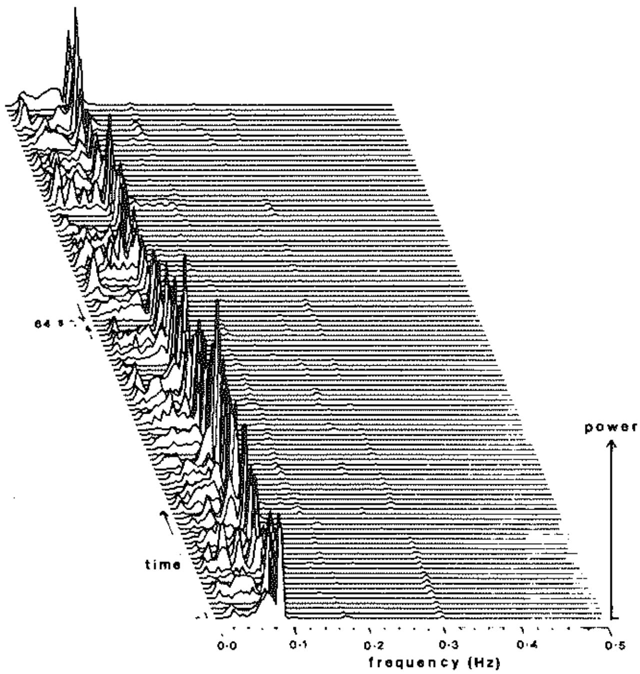

FIG. 6. Pseudo-three-dimensional, running-spectrum display of 114.1 min of recorded electrogastrogam (signal R-L, part of which is shown in Fig. 4). Minute rhythm. From *dog 4*. (Second and third harmonics of gastric frequency may be seen very weakly part of time; duodenal frequency is 0.030 Hz.)

inaccuracy of the detection method used and partly to noise and variability (of as yet unknown origin) in the cutaneous signal itself. Trace 6 of Fig. 5 demonstrates more clearly than Fig. 4 the amplitude variations of the EGG associated with contractile activity. The relatively high amplitude of the ultra-low-pass-filtered cutaneous signal (trace 7) coincides with the prolonged ECA intervals and with the highest EGG maxima, indicating the existence of relatively high-powered low frequencies in the EGG. At this stage we have to conclude that the prolonged ECA intervals are reflected in the EGG, thereby affecting its frequency contents with preference for low frequencies.

The spectral analysis of the cutaneous signal R-L shown in Fig. 6 demonstrates a considerable variation in the power magnitude at the gastric frequency (≈0.081 Hz) and the presence of low frequencies ranging from the gastric frequency down to about 0.01 Hz, irregularly spaced in time. Figure 7, *A–C* (*panel C* presenting part of the same data as Fig. 6) reveals a striking correlation between the peaks in the ECA interval function, contractile activity, and the low-frequency bands in the spectral representation. This detailed correlation in time is far more pronounced than that with the activity front of the IMC (Fig. 3), where time separation is not possible. A correlation between the serosal and cutaneous signals of the degree shown in Fig. 5 was found in 60% of the 80 h of the recordings made during the presence of minute rhythms. Obviously in those cases also serosal signals and the cutaneous running spectrum (as in Fig. 7, *A–C*) give good correlation. In the remaining 40% a poor resemblance was found between the measured EGG in-

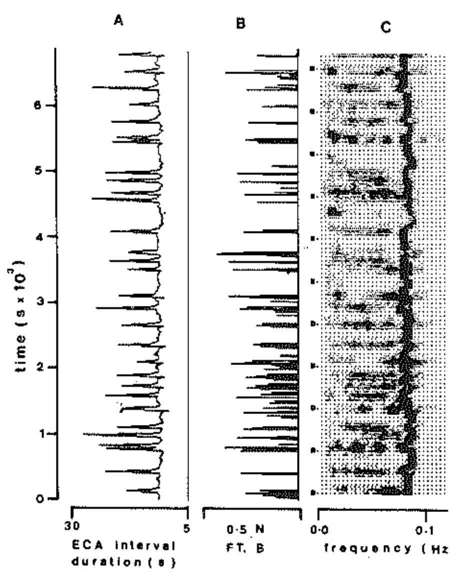

FIG. 7. *A*: interval function (electrode 4). *B*: gastric motor pattern as measured by force transducer B. *C*: gray-scale plot of spectral data (broken off at 0.12 Hz) of Fig. 6.

terval function and the corresponding ECA interval function, while in the recordings made during the activity front of the IMC the EGG interval function could not be interpreted at all. However, in all these cases a relation of the type shown in Fig. 3 could be observed between the ECA interval functions, contractile activity, and the spectral contents of the EGG.

DISCUSSION

This study demonstrates that the presence of frequencies lower than the normal gastric one in the running-spectrum representation of analyzed EGGs recorded in fasting dogs is indicative of strong antral contractions and that the mechanism through which this is brought about involves prolongation of contraction-related ECA intervals.

The behavior of the power magnitude near the normal gastric frequency itself can be understood by realizing that the power magnitude of the peak at a particular frequency in a spectrum depends on *1*) the amplitude of that frequency component in the time signal and *2*) the number of cycles of that frequency component within the signal stretch to be analyzed. Both these quantities are affected during IMCs and minute rhythms. During minute rhythms the disturbing phenomenon, i.e., the ECA interval prolongation, is of short duration with respect to the chosen time step (64 s) as well as to the signal stretch used for one spectrum (256 s). Therefore, each disturbance can be distinguished in the running-spectrum plots. For the same reason the normal gastric frequency remains to be recognized in all spectra, although with a considerable variation in power magnitude. This variability may serve as a rough indication of the existence of contractile activity; however, the appearance of the low-frequency bands has been shown to be more indicative.

During the activity front of the IMC, the disturbances caused by the ECA interval variations last much longer with respect to the chosen time values. As a consequence all spectra during the activity front are disturbed in an irregular way. In this case, during the 256 s of one spectrum, there is no steady gastric frequency present, and thus the gastric frequency cannot be distinguished anymore.

The difference in nature of the ECA interval functions, especially concerning the duration of the contiguous disturbances, thus accounts for the generally better correlations found during minute rhythms (Fig. 7) compared with those of the activity front of the IMC (Fig. 3).

Finally it should be emphasized once again that we were not dealing with individual contractions detected by spectral analysis but with groups of strong contractions irregularly spaced in time: this is why we used the term "contractile activity" throughout this study. It remains to be seen whether future developments will enable us to detect individual contractions, either from the time signal or from its spectrum.

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5.5 Relation between level-dependent contractile behaviour and the electrogastrogram during minute rhythms.

5.5.1 Introduction

In section 5.4 we concluded that the appearance of low-frequency bands in the RS-analysis is the result of prolonged gastric ECA intervals which in turn are associated with large antral contractions.
However, we did not account so far, for the level dependency of the contractile behaviour, especially as it appears during the *minute rhythm* as illustrated in figure 5, page 72. The figure reveals that as a rule prolonged ECA intervals at the proximal antral level coincide with strong contractions, whereas at the distal level the intervals *following* the strongest contractions were lengthened. This finding confirms our earlier observations (Smout et al., 1979) where an ERA-score was used as a measure of contractile strength. The underlying mechanism of this phenomenon can be understood by realizing that ECA is propagated whereas ERA is not. Regarding this behaviour it is still not clear to what extent the contraction pattern in either the proximal antrum or distal antrum plays a dominant role in the genesis of the pronounced low-frequency bands appearing in the running spectrum of the EGG. In this part of the study we will investigate this level-dependent behaviour in more detail.

5.5.2 Methods

We generated three fully deterministic signals and subjected them to RS-analysis too. These signals were composed of two basis waveforms shifted in time according to a chosen interval function. The basis waveforms were computed from an improved version of the dipole model proposed by Smout et al. (1980a), one for 'ECA' only and the second one for the presence of 'ECA' + 'ERA'. The in this application relevant difference between the two waveforms is the greater amplitude of the latter with respect to the former.
The three artificial signals were composed according to the interval function of figure 7,A (page 73), but with different criteria for the insertion of either an 'ECA-source' or an 'ECA + ERA source' related waveform. The three signals are shown in part in figure 22. The criteria were:

1) no contraction-associated waveforms (Fig. 22,A);
2) no contraction-associated waveforms when contractions greater than

0.05 N were measured by force transducer B (B) under the assumption that the contractions at B originated all in the proximal antrum;

3) as 2), but for contractions measured by force transducer A (C) under the assumption that during propagation of the ECA no other contractions are initiated.

5.5.3 Results and discussion

The grey-scale plots of the running spectra obtained from the artificial signals are shown in figure 23, D, E and F respectively.
It should be emphasized that possible higher harmonics in the spectra are of minor importance since we are only interested in the frequency range around the fundamental frequency down to lower frequencies.
A slight tendency to lower frequencies can be seen in figure 23,D, which shows the spectrum of the time signal containing the ECA-interval function only, but the signal power of these frequencies appears to be very small. When contraction-associated waveforms are inserted during (prolonged) ECA-intervals that coincide with contractions at the proximal antrum (see Fig. 22,C) the signal power increases, as shown in figure 23,F. The quadratic relationship between signal amplitude and power magnitude should be realized in this connection.
The spectrum of figure 23,E differs notably from that of figure 23,F. This may be explained by the following two facts:

1) all synthetic EGG waveforms corresponding to contractions above 0.05 N were identical, and
2) prolonged ECA-intervals at the distal antrum do not always coincide with contractions.

At the proximal antrum, all prolonged ECA intervals coincide with a strong contraction. The simulation of this characteristic, resulting in figure 23,F gives the best correspondance with the spectrum of the cutaneous signal actually recorded (Fig.23,C). This observation may be explained as an indication that in fasting dogs the appearance of the low-frequency bands during minute rhythms are indicative for the contractions which are present or initiated at the *proximal* antrum.

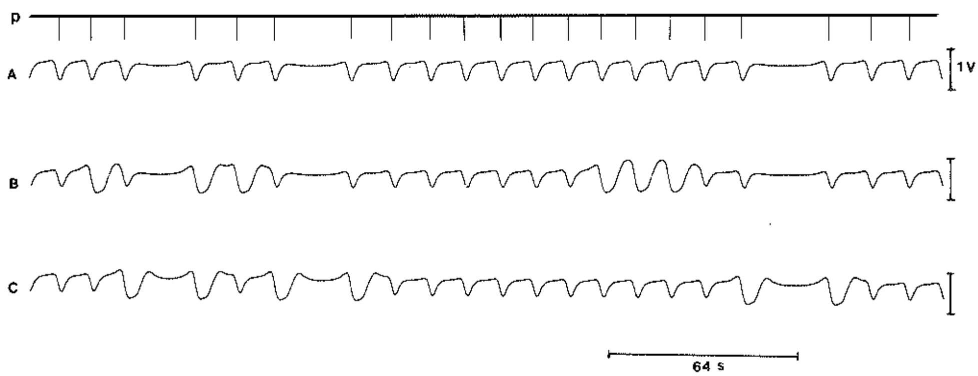

Fig.22. Segments of artificially generated signals containing the interval function of figure 7,A, page 73.
P = pulse train, indicating consecutive ECA intervals.
A = signal without contraction-associated waveforms.
B = signal with insertion of contraction-associated waveforms at the moment that contractions occur at force transducer B.
C = as B, but at the moment that contractions occur at force transducer A.

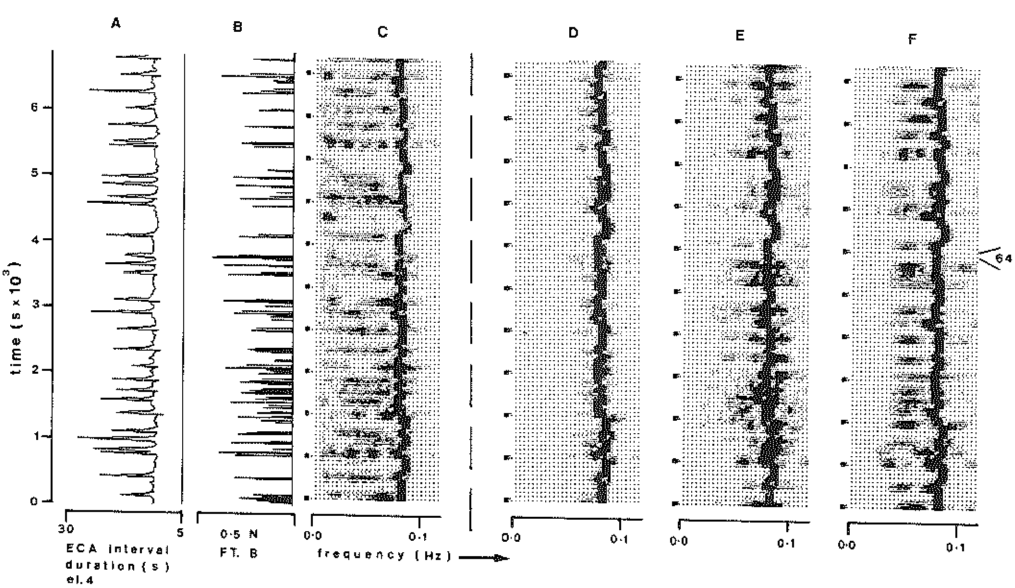

Fig.23. A, B and C as in figure 7, page 73.

D, E and F = Running spectrum analysis, displayed as grey-scale plots, applied to artificially generated 'cutaneous' signals, segments of which are shown in figure 22,A, B and C respectively.

5.6 Gastric rhythm alterations and arrhythmias in dog and man

5.6.1 Abstract

The extent to which the myoelectric characteristics of various types of antral (ectopic) arrhythmia, occurring in 9.5% of the total recording time of 201 hours, in 5 healthy conscious dogs implanted with serosal electrodes and force transducers could be recognized after applying running spectrum analysis to signals derived from abdominal surface electrodes (electrogastrograms), has been investigated. Also we compared the running spectrum of the electrogastrogram of a patient in which serosal electrodes were implanted during a cholecystectomy, with the spectrum of the simultaneously recorded serosal signal. Together with some examples of patients suffering from gastric disorders we discussed the clinical perspectives of electrogastrography.

In dog it was found that regular and irregular tachy-arrhythmias that lasted for 30 seconds or more, could be detected but that detailed characteristics as measured by serosal electrodes could not be revealed. In the patient no ectopic arrhythmias occurred during the total of 32 hours of recording made (up to the fifth postoperative day). Instead, spontaneous frequency alterations occurred. We demonstrated the electrogastrogram to be undoubtedly from gastric origin and that short during frequency changes could be followed in course of time.

We concluded that our study confirms the potentialities of EGG as a diagnostic tool and validates the importance of thorough electrogastrographic investigations in large groups of patients suffering from gastric dyspepsia but well-defined in their symptoms.

5.6.2 Introduction

The study of gastric myoelectric activity, and in particular of arrhythmias in both dog and man, has been gaining increasing interest. Antral arrhythmias in the canine stomach were first described in detail by Code and Marlett (1974). These arrhythmias consisted of regular tachygastrias (a rapid succession of control potentials lasting for more than one minute) and mixed antral rhythms of variable frequencies, all occurring during the period of motor quiescence in the fasting state (phase I of the interdigestive migrating complex (IMC)).

Gullikson et al. (1980) quantified the incidence of electrical arrhythmias in 32 unanaesthetized dogs using implanted serosal electrodes and force transducers. They concluded among other things that antral arrhythmias may be present during both normal and pathophysiological states.
Stoddard et al. (1981) reported that gastric arrhythmias occur in man post-operatively but disappear on recovery.
Recently, relations have been reported between antral dysrhythmias and nausea, bloating, vomiting or gastric retention (Telander et al., 1978); You et al., 1980a, 1980b, 1981; Chey et al., 1981). In these studies peroperative recording techniques or peroral mucosal electrodes were used. Electrogastrography (EGG), i.e. the recording of gastric electrical activity by means of cutaneous electrodes applied to the external abdominal wall, provides a non-invasive method of determining gastric myoelectric frequencies. The EGG signal can be considered to be a summation of the time-shifted waveforms generated by the control potentials (CP's) and, if present, the contraction-related second potentials travelling along the stomach (Smout et al., 1980a). Hence, the EGG usually has a dominant frequency of about 0.050 Hz (3 cpm) in man and 0.085 Hz (5 cpm) in dog. Previous studies in the dog (Smout et al., 1980a, 1980b) have demonstrated that regular tachygastrias of relatively long duration could be recognized in the EGG after Fourier analysis.
The introduction of running spectrum analysis (RSA) into the field of electrogastrography (Van der Schee et al., 1982) provided a means for fast, concise representation of EGG recordings from dog and man. In this method Fourier analysis is used to provide a series of power spectra over periods that overlap in time, thus permitting the extraction of quantitative frequency information as a function of time. By applying RSA to simultaneously recorded serosal and cutaneous electrical signals we showed the possibility of detecting short (duration about 1 minute) regular tachygastrias in the dog (Van der Schee et al., 1982). Although the gastric origin of the EGG in man has been well established (Alvarez, 1922; Nelsen and Kohatsu, 1968; Brown et al., 1975; Smallwood, 1976), it has never been proved that short-term gastric frequency variations as can be observed in the signal obtained from serosal electrodes implanted in the human stomach wall, can be extracted from the EGG.
In the light of these facts the objectives of the present study were threefold:

1) to investigate to what extent the myoelectric characteristics of antral arrhythmias in the dog can be recognized in the running spectrum obtained from the EGG signal;
2) to validate the method of EGG in man by applying RSA to simultaneously recorded serosal and cutaneous electrical signals obtained from a patient in whom serosal electrodes were implanted during a cholecystectomy, and
3) to indicate the clinical perspectives for electrogastrography on the basis of the results of 1) and 2), and that are illustrated by EGG data from patients with gastric disorders.

5.6.3 Materials and methods

Recordings in dog

Five healthy dogs (Beagles) weighing between 8 and 15 kg were anaesthetized with thiopental sodium (20 mg/kg iv) and maintained at a surgical level of anaesthesia with nitrous oxide and enflurane. Four to six bipolar electrodes were sutured to the serosal surface of the stomach using a sterile operating technique. In addition, one electrode was placed on the proximal duodenum (3 cm from the pylorus) in dogs 1 and 4. The serosal electrodes consisted of pairs of silver/silver-chloride conical tips, 3 mm long, base diameter 0.2 mm, mounted 2 mm apart in a small plate. Four electrode positions along the greater curvature were standard in all five dogs (Fig. 24). In dogs 1, 3 and 4 two extraluminal strain-gauge force transducers were placed in a transverse direction opposite electrodes S2 and S4. In dog 5 a force transducer was implanted on the duodenum 3 cm from the pylorus while transducer A (Fig.23,A) was omitted. The signals were transmitted to the recording equipment by means of either a 6-channel radio transmitter implanted subcutaneously (dogs 2 and 5) or by means of a multipin connector. For cutaneous recording, disposable silver/silver-chloride ECG electrodes (14245 A, Hewlett Packard) were used. Some electrolyte paste (Redux Paste, Hewlett Packard) was rubbed on the shaved skin before placement of the electrodes. Two electrodes were placed on the skin of the abdomen at sites selected in preliminary experiments (Fig. 24,B). During the recording sessions, lasting from 1 to 16 hours (after a fasting period of at least 18 hours) the conscious dogs were standing in a canvas support mounted in a rack. Weekly recordings, starting five days after implantation, were made

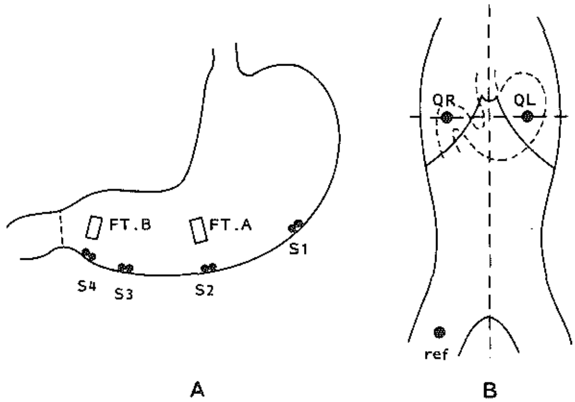

Fig.24. Positions of electrodes and force transducers on the stomach and the skin of the abdomen.
A: Serosal electrodes (S) and force transducers (FT); S1 is located 12 cm from the pylorus, S2 and FT.A 7 cm, S3 4 cm and S4 and FT.B 2 cm.
B: Two cutaneous electrodes QR and QL, 8 cm apart on Addison's line, reference electrode on the right hind leg; ventral view.

both in the fasting and postprandial state for at least two months. When not subjected to fasting, the dogs were fed *ad libitum* with dry food (Canex). Monopolar electrical recordings were made with respect to a reference ECG electrode attached to the right hind leg. All recordings were made on one or two 8-channel curvilinear chart recorders (Van Gogh EP-8b) as well as on magnetic tape (Racal Store 14). For monopolarly recorded serosal signals the high-pass and low-pass filters (6 dB/octave) were set to 0.012 Hz and 15 Hz respectively, for bipolarly recorded signals to 0.5 Hz and 15 Hz and for cutaneous recordings (both monopolar and bipolar) to 0.012 Hz and 0.46 Hz.

The strain-gauge force transducers were connected in a half bridge configuration using a Wheatstone bridge (Peekel 884 DNH, Automation Industries) without filter circuit. In dog 5 the low-pass frequency of the force transducer signals was limited to 100 Hz as a consequence of the radio transmitter system used (Groeneveld and De Bakker, 1983).

The force transducers were calibrated as described by Schuurkes et al. (1978).

Recordings in man

In a 37-year-old male patient undergoing a cholecystectomy, three pairs of stainless steel electrodes (with a spacing of 5 mm between the two members of each pair) were attached to the serosal surface of the antrum 1, 3 and 5 cm from the pylorus*). Each stainless steel wire (diameter 0.15 mm) was stripped off its coating (Trimel®, Johnson Matthey Metals Ltd.) over a distance of 6 mm, introduced into the serosa in transverse direction and fixed with 5×0 atraumatic catgut stitches. The wires were exteriorized via a medical grade silastic tubing (Dow Corning) of 75 cm length (inner diameter 2.0 mm, outer diameter 3.1 mm) sealed off at the distal end with Scurasil® 20350 (Rhône-Poulenc) and at the proximal end with Silastic® 382 (Dow Corning). The Silastic® was used to permit easy withdrawal of the wires one by one after completion of the measurements, as it preserves a certain degree of viscosity. The wires were connected to a multipin connector at the distal end. The silastic drain left the abdomen at the lower end of the median incision used for the operation. The assembly was gas sterilized before the distal end was sealed off, and the whole unit including the connectors was sterilized again before the operation. After closure of the wound 5 ECG electrodes (1 shield electrode and 4 recording electrodes; Red Dot 2256, 3M) were attached to the skin of the abdomen (Fig.25). A reference electrode was placed on the right ankle. Both monopolar and bipolar serosal recordings were made, with cut-off frequencies set to 0.012 Hz and 15 Hz, respectively. The corresponding values for the cutaneous recordings were 0.012 Hz and 0.46 Hz. A strain-gauge respiration transducer was attached to the abdomen using a sticking-plaster.

All signals were recorded on paper and simultaneously stored on magnetic tape. The recording apparatus was modified to meet the safety requirements for invasive measurements**).

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*) Prof.Dr. H. van Houten is greatly acknowledged for his willingness to perform the electrode implantation.

**) The research protocol was approved by the Medical Ethics Committee and the Director of the Dijkzigt University Hospital, Rotterdam, on September 20th, 1982. Written informed consent was obtained from the patient for implantation of the electrodes and subsequent measurements.

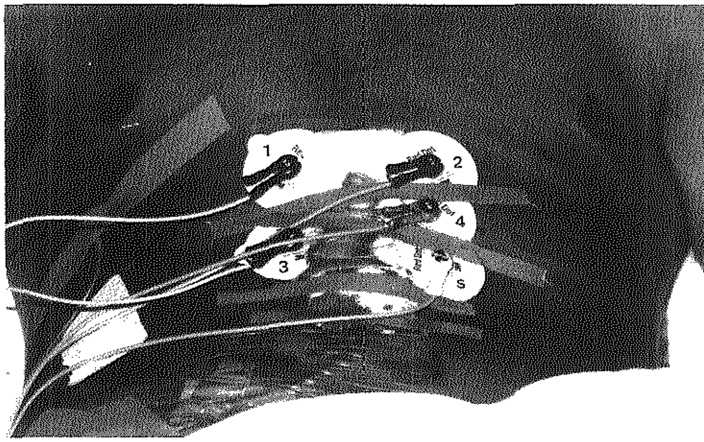

Fig.25. Positions of surface electrodes on both sides of the median incision. S is a shield electrode.

The recording sessions started two hours after the operation and were continued at intervals during the recovery period till the fifth postoperative day, when the measurements were terminated.
EGG data obtained from 4 patients with gastric complaints of various kinds are also presented. The same electrode positions as shown in Fig.25 were used, while one additional electrode was placed between the sternum and the umbilicus.

Signal analysis
A fast Fourier-transform algorithm, implemented on a Nova-2 digital computer, was used to obtain the power spectrum of the signals. The signals replayed from tape at a speed up to 16 times real time, were preprocessed by band-pass filtering using an analog Butterworth filter (24 dB/octave) with (real time) cut-off frequencies set at 0.01 Hz and 0.05 Hz to remove possible DC components and to avoid aliasing. They were then digitized (sampling rate 1 Hz) and fed into the computer. Running spectra were obtained as follows: Every ΔT seconds a power spectrum was computed from the preceding T seconds of signal, to which a Hamming window was applied to reduce leakage (Blackman and Tukey, 1958). This procedure generates a series of overlapping spectra which we plotted in two different

ways, using pseudo-three-dimensional and grey-scale plots. In the latter case each point in the frequency-time plane is represented by a picture element (pixel), the blackness of which is proportional to the corresponding power. The resolution here is determined by the number of grey levels used (16 in the present case). This kind of display greatly facilitates the recognition of frequency patterns. All drawings and plots were made on a Versatec 1100 A printer-plotter. Previous studies (Van der Schee et al., 1982, 1983) had shown already that values of 256 s and 64 s for T and ΔT, respectively, were satisfactory for the extraction of relevant information from the EGG, giving 128 points in each spectrum and a frequency resolution of 0.0039 Hz. However, as will be shown, lower values of T and ΔT are sometimes desirable. The choice of a lower value of T improves the time resolution at the expense of the frequency resolution. To overcome this problem, 'zero padding' (Oppenheim and Schafer, 1975) was used, i.e. the sampled data points were filled up with zeroes to give a total of 256 points before Fourier transformation. This leads to broadening of spectral peaks but does not affect the position of the maximum value of the frequency peak on the frequency axis. The procedure may thus be considered as an interpolation process in the frequency domain. It is obvious that a lower value of ΔT expands the time scale of the RS representation, and may thus facilitate the recognition of the short-during phenomena.

5.6.4 Results from dogs

A total of 201 hours of recording were made: 151 hours in the fasting state and 50 hours in the postprandial state. Ectopic arrhythmias consisting of regular tachygastrias (up to 70 minutes in duration), irregular tachyarrhythmias (lasting from 0.5 minute to about 4 minutes), series of premature control potentials followed by a compensatory pause and totally disorganized mixed antral rhythms were observed during 9.5% of the total recording time. A much higher percentage of incidence of arrhythmias was observed during the first recording session, which fell in the first week after operation (Table 1); this was probably due to the surgery performed (Ormsbee et al., 1975). All ectopic arrhythmias occurred during phase I of the IMC, or during short during periods of motor quiescence in the absence of IMC (dogs 3 and 4), except on two occasions where a tachy-arrhythmia, lasting about 30 s, was seen in the postprandial state (dogs 4 and 5). The considerable variations in interval duration between successive CP's

Table 1 Incidence of arrhythmias during 201 hours of recording in 5 healthy Beagle dogs.

Dog No.	First recording session		Total of all recording sessions	
	Duration (hours)	Incidence of arrhythmias (%)	Duration (hours)	Incidence of arrhythmias (%)
1	1.7	50.0	17.3	35.0
2	4.3	26.6	62.3	1.8
3	2.6	89.8	74.5	6.0
4	3.1	36.4	31.3	19.1
5	2.0	12.5	15.6	9.0
Total	13.7	41.7	201.0	9.5

always observed during phase III of the IMC, may be considered as arrhythmias too. They are not ectopic but originate in the pacemaker area, as illustrated in Fig.26. This kind of arrhythmia is not included in Table 1, since we have dealt with this phenomenon in previous studies, both gastroelectromyographically (Smout et al., 1979) and electrogastrographically (Smout et al., 1980b; Van der Schee et al., 1982, 1983). The characteristics of the types of tachy-arrhythmias most often observed in phase I of the IMC are illustrated in figure 27. A tachygastria starts as an irregular arrhythmia. The ectopic focus is located somewhere between electrodes S3 and S4, as indicated by the reversed polarity of the bipolar electrode signals. These reversed polarities also reveal oral propagation of the CP's. The 1 : 2 block frequently seen between electrodes S3 and S2 overrides the normal pacemaker after about 2 minutes (in this example). Figure 27 also reveals a jump of the ectopic focus to a point distal to electrode S4 (wandering ectopic pacemaker), followed by retrograde conduction only. The phenomenon is accompanied by a change in the monopolar waveform from electrode S4. The termination of the tachygastria is followed by a compansatory pause of several tens of seconds.

During the overall recording time of 201 hours, about 5% of the cutaneous signals contained excessive noise lasting for more than 15 minutes at a time, mainly due to motion artefacts. Artefacts lasting for more than

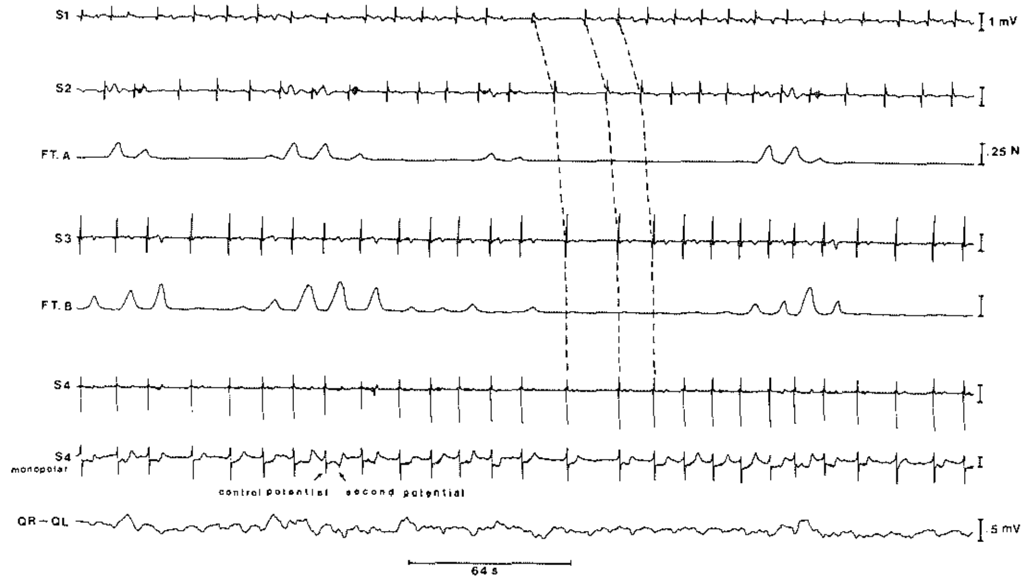

Fig.26. Recording of myoelectric and mechanical activity (bipolar serosal electrodes 1, 2, 3 and 4, force transducer FT.A and FT.B) and the corresponding cutaneous signal (QR - QL). Trace 7, the monopolar signal from one electrode of the electrode pair S4 reveals the second potentials associated with contractions more clearly than the bipolar signals. Phase III of the IMC. Dog 3.

2 minutes occurring during arrhythmic episodes were rejected for running spectrum analysis. This was the case for 7.9% of the 19 hours of arrhythmias. The remaining 17.5 hours were subjected to RSA.

Figure 28,A and B show the pseudo-three-dimensional display and corresponding grey-scale plot obtained by RSA of 45.9 minutes of EGG signal covering one activity front of an IMC followed by the arrhythmia shown in figure 27. The high-power low-frequency components ranging from the normal gastric frequency (about 0.086 Hz) down to about 0.01 Hz (the cut-off frequency of the high-pass filter) are characteristic for the activity front of the IMC's (Van der Schee et al., 1982, 1983) as is the (slight) increase in duodenal frequency related to the activity front (Szurszewski, 1969). Although the arrhythmia is easily recognizable and may be interpreted (from the grey-scale plot) as being more or less irregular, the detailed characteristics seen in figure 27, including the

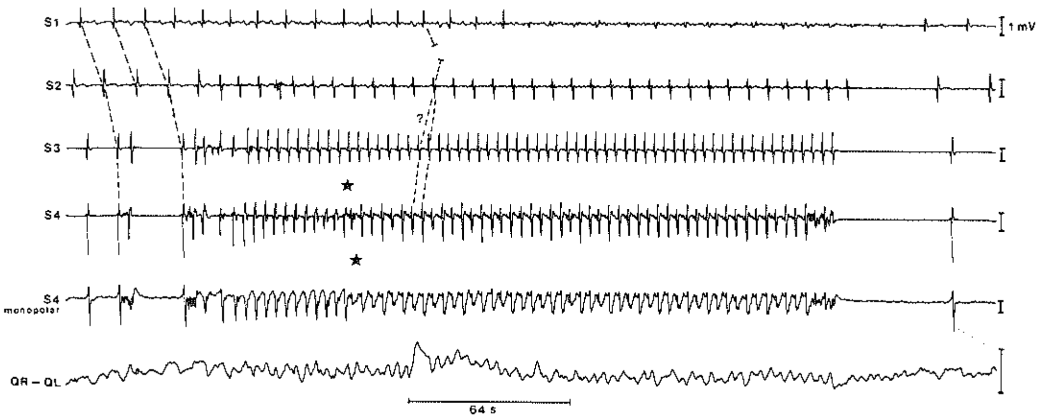

Fig.27. Myoelectric characteristics of a frequently observed tachy-arrhythmia. The reversed polarity of the bipolar signals indicates oral propagation and the site of origin of the ectopic focus. Asterisks denote a jump of the ectopic focus from a location between electrodes S3 and S4 to a location distal to electrode S4. Between electrodes S3 and S2 a 1 : 2 block occurs. Question mark indicates the uncertainty about which CP's at electrode S3 are related to CP's at electrode S2. The 5th trace was recorded monopolarly from electrode S4. The bottom trace is the corresponding electrogastrogram. Motor quiescence. Dog 3.

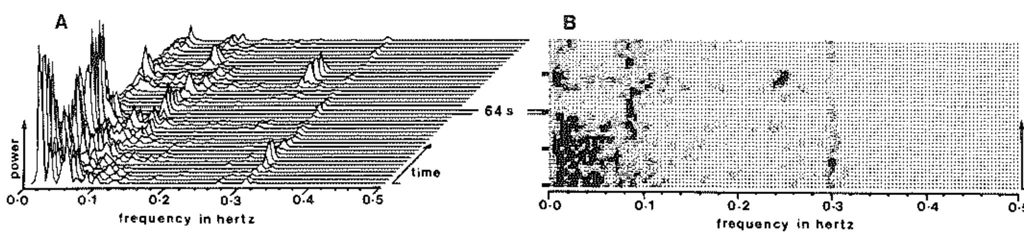

Fig.28. Running spectra of 45.9 minutes of the cutaneous signal QR - QL, comprising one IMC activity front and the tachy-arrhythmia during the motor quiescence phase shown in Fig.27.
A: Pseudo-three-dimensional display.
B: Grey-scale plot.
The normal gastric frequency is about 0.086 Hz (5.2 cpm). Both forms of presentation cleayrly show the tachy-arrhythmia at about 0.25 Hz (15.0 cpm).

repetition frequency of the CP's at the proximal antrum, cannot be extracted from the running spectrum.

Several other types of arrhythmias observed are depicted in figure 29, which also illustrates the variability in quality of the cutaneous signals; as a rule, the bipolar signal (QR - QL) was found to be the best. The disorganized rhythm seen in Fig.29,A (electrode S4) results from interference with ectopic antral premature CP's and aborally propagated CP's of variable interval durations, originating in the pacemaker area at the moment contractions are initiated.

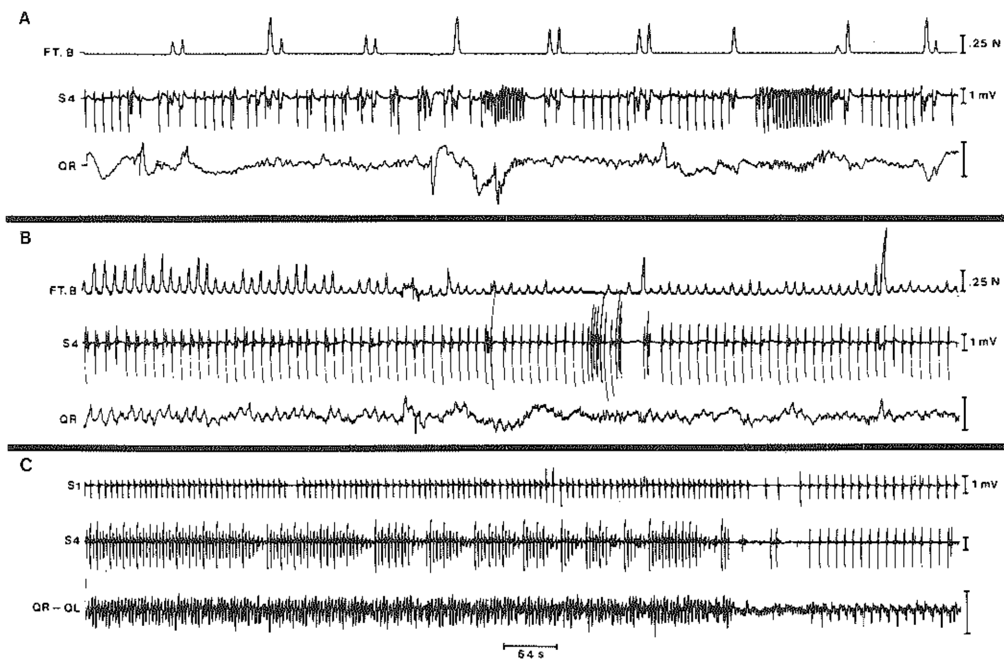

Fig.29. A: Monopolar recordings from electrode S4, showing periods of disorganized rhythm alternating with short-lived tachy-arrhythmias occurring during brief episodes of motor quiescence. Minute rhythm. Dog 3.

B: Short postprandial tachy-arrhythmia (bipolar electrode S4), while motor activity is absent. Dog 4.

C: 'Amplitude modulated' tachy-arrhythmia from bipolar electrode S4. Note the abnormally high repetition frequency of the CP's at electrode S1; these CP's must have originated distal to this electrode, as indicated by their reversed polarity. Motor quiescence. Dog 1.

The running spectra computed from serosal electrode S4 and cutaneous electrode QR, with a total duration of 46.9 minutes, are shown in figure 30. The signals of Fig.29,A containing two tachy-arrhythmias accounts for the first 18.7 minutes of this time. The disorganized rhythm, including four tachy-arrhythmias, can of course easily be recognized in figure 30,A. The running spectrum of the corresponding EGG (Fig.30,B) exhibits low-frequency components due mainly to the poor quality of the EGG.

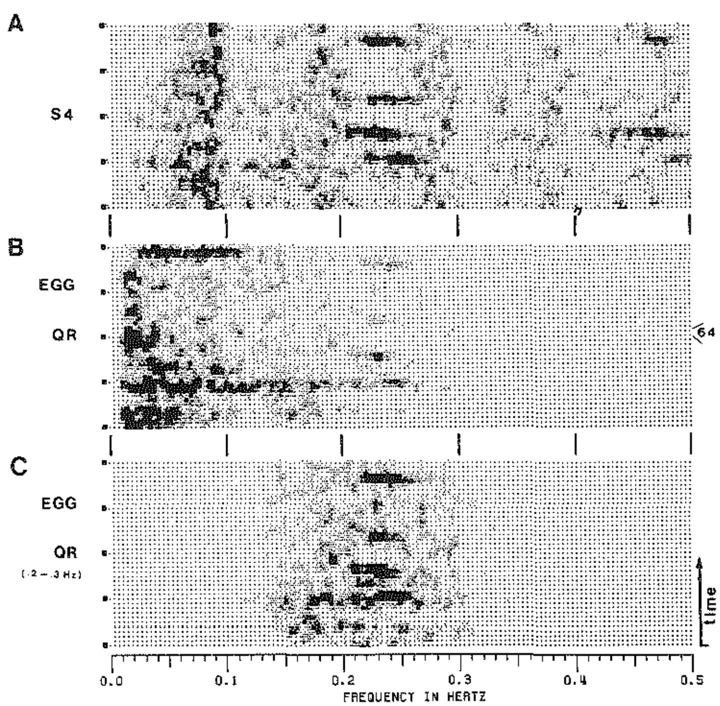

Fig.30. Grey-scale plots of running spectra from 46.9 minutes of simultaneously recorded serosal and cutaneous electrical signals, part of which are shown in Fig.29,A.

A: Serosal electrode S4 (after low-pass filtering with cut-off frequency at 0.5 Hz), showing variable fundamental gastric frequencies with higher harmonics and four episodes of tachy-arrhythmia at about 0.25 Hz (15 cpm).

B: Cutaneous electrode QR, and

C: Cutaneous electrodes QR after band-pass filtering between 0.20 and 0.30 Hz (24 dB/octave) and adjustment of the grey-scale level.

The duodenal frequency cannot be established with certainty. T = 256 s, ΔT = 64 s.

The artefact in QR nearly coinciding with the onset of the first arrhythmia and the artefact about 80 seconds prior to this (Fig.29,A)disturb the spectrum in the higher-frequency range, thus hampering recognition of the first arrhythmia as such in the spectrum. The running spectrum of a band-pass filtered version of the EGG, adjusted for maximum blackness level (Fig.30,C), clearly reveals the four arrhythmias observed in the serosal spectrum; however, if we consider Fig.30,C alone, we cannot exclude the possibility that the first 'arrhythmia' is due to a pulse-shaped artefact. The chosen values of 256 s for T and 64 s for ΔT were apparently not sufficient to give adequate resolution in this case.
As mentioned above, a very short-during tachy-arrhythmia occurred during the postprandial state on two occasions. This phenomenon is illustrated in figure 29,B. The rapid succession of premature CP's was not observed at the proximal electrodes, indicating that they were not propagated orally to an appreciable extent. The RS displays of the corresponding EGG are shown in figure 31.

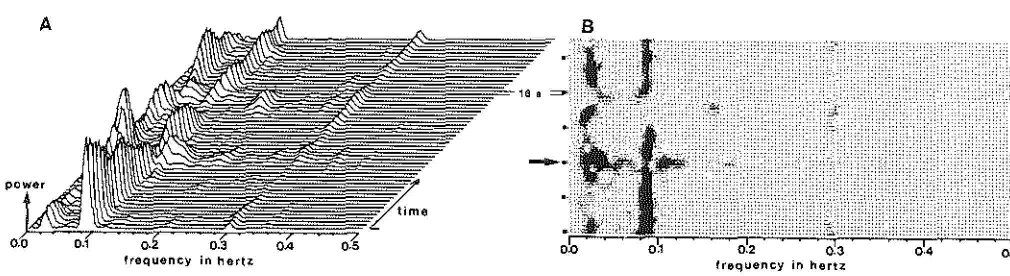

Fig.31. Pseudo-three-dimensional display (A) and grey-scale plot (B) of running spectra from the cutaneous signal of Fig.29,B (postprandial state). The gastric frequency at 0.085 Hz (5.1 cpm), tachy-arrhythmia at about 0.17 Hz (10.2 cpm) and duodenal frequency at about 0.30 Hz (18.0 cpm) may be clearly seen. The arrow indicates the effect of a pulse-shaped artefact present in QR. The frequency at 0.015 Hz (0.9 cpm) is of unknown origin. Note the variation of power level with contraction amplitude (Fig.29,B) and the absence of the normal gastric frequency during the tachy-arrhythmia. T = 128 s, ΔT = 16 s.

The values of T and ΔT were 128 and 16 seconds respectively in this case. It may be observed from figure 31,A that the power magnitude at the normal gastric frequency of 0.085 Hz runs practically parallel to the amplitude

of the contractions as measured with force transducer B (Fig.29,B), a finding in agreement with previous observations (Smout et al., 1980a; Van der Schee et al., 1983). No contractions occur during the short episode of tachy-arrhythmia (frequency about 0.17 Hz) and the normal gastric frequency is absent in the spectrum.
The artefact present in the cutaneous signal may be easily recognized.
Finally, we see a high-power, low-frequency component at about 0.015 Hz in figure 31. Such a frequency was often found in the postprandial state; its origin is not yet known.
A type of tachy-arrhythmia that to our knowledge has not previously been reported, may be seen in figure 29,C. This type was observed only in dog 1, and accounted for about 80% of all arrhythmias in this animal. It looks as if there are two frequencies simultaneously present and interfering with each other. The CP's do not show consistent oral propagation as may be seen from the facts that the repetition frequency at corporal level is fairly constant although established by CP's originating distal to electrode S1, and that no 1 : 2 block occurs. The (bipolar) cutaneous signal is of extremely good quality and relatively high amplitude. The RS display of this EGG, shown in figure 32, reveals the existence of two frequencies. The frequency of 0.15 Hz, traces of which may be seen in figure 32, corresponds to the frequency at corporal level. This component can be brought out more clearly by another choice of the maximum grey level.
A special type of arrhythmia observed in all dogs is a sequence of doublets, each one consisting of a normal CP, a premature ectopic CP and a compensatory pause, in that order (see Fig.33). The premature CP's originate distal to electrode S4 and are conducted orally to the level of electrode S3. They are not observed at the level of electrode S2 and S1. It follows that the compensatory pause must be due to blocked conduction of the next non-ectopic CP, caused by the refractory period following the ectopic premature CP. The frequency content of the time signal appeared to be rather unpredictable during the occurrence of these doublets, as may be seen from the RS display of this EGG shown in figure 34. While the first and second harmonics of the normal gastric frequency (at 0.10 and 0.20 Hz respectively) and the duodenal frequency can be recognized, artefacts disturb the spectra a good deal in the low-frequency region. The series of doublets probably leads to a dominant frequency at about 0.15 Hz, dropping to about 0.13 Hz in course of time. The duodenal frequency can hardly be

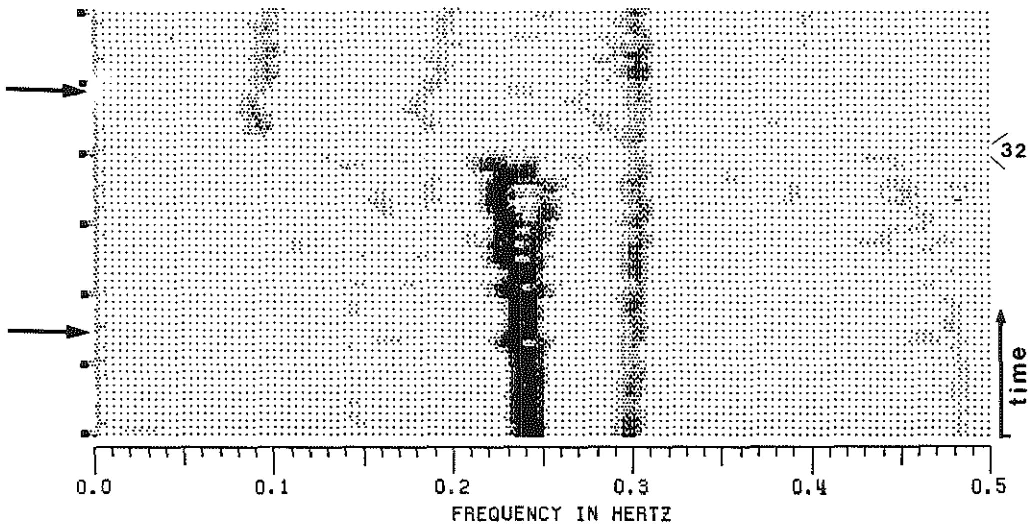

Fig.32. Grey-scale plot of running spectra from 32.1 minutes of the cutaneous signal QR - QL containing the arrhythmia shown in figure 29,C. The distance between the arrows indicates the period of the latter signal. Normal gastric frequency at about 0.10 Hz (6.0 cpm), tachy-arrhythmia at about 0.24 Hz (14.4 cpm) and duodenal frequency at 0.30 Hz (18 cpm). T = 128 s, ΔT = 32 s.

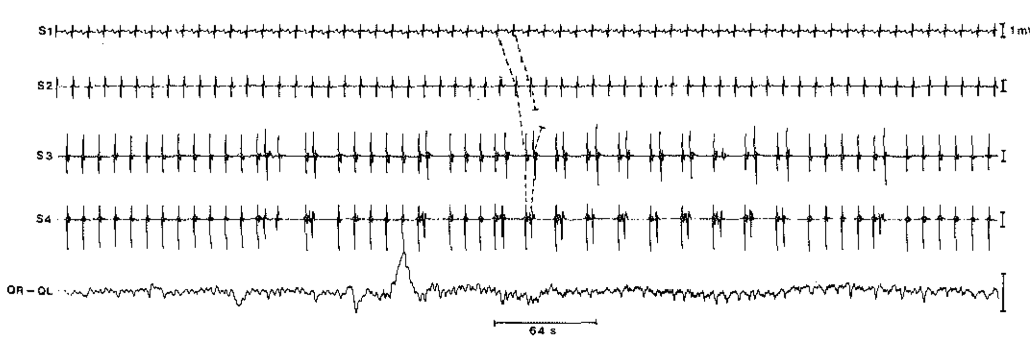

Fig.33. Formation of myoelectric doublets. The premature CP's (with ectopic focus distal to electrode S4) are propagated orally to electrode S3. Note the blocked conduction of the CP and ectopic premature CP between electrode S3 and S2 and the resulting compensatory pause. Motor quiescence. Dog 3.

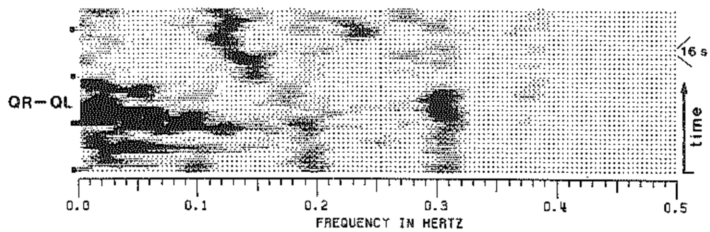

Fig.34. Grey-scale plot of running spectra from 9.8 minutes of the cutaneous signal QR - QL shown in Fig.33. Normal gastric frequency and second harmonic at 0.10 Hz (6.0 cpm) and 0.20 Hz (12.0 cpm) respectively and duodenal frequency at 0.31 Hz (18.6 cpm). The corporal frequency cannot be detected from these spectra. In this example the frequency varying from 0.15 Hz (9.0 cpm) to 0.13 Hz (7.8 cpm) is probably constituted by the occurrence of doublets. $T = 64$ s, $\Delta T = 16$ s.

seen during this period. The existence of some kind of abnormal gastric activity can be deduced from this spectrum but the nature of the abnormality cannot be specified with certainty.

Summarizing, we may state that RSA of EGG signals in dogs allows the following conclusions to be drawn:

1) both regular and irregular tachy-arrhythmias lasting about 30 seconds or more can be detected;
2) detailed characteristics detected by serosal electrodes cannot be extracted from the spectra;
3) the spectra do not allow a distinction to be drawn between aboral and oral propagation of control potentials;
4) single premature control potentials cannot be detected;
5) the spectra tend to be disturbed in an irregular fashion by doublet sequences;
6) little or no trace of the corporal frequency can be seen in the case where this frequency differed from the antral one, indicating that the myoelectric activity picked up by the cutaneous electrodes is mainly of antral origin.

5.6.5 Results from humans

From the patient a total of 32 hours of recording was collected. This period was divided into sessions of about 2 hours each. The bipolar serosal signals were of extremely good quality throughout the whole recording time of 32 hours in the human volunteer. Since the monopolar signals, both serosal and cutaneous, were derived with respect to the reference electrode at the right ankle, the leads were very sensitive to motion artefacts occurring e.g. during necessary medical care or when the patient became restless. However, these artefacts generally had much less effect on the bipolar signals. Both, serosal and cutaneous signals depicted in figure 35 (second postoperative day) are representative for about the first 16 hours of recording. No electrical correlate of IMC's was observed during the recording sessions. On a few occasions, a single premature CP occurred at the level of the most distal serosal electrode. Tachy-arrhythmias were

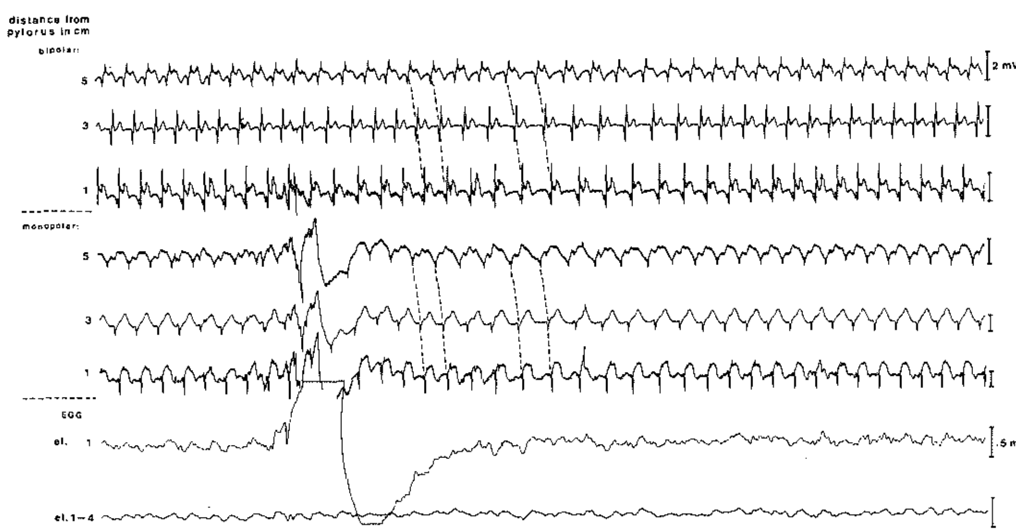

Fig.35. Myoelectric recordings from the human antrum: the first three traces are bipolar; the next three are monopolar, with low-pass filtering (cut-off frequency 4 Hz) to remove excessive ECG. The seventh trace is the monopolar cutaneous signal from electrode 1 (see Fig.25), and the bottom one the bipolar cutaneous signal 1-4. Note the relative insensitivity to artefacts in the bipolar recording. Second postoperative day.

not observed, but slight spontaneous variations in interval time between successive CP's were seen, apparently originating in the proximal antrum (or pacemaker area) as also visible in figure 35. Visual inspection of the EGG's from the last 16 hours of recording led to the rejection of 6 hours of recording for RSA because of the poor quality of the EGG. The gastric frequency could be established for about 80% of the remaining 10 hours' recordings. Additional band-pass filtering was sometimes required to cope with the poor signal-to-noise ratio, which appeared not to be due to the surface electrodes. The cause for this decline in quality during the last 16 hours of recording, mainly performed on the third and fourth postoperative day, is not known. Figure 36 shows the grey-scale representation of the results of RSA of 66.1 minutes of simultaneously recorded serosal and cutaneous signals. A very good agreement is observed between the fundamental frequencies of the gastric serosal and cutaneous signals. The figure proves without doubt that firstly, the cutaneous signal in man is of gastric origin, and secondly, short-during myoelectric gastric frequency alterations in man can be detected by RSA of the EGG signal.

Further clinical observations

As illustrated in the figures 37 and 38, myoelectric abnormalities in patients can be detected with the aid of EGG. Figure 37 shows the spectra of a healthy volunteer (A) and a patient suffering from (unexplained) epigastric pain accompanied by nausea and vomiting after food-intake (B), before and after the ingestion of a test meal (250 ml of yoghurt and 20 g of sugar). Figure 37,A exhibits all the characteristics of normal healthy subjects, as described previously (Van der Schee et al., 1982).

Although the EGG amplitude in the direct recordings and the power levels in the derived spectra cannot be translated directly into gastric contractile force (Smout et al., 1980a), it is obvious that the patient's response to food depicted by figure 37,B is abnormal. The pattern shown in this figure was very reproducible: three successive measurements on this patient, at intervals of 14 days, showed the same behaviour.

Figure 38 shows grey-scale representations of EGG spectra of patients, suffering from gastroparesis lasting for more than 8 days after abdominal surgery (A), a gastric ulcer accompanied by nausea and vomiting (B) and unexplained nausea and vomiting (C). In figure 37,A a normal gastric fre-

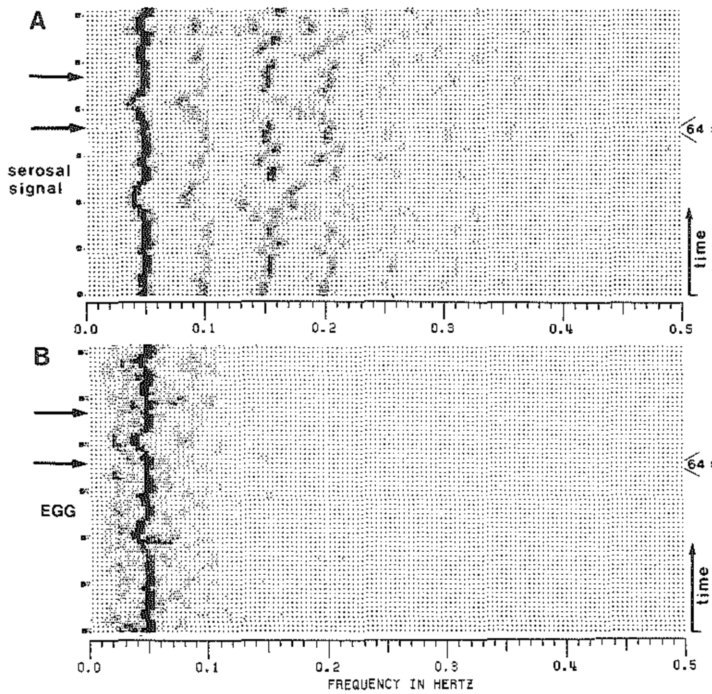

Fig.36. Grey-scale plots of running spectra from 66.1 minutes of simultaneously recorded serosal and cutaneous signals in man (Fig.35).
A: Bipolar serosal signal from the electrode at 2 cm from the pylorus (low-pass filtered at 0.5 Hz) clearly shows the gastric fundamental frequency (≈ 0.05 Hz; 3.0 cpm) and three higher harmonics.
B: Bipolar cutaneous signal 1-4, showing the fundamental gastric frequency. The distance between the arrows indicates the period of original signals of Fig.35. $T = 256$ s, $\Delta T = 64$ s.

quency seems not to be present. Instead, a consistent frequency of 0.17 Hz shows up which is not of respiratory origin, as was demonstrated by analysis of the simultaneously recorded repiration signal. Neither is it likely that it is of duodenal origin since the human EGG seldom contains the duodenal frequency (Van der Schee et al., 1982). The most obvious conclusion is therefore that we are dealing here with a regular tachygastria.
In figure 38,B a gastric frequency at 0.05 Hz may be present during the first 10 minutes, then the frequency jumps to a significantly higher value (0.08 Hz). It can be considered to be abnormal. The transient component at 0.19 Hz is of respiratory origin (as was also demonstrated by analysis

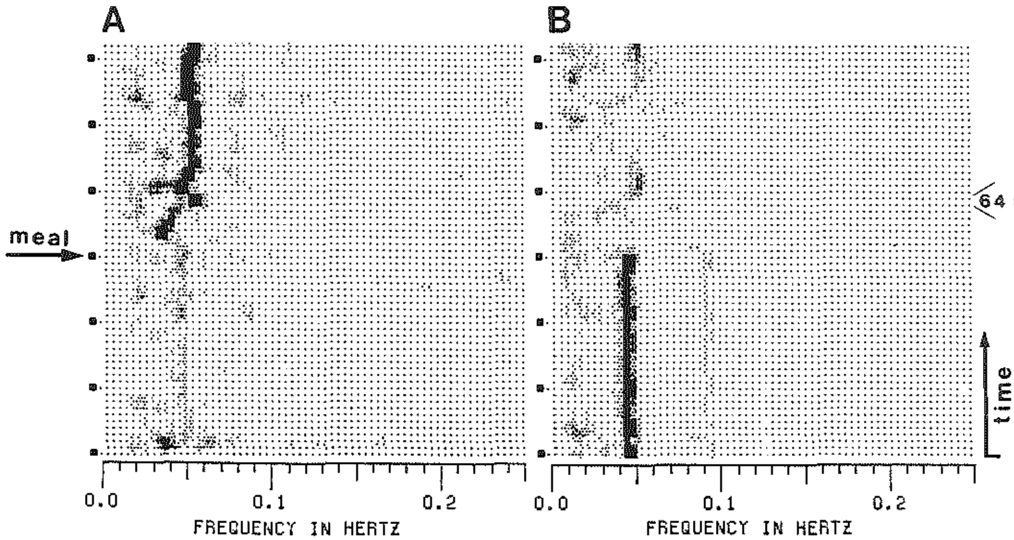

Fig.37. Grey-scale plots of human EGG spectra before and after a test meal.
A: Healthy volunteer, showing the normal frequency dip and power level increase following ingestion of the meal.
B: Patient with unexplained epigastric pain, nausea and vomiting. The fasting EGG amplitude is higher than the postprandial amplitude.
$T = 256$ s, $\Delta T = 64$ s.

of the respiration signal). The spectrum of figure 38,C shows severe frequency abnormalities resembling those of figure 30, probably indicating the presence of short-during tachy-arrhythmias in this patient. It should be emphasized here that the above given examples of EGG abnormalities are not typical for the gastric disorders in question. Recent studies on patients complaining of nausea and vomiting, due to various causes (Geldof et al., 1983a, 1983b) yielded postprandial EGG spectra, mainly characterized by a great variability in gastric frequency and a drop in power level as compared to the fasting state.

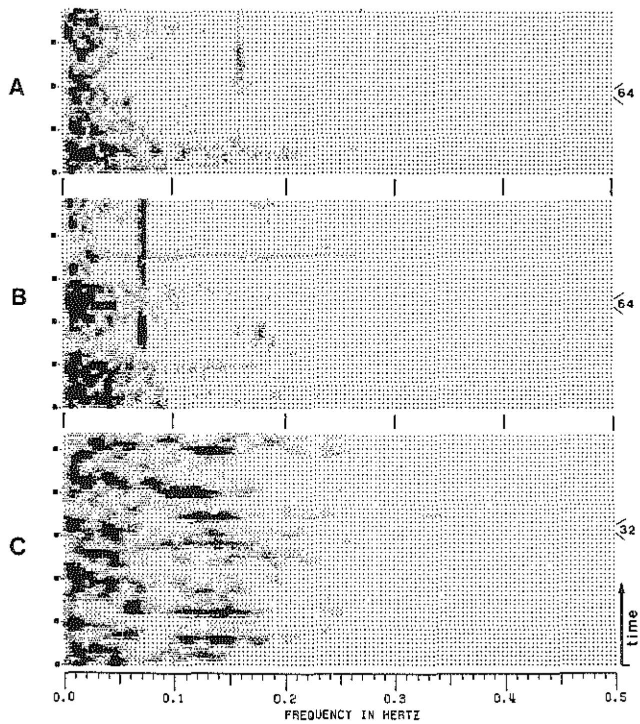

Fig.38. Grey-scale plots of EGG spectra from patients manifesting abnormal electrogastrographic behaviour in the fasted state.
A: Gastroparesis after abdominal surgery.
B: Gastric ulcer accompanied by nausea and vomiting, and
C: Unexplained nausea and vomiting. Fasting state.
(A and B: $T = 256$ s, $\Delta T = 64$ s. C: $T = 128$ s, $\Delta T = 32$ s).

5.6.6 Discussion

This study demonstrates that running spectrum analysis of electrogastrographic signals can be an informative tool for the detection of gastric arrhythmias and rhythm variations in both dog and man. However, referring to the conclusions made from observations in the dog, the method has certain limitations, in particular as regards the amount of final detail that can be extracted from the spectral data. Improvement of the time resolution and/or expanding the time scale may minimize this drawback, although it must be realized that RSA only deals with the frequency content of the signals. If no consistent frequency is present, as is the case for example during the occurrence of doublets, the type of arrhythmia involved is obviously difficult to establish. Moreover, RSA, like any kind of spectral analysis, excludes essentially the possibility to detect retrograde conduction of control potentials. The evidence provided by the present investigation that the abdominal cutaneous electrodes 'see' mainly the antral region corroborates our previous findings, obtained by analyzing the waveform of EGG signals (Volkers et al., 1983).

Several authors reported in the past on the clinical usefulness of electrogastrography: in the diagnosis of gastric cancer, gastric and duodenal ulceration (Sobakin et al., 1962), pyloric stenosis and psychogenic vomiting in infants (Combe et al., 1972), post-vagotomy states (Martin et al., 1972), psychosomatic disorders of the gastrointestinal tract (martin et al., 1970) and acute pancreatitis (Nechiporuk et al., 1973). Unfortunately, all these publications claiming diagnostic relevance for EGG data were not very convincing, mainly -at that time- owing to a lack of:

1) thorough knowledge of gastric myoelectric activity and the mechanism underlying the EGG, required for interpretation of the cutaneous signals;
2) suitable techniques for analysis of the recorded signals, and
3) knowledge of how myoelectric activity is related to gastric disorders.

Over the past few years advances have been made with respect to the first two points, but the third remained largely unexplored.

Our results suggest that electrogastrography may be considered a promising tool for the study of abnormal electrical behaviour and therefore may contribute to our insight in the inter-relationship between gastric disorders and abnormal gastromyoelectric activity.

In conclusion, we may state that while our study confirms the potentialities of EGG as a diagnostic tool, more research is needed before this method could be used in routine clinical practice.

In particular, referring to the findings of Geldof et al. (1983a, 1983b), it would be desirable to carry out a systematic search for specific EGG spectral responses in large groups of patients, suffering from gastric dyspepsia but well-defined in their symptoms.

5.7 *The interdigestive migrating complex in man*

5.7.1 *Introduction*

As demonstrated in section 5.4, the activity front (phase III) of the interdigestive migrating complex (IMC) in *dogs* can easily be recognized from the EGG by the appearance of high-power low-frequency components in the running spectrum.

Manometrically performed studies in man revealed IMC patterns that were less regular with regard to periodicity and to the point of origin in comparison to those in dogs (Vantrappen et al., 1977b). It has been reported that even not all IMC complexes start in the stomach (e.g. Finch et al., 1980). Instead, the duodenum was found to be the point of origin, where the activity front is characterized by the occurrence of contractions at its maximum rate, i.e. each duodenal control potential is followed by a contraction, the total phase III lasting for about 3 to 6 minutes.

Apart from the motor component, the IMC also appears to have secretory components that fluctuate in accordance with the phases of cyclic motor activity (e.g. Peeters et al., 1980). Therefore, non-invasive detection of phase III activity of the IMC may be considered a welcome aid in the study of fasting gastric activity. EGG provides such a possibility. An electrogastrographic study focussed on this topic in humans, however, has never been described. Our aim in this part of our study was to verify whether the occurrence of the (gastric) activity front of the IMC in man could be detected by means of electrogastrography.

5.7.2 *Methods*

Pressure recordings were made from 7 healthy human volunteers, ranging in age from 19 to 25 years, using three semiconductor strain-gauge pressure transducers mounted 5 cm apart in a commercially available pressure probe (model 31, Kulite semiconductor products, Inc., New Jersey). The probe was introduced into the stomach through the mouth and positioned under fluoroscopic control in such a way that the most distal transducer was located in the terminal antrum. After introduction and positioning, the proximal end of the probe was fixed at the chin with the aid of a sticking plaster.

Since the distal end was not fixed, the possibility remained that one or two transducers slipped through the pylorus into the duodenum. This ap-

peared to occur in four of our subjects. So, in all subjects, at least one pressure transducer was present in the antrum*).
The electrodes and electrode positions used for simultaneous recording of the EGG's, and the methods of recording and signal analysis were identical to those described in section 5.3..
The subjects were asked to lie down in supine position as quietly as possible. Recordings were made during at least 3 hours. When the subjects became restless or complained about cramp, which usually resulted into excessive artefacts in the cutaneous signals, the measurements were terminated.

5.7.3 Results

A total of 10 gastric IMC's were recorded. In two subjects no activity front was observed in the stomach. Instead, isolated contractions and/or long lasting phase II activities were found. In general, the occurrence of gastric IMC appeared to be highly variable with respect to the duration and the nature of the different phases of the IMC as well as with respect to the electrogastrographical properties. Figures 39,A and B show two gastric IMC's, recorded from the same subject.
P1 represents the pressure signal measured from the most proximal transducer and P3 the signal measured from the most distal one. As can be seen in Fig.39 the activity front in the terminal antrum manifests itself by the occurrence of contractions at its maximum rate (repetition frequency about 0.05 Hz), lasting for about 4 to 5 minutes. The second complex (Fig. 39,B) was observed 108 minutes after termination of the first one (Fig.39,A). The simultaneously bipolarly recorded EGG's (electrode 1-4; see Fig.1,C, page 60) are shown too. The pulses at the bottom of the figures mark the consecutive moments at which an EGG spectrum was computed (duration 256 s, amount of overlap 64 s). The numbers correspond to the numbers in the grey-scale representation, as shown in Fig.40. The figures 40,A and B correspond to the figures 40,A and B, respectively. When comparing the time signals with the spectra it should be realized that, for example, spectrum

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*) The research protocol was approved by the Medical Ethics Committee of the Erasmus University Rotterdam and informed consent was obtained from the volunteers.

number 41 in the grey-scale plot predominantly contains the power content of the EGG 'located' between pulse numbers 38 and 40, as outlined in section 5.2 (see Fig.21, page 57).

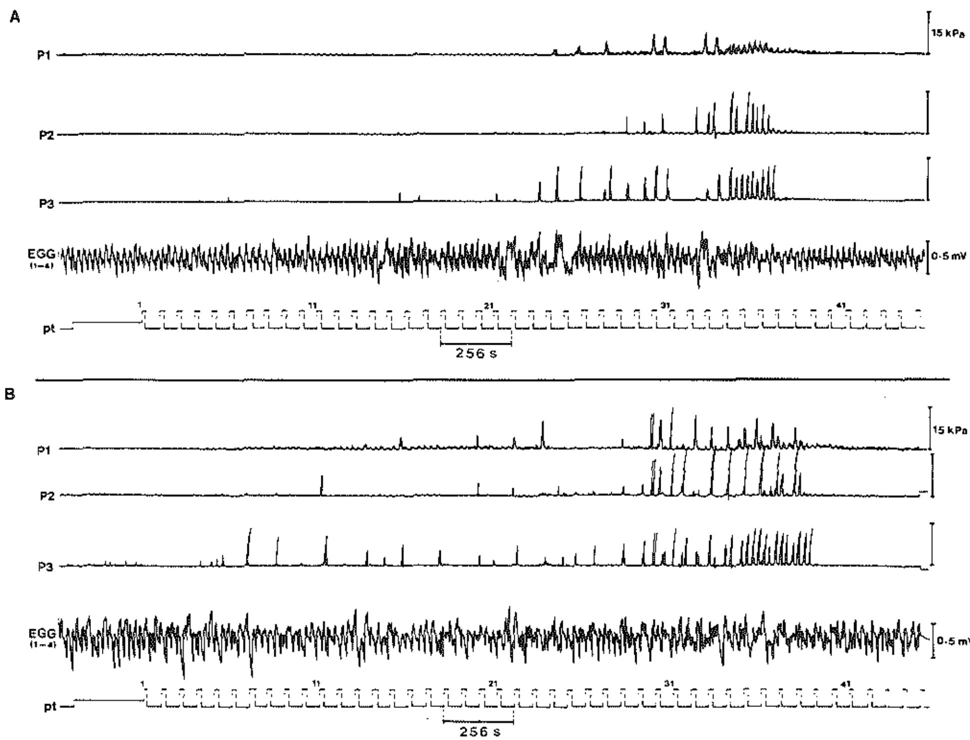

Fig.39. Pressure recordings from the stomach and simultaneously recorded bipolar EGG (electrodes 1-4, see Fig.1,C, page 60) in the fasted state. Pressure transducer P3 is located in the terminal antrum, P2 and P1 are located 5 and 10 cm orally from P3, respectively. Pt shows the echoed pulse train, indicating the time relations between the EGG and the computed spectra (see text). One activity front of the IMC (A) occurred about 30 minutes after introduction of the pressure probe. The second IMC (Fig.B) was recorded 108 minutes later (subject W.D.).

Although some low-frequency components can be observed in Fig.40,A coinciding with phase III activity, they certainly cannot be proven to be or be not indicative for the occurrence of an activity front. Such frequencies were often observed in the spectra of EGG's in cases where there was no question of contractile activity. Moreover, the frequency and power pattern during phase II activity exhibits the same behaviour in this case.

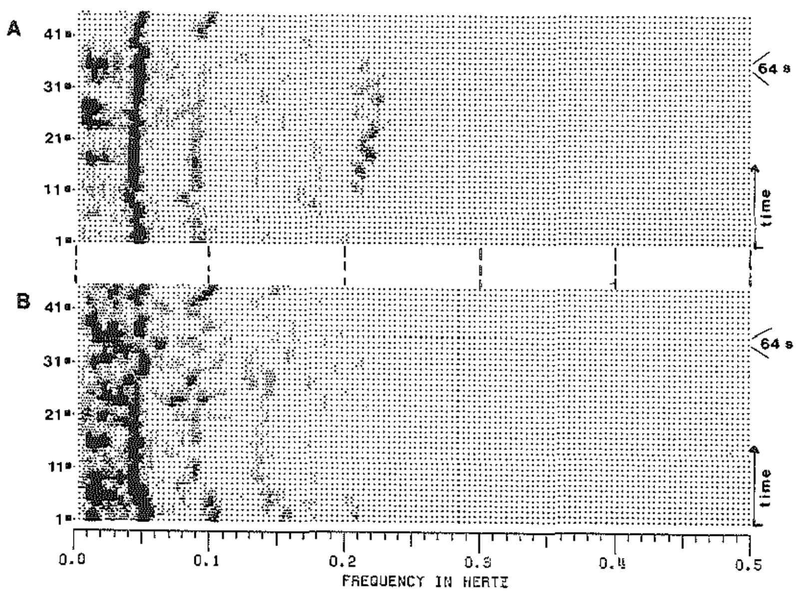

Fig.40. Grey-scale plots after RSA of the EGG's shown in figure 39 (T = 265 s, ΔT = 64 s). Fig.A corresponds with Fig.39,A and Fig.B with Fig.39,B. Higher harmonics of the fundamental gastric frequency can be observed. The frequency of about 0.22 Hz is of respiratory origin.

A consistent gastric frequency appears to remain present throughout the entire recording period, be it that small variations can be noticed. In order to look into more detail at the *power magnitude* of the gastric component (by means of inspection of the individual spectra and by computation of the average power of the fundamental gastric component of consecutive spectra) we found the average power during the period of motor quiescence to be equal to that during phase II and phase III activity. RSA applied to the EGG recorded during the second IMC (Fig.40,B) exhibits different characteristics. A consistent gastric frequency seems not to be

present during the passage of phase III activity. The ratio between the average power of the gastric component during phase II and that of phase III was found to be in the order of 4 : 1.
The variable nature of both, the pressure recordings and the RS of the corresponding EGG is further illustrated in the Figs 41 and 42 respectively. The pressure recording from the terminal antrum is represented by Pa, from the duodenal bulb by Pb and from the duodenum, about 7 cm from the pylorus, by Pd, respectively. No gastric phase III activity is seen. The Pb and Pd tracings agree to the contractile patterns that are commonly described in literature. The grey-scale plot of RSA of the corresponding EGG is depicted in Fig.42. Apparently a gastric frequency increase occurs that coincides with duodenal phase III activity. During motor quiescence a decrease in power magnitude is observed in this subject.

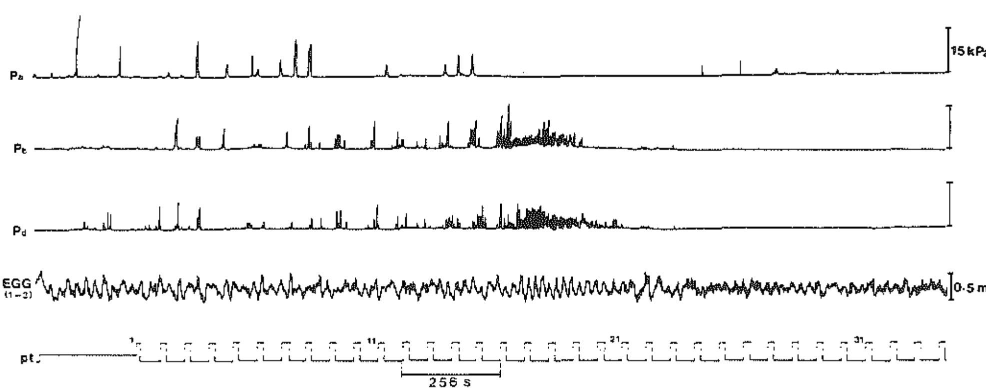

Fig.41. Same as in Fig.39 but now the pressure transducers located in the terminal antrum (Pa), in the duodenal bulb (Pb) and about 7 cm distal to the pylorus (Pd). (Subject D.C.)

Low-frequency components coinciding with phase II activity seem to be less pronounced than those observed in the previous example.
Figure 43 presents pressure recordings and the corresponding RS-display of an EGG recording over a period of about 5 hours. The antral pressure recording (Pa) suggests the occurrence of 3 IMC's, however, since most authors, dealing with the study of the IMC in man, consider duodenal phase III activity as the main criterium for the occurrence of an IMC, 4 IMC's are observed (Pb) in this subject. This result confirms the variability

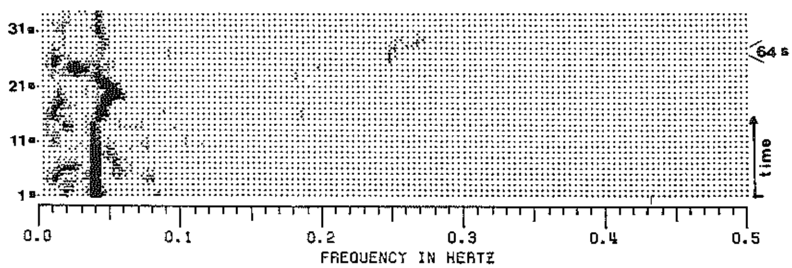

Fig.42. Grey-scale plot of the EGG shown in Fig.41 (T = 264 s, ΔT = 64 s).

of the human IMC both, with respect to the point of origin and duration of the different phases. The RS-display shows slight variations in gastric frequency as well as in power magnitude. The appearance of low-frequency

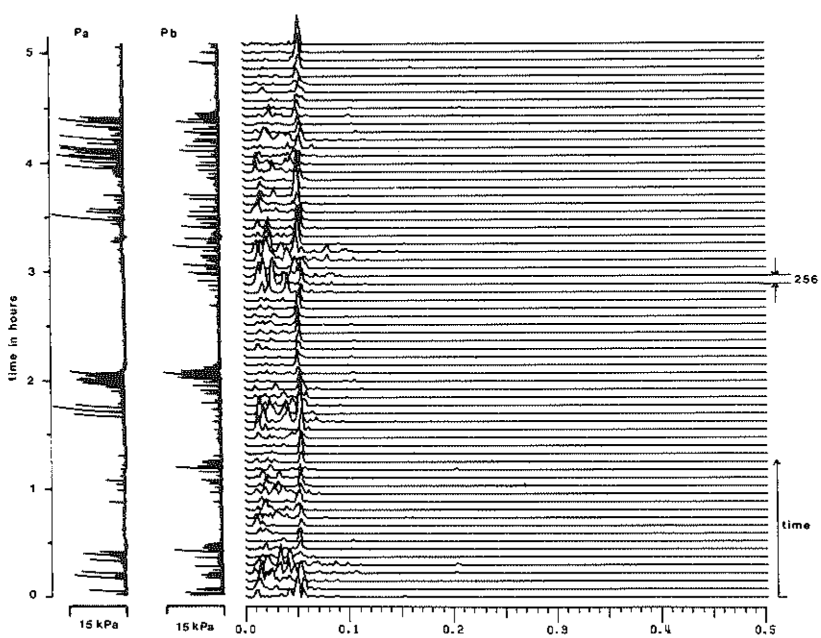

Fig.43. Pressure recordings from the terminal antrum (Pa) and the duodenal bulb (Pb) during about 5 hours, showing 4 IMC's. The right side shows the running spectrum of the simultaneously recorded EGG (electrodes 1-4; T = 512 s, ΔT = 256 s; subject A.S.).

components seems to coincide with duodenal phase II activity, suggesting a more pronounced relation with duodenal contractile activity than with gastric motor activity. It is still unclear, however, to what mechanism such a possible relation has to be attributed to.
Finally, it should be reported that a frequency of about 0.16 Hz (9.6 cpm) was observed in two subjects. This value corresponds to the repetition frequency of duodenal ECA that is normally found in man. In one subject this frequency was present during the entire recording period over 3 hours. Unfortunately, the 3 pressure transducers were all located in the stomach in this case (showing only phase II activity). As a consequence the duodenal origin could not be established with certainty. In the other subject this frequency appeared to be equal to the repetition rate of the duodenal contractions during phase III of the IMC. However, the moment of appearance of this frequency in the spectrum did not coincide with the moment that duodenal phase III activity was observed. Nevertheless it seems reasonable to conclude that the observed frequency was of a duodenal origin.

5.7.4 Discussion

Our findings with respect to the characteristics of the human IMC as measured with pressure recording techniques are in agreement with those reported by other authors working in this particular field (Vantrappen et al., 1977b; Lux et al., 1980; Finch et al., 1980; Daniel et al., 1981). The corresponding electrogastrographic characteristics, however, have not been described before. In the light of our results we are forced to the conclusion that electrogastrography does not enable us to detect with certainty that *gastric* motor activity exists during the IMC in man. The low-frequencies in the spectrum of Fig.43 might be considered to be indicative for duodenal phase II activity, but certainly not for either the gastric or the duodenal activity front (phase III). It should be emphasized in this connection that the measured EGG was of an exceptionally good quality during the entire recording session of over 5 hours. In normal human electrogastrographical practice low-frequencies are often observed, sometimes as a result of small (motion) artefacts but they are frequently the result of an unknown origin. Our conclusion is, therefore, that the appearance of such frequencies are in general not conclusive with respect to motor activity.

At this stage it is worthwhile to compare the electrogastrographic characteristics of the IMC occurring in man with those described in the dog. In section 5.4 it was concluded that 'the presence of lower frequencies ranging from the normal gastric one to about 0.01 Hz in the running spectrum representation of electrogastrograms recorded in fasting dogs, is indicative of strong antral contractions and that the mechanism through which this is brought about involves prolongation of ECA intervals associated with these contractions'. In fasting men such pronounced high-power low-frequencies appear, so far, not to occur. A highly interesting major conclusion can therefore be drawn from our results in man: Electrogastrography reveals that normal gastric pacemaker rhythm during the activity front of the IMC in man is far more stable than its canine counterpart, i.e. *considerable variations in the ECA-interval duration as described in conscious dogs (Smout et al., 1979) do not occur in man.* Finally, we have to realize that all observed EGG-characteristics during the fasted state cannot be understood on the basis of manometrically performed studies. From a theoretical point of view, the interpretation of pressure recordings is hampered by the fact that pressure variations can only be measured when intercompartmentalization is present. It seems that this condition is frequently fulfilled in the duodenum and in the terminal antrum. Recordings obtained from those areas may be interpreted as pressure waves, passing by. However, pressure recordings obtained from more proximal gastric levels have to be considered highly unreliable in this respect. In order to investigate thoroughly the characteristics which we dealt with in this section, studies are required that take into account the associated gastric myoelectrical activity, similar to the studies performed in dogs. However, such studies are seriously hampered by practical limitations.

6. CONCLUDING REMARKS

With regard to the two main aspects which are dealt with in this thesis, namely

a. The development of methods that enable us to study the relationship between the waveform of the EGG and the myoelectrical characteristics as measured with serosally implanted electrodes,

and

b. The development of an accessible technique that provides clinically relevant, interpretable information from the EGG,

the following comments can be made.

The electrogastrogram can be considered as the result of a summation of mutually time-shifted waveforms generated by the ECA and, if present, the ERA. As a consequence, the interpretation of the *waveform* of the EGG is seriously impeded by the fact that at least two or more ECA-fronts are simultaneously present on the stomach wall: no 'single EGG-waveform' can be measured. This in contrast to the waveform of, for example, the surface electrocardiogram. It is therefore difficult to specify the characteristics which can be ascribed to the EGG-waveform (apart from the amplitude increase when contractions occur) that are conclusive for the actual myoelectrical processes in the stomach wall. Moreover, apart from artefacts, it is still not clear which factors are responsible for the high variability in the properties of the derived EGG's, both from dogs and humans.
The application of special silter techniques indeed improved our knowledge of the relationship between cutaneous signals and serosally measured signals, given the limitations discussed in Chapter 4. The described qualitative model, initially based upon recordings obtained during the postprandial state, appeared to be supported by the results of the study where an averaging technique has been used in order to perform waveform analysis in more detail. Such studies, that make use of statistical methods, may be considered to be most promising for future developments. They will undoubtedly contribute, side by side with *in vitro* and simulation studies (either computationally or with the aid of a

hardware model), to a better understanding of the genesis and interpretation of the EGG.

Our main aims in applying running spectrum analysis, were firstly, to search for a fast and concise way of representing electrogastrographically obtained data, and secondly, to investigate to what extent the serosally measured electrical characteristics could be interpreted from the spectra. We conclude that both, the pseudo-3D and the grey-scale representation fulfill the first objective. The grey-scale plots enable us only to estimate globally the relative power distribution over the various frequency components and a more easy recognition of frequency patterns. The pseudo-3D representation may be considered to be complementary in this respect. Computational inspection of the individual spectra provides *quantitative* information.
Running spectrum analysis may certainly be regarded as an accessible technique with which relevant information can be extracted from the EGG. With respect to our second objective, it has been demonstrated that the possibility exists to detect abnormal gastric myoelectrical behaviour and to interpret it from the spectra predominantly in terms of tachygastrias and tachy-arrhythmias. Furthermore, abnormalities in postprandial power behaviour of the gastric component seems to be of clinical relevance. We conclude therefore, that running spectrum analysis of electrogastrographic signals may be considered a promising technique for future diagnostic application. We finally conclude that electrogastrography can be regarded to be a powerful tool in revealing the relationship between gastric myoelectrical activity and gastric dysfunction.

SUMMARY

This thesis deals with signal analytical aspects and interpretation of electrical signals originating from the smooth muscle cells of the stomach wall, and that are recorded by using electrodes attached to the abdominal skin.

In Chapter 1, being an introductory chapter, a justification is given with respect to the present study; its aims are formulated.
In Chapter 2 the electrical and mechanical properties of the stomach, both, as known from literature as well as according to own observations, is summarized. The stomach may be considered to have a pacemaker area, located somewhere in the orad corpus from which cyclic recurring change of electrical potentials are generated. This so-called electrical control activity (ECA) sweeps distally through the longitudinal muscle fibers to the pylorus. When contractions occur the ECA is followed by the electrical response activity (ERA). The ECA determines the positions, the direction and the propagation velocity of contractions. The ERA is related to the contractile strength. In the dog the repetition frequency of the ECA is about 0.085 Hz and in man about 0.050 Hz.
In Chapter 3, the literature dealing with surface recording of gastric electrical activity is surveyed. It appears that most authors assumed that the electrogastrogram (EGG) reflects the motor activity of the stomach and claimed, sometimes, extreme diagnostic significance for the EGG. Authors, aware of the possible gastric myoelectrical origin of the EGG were more reserved in their claims.
In the same chapter the recording techniques used in our studies are described.
Chapter 4 deals with waveform analysis of the EGG recorded from the dog. Since the recorded cutaneous signals, especially those derived *monopolarly* (with respect to a reference electrode placed on the right hind leg), are of poor quality, a special digital filter technique is applied which enables the removal of various kinds of disturbing factors, without distortion of the waveform, phase and amplitude of the gastric component. The waveform thus obtained is comparable with serosally derived waveforms. It

appears that the filter performance is most efficient when signals are filtered that are recorded during the postprandial state. The filter fails to reveal a consistent relation between serosally derived signals and the waveform of the EGG recorded during the interdigestive state. On the basis of the results obtained during the postprandial state and on the results of a more detailed study dealing with waveform analysis which is presented in an appendix, a qualitative model is discussed with which some characteristics of the EGG waveform with respect to serosally recorded signals can be described.

Chapter 5 deals with spectral analysis of the EGG's recorded from both, the dog as well as from man. A fast Fourier transform (FFT) algorithm is used to compute the power spectra of the cutaneous (and serosally) derived signals. In section 5.2, first, the general computational procedure is outlined, then the theoretical background is summarized, next, running spectrum analysis (RSA) is treated in more detail. Subsequently the standard procedure for EGG signals is described. It appears that RSA provides for a method with which varying frequencies, lasting for relatively short periods, can be easily visualized, since interpolation in the time domain occurs. In section 5.3 the possibilities of RSA are described in detail. In the dog it is demonstrated that the frequency components of about 0.085 Hz and 0.030 Hz are of gastric and duodenal origin, respectively. Attention is paid to the electrogastrographic characteristics as they appear in the RS during the passage of the motor activity front of the so-called interdigestive migrating complex (IMC). Regular tachygastrias can be recognized from the spectra and it is shown that RSA is useful in the study of the effect of drugs. Subsequently the electrogastrographic characteristics as they occur in healthy subjects before and after a test meal are described.

In section 5.4 special attention is paid to the passage of the motor activity front of the IMC and the occurrence of minute rhythms. It is demonstrated that the presence of lower frequencies ranging from the normal gastric one to about 0.01 Hz in the RS is indicative of strong antral contractions and that the mechanism through which this is brought about involves prolongation of ECA intervals associated with those contractions. Next, the level-dependent characteristics of the EGG during minute rhythms are described, using artificially generated cutaneous signals (section 5.5). The occurrence of low-frequency bands during minute rhythms appears to be

indicative for the contractions that are initiated at the proximal antrum. Section 5.6 deals with gastric rhythm alterations and arrhythmias in dog and man. It is shown that in dogs regular and irregular tachy-arrhythmias that lasted for 30 seconds or more could be detected but that detailed characteristics as measured by serosal electrodes could not be revealed. By means of comparison of RSA applied to simultaneously recorded cutaneous and serosal signals obtained from a patient in which serosal electrodes were implanted during a cholecystectomy the method of EGG is validated in humans. Together with some examples of patients suffering from gastric disorders the clinical perspectives of electrogastrography are indicated. Next, the EGG characteristics of the IMC in man are described (section 5.7). It is concluded that the occurrence of a gastric motor activity front cannot be recognized from the EGG. Furthermore it is concluded that considerable variations in ECA-interval duration as described to occur in dogs during the activity front do not occur in man.
Finally, it is concluded that, besides future clinical applications, EGG has the potentialities to contribute to the understanding of the, still unknown, relationship between electrical activity and disease.

SAMENVATTING

In dit proefschrift worden de signaal-analytische aspekten en de interpretatie van elektrische signalen die hun oorsprong vinden in de gladde spierweefsel-cellen van de maagwand en welke geregistreerd worden met behulp van elektroden, aangebracht op de buikwand, behandeld. Deze techniek van registratie wordt elektrogastrografie genoemd.

In Hoofdstuk 1 wordt verantwoording afgelegd ten aanzien van de verrichte studies en worden de doelstellingen van deze studies vermeld.
In Hoofdstuk 2 worden de elektrische en mechanische eigenschappen van de maag op grond van literatuurgegevens en eigen observaties, samengevat.
De maag bezit een "pacemaker"-gebied dat zich ergens in het bovenste gedeelte van het corpus bevindt en van waaruit elektrische potentiaalveranderingen hun oorsprong vinden. Deze zogenoemde elektrische stuur-aktiviteit (ECA) plant zich in de richting van de pylorus voort door de longitudinale spierlaag. Als contracties optreden, wordt de ECA gevolgd door elektrische "response" aktiviteit (ERA). De ECA bepaalt de plaats, de voortplantingsrichting en de voortplantingssnelheid van contracties. De ERA is gerelateerd aan de sterkte van de contractie. De herhalingsfrekwentie van de ECA is in de hond ongeveer 0.085 Hz en in de mens ongeveer 0.050 Hz.
In Hoofdstuk 3 wordt een overzicht gegeven van de literatuur die handelt over huid-registratie van elektrische maagaktiviteit. Het blijkt dat door de meeste auteurs werd verondersteld dat het elektrogastrogram (EGG) de motor-aktiviteit van de maag weergeeft. Er werden in sommige gevallen verregaande, diagnostische waarden toegekend aan het EGG. Auteurs die zich bewust waren van de mogelijke myo-elektrische oorsprong van het EGG waren wat voorzichtiger in hun interpretaties.
In hetzelfde hoofdstuk worden de registratietechnieken zoals die in onze experimenten gebruikt zijn, beschreven.
In Hoofdstuk 4 wordt golfvorm-analyse van het bij de hond geregistreerde EGG behandeld. Omdat vooral de monopolair afgeleide huidsignalen (afgeleid ten opzichte van een referentie-elektrode die zich op de rechter achterpoot bevindt), een slechte signaal-ruis verhouding bezitten, wordt

een digitale filtermethode toegepast waarmee verschillende storingen van het signaal geëlimineerd kunnen worden, zonder dat de golfvorm, de fase en de amplitude van de maagcomponent aangetast worden. De zo verkregen golfvorm wordt vergeleken met de golfvormen die van het maagspierweefsel (de serosa) zelf geregistreerd worden. Het filter blijkt zeer goed te voldoen in het geval dat signalen gefilterd worden die afgeleid zijn gedurende de periode na voedsel inname (post prandiale periode). In de nuchtere periode wordt geen duidelijke relatie gevonden tussen de golfvormen van het gefilterde EGG en de serosa signalen. Op grond van de resultaten die verkregen worden in de post prandiale periode en de resultaten van een gedetailleerde studie met betrekking tot golfvorm analyse (deze studie is toegevoegd als een appendix), wordt een kwalitatief model besproken waarmee een aantal karakteristieken van de EGG golfvorm in relatie met serosa signalen beschreven kunnen worden.
Hoofdstuk 5 handelt over spectrale analyse van EGG's die afgeleid zijn van zowel de hond als de mens. Een "fast Fourier transform" (FFT) algoritme wordt gebruikt om de vermogensspectra van de huid- en serosa signalen te berekenen. In deel 5.2 wordt eerst de algemene rekenprocedure uitgelegd, dan wordt de theoretische achtergrond samengevat, waarna het concept van "running spectrum analysis" (RSA) wat diepgaander wordt behandeld. Vervolgens wordt de standaardprocedure met betrekking tot EGG-signalen beschreven. Het blijkt dat met behulp van RSA, relatief kort durende frekwentieveranderingen gemakkelijker gevisualiseerd kunnen worden, omdat geïnterpoleerd wordt in het tijdsdomein. In deel 5.3 worden de mogelijkheden van RSA gedetailleerd beschreven. Er wordt aangetoond dat de frekwentie-componenten van 0.085 Hz en 0.030 Hz afkomstig zijn van de maag, respektievelijk het duodenum. Ook wordt aandacht besteed aan de elektrogastrografische karakteristieken zoals die zich voordoen in het RS gedurende de aanwezigheid van het motor-aktiviteitsfront van het zogenoemde interdigestieve migrerende complex (IMC). Regelmatige tachygastrieën kunnen in de spectra herkend worden en er wordt aangetoond dat RSA waardevol kan zijn bij de bestudering van de effekten van drugs. Vervolgens worden de elektrogastrografische karakteristieken beschreven zoals deze zich voordoen in gezonde proefpersonen, vóór en na het nuttigen van een testmaaltijd. In deel 5.4 wordt speciale aandacht geschonken aan het motor-aktiviteitsfront van het IMC en het optreden van minuten ritmen. Er wordt aangetoond dat de aanwezigheid van laagfrekwente

banden in het RS een aanwijzing is voor het bestaan van sterke antrale contracties en dat het mechanisme waardoor dat veroorzaakt wordt, gelegen moet zijn in de verlenging van ECA-intervallen die gepaard gaat met deze contracties. Vervolgens worden in deel 5.5 de niveau-afhankelijke eigenschappen van het EGG bij het optreden van minuten ritmen beschreven, waarbij gebruik gemaakt wordt van kunstmatig gegenereerde "huid"signalen. Het optreden van laagfrekwente banden tijdens het minuten ritme blijkt een aanwijzing te zijn voor de initiëring van contracties in het proximale antrum.

Deel 5.6 handelt over veranderingen in de maagfrekwentie en aritmiën die optreden in de hond en in de mens.

Er wordt aangetoond dat in de hond regelmatige en onregelmatige tachyaritmieën, die 30 seconden of meer duren, gedetekteerd kunnen worden, maar dat details van de elektrische processen zoals die zich in de serosa zelf voordoen, niet onderkend kunnen worden. Door middel van vergelijking van het RS van huid- en serosa signalen, geregistreerd bij een patient waarbij serosa elektroden werden geïmplanteerd tijdens een galblaas operatie, wordt elektrogastrografie gevalideerd bij de mens. Te zamen met voorbeelden van patienten met diverse maagklachten worden de klinische perspektieven van elektrogastrografie aangegeven. Vervolgens worden de EGG karakteristieken van het IMC bij mensen beschreven (deel 5.7). De konklusie daarvan is, dat het optreden van een gastrisch aktiviteitsfront niet onderkend kan worden met behulp van EGG. Vervolgens wordt gekonkludeerd dat de aanzienlijke variaties in de duur van ECA-intervallen, zoals die bij de hond optreden, niet bij de mens plaatsvinden.

Tenslotte wordt gekonkludeerd dat naast toekomstige diagnostische toepassingen, EGG wezenlijk kan bijdragen tot het begrip van de, tot dusverre nog steeds onbekende, relatie tussen elektrische aktiviteit en maagklachten.

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CURRICULUM VITAE

De schrijver van dit proefschrift werd op 28 februari 1945 geboren te De Lier. Hij verkreeg in 1962 het einddiploma HBS-B te Delft en studeerde in 1970 af als natuurkundig ingenieur aan de Technische Hogeschool aldaar, bij de afdeling Signaalverwerking (hoofd: prof.ir. B.P.Th. Veltman). Tijdens zijn studie is hij een 5-tal jaren werkzaam geweest als leraar natuurkunde bij het middelbaar onderwijs. Van 1969 tot medio 1972 werkte hij bij bovengenoemde afdeling, respektievelijk als student-assistent, ingenieur-assistent en wetenschappelijk medewerker. Na een periode van een half jaar in Engeland gewerkt te hebben bij de computerafdeling van een olie-exploratie maatschappij en vervolgens gedurende negen maanden werkzaam te zijn geweest bij de Koninklijke Nederlandse Vliegtuigfabriek Fokker N.V., op het laboratorium voor Fabricage en Productontwikkeling, trad hij op 1 februari 1974 in dienst van de afdeling Medische Technologie van de Medische Faculteit der Erasmus Universiteit Rotterdam (toenmalig hoofd: prof.ir. Y.J. Kingma). Gedurende de afgelopen drie-en-een-half jaar werd hij in de gelegenheid gesteld een deel-onderzoek met betrekking tot de elektrische en mechanische aktiviteit van het maagdarm kanaal, te bewerken tot dit proefschrift.

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Electrogastrography in the dog: waveform analysis by a coherent averaging technique

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Abstract—*Electrogastrograms (e.g.g.s) recorded cutaneously in the dog were subjected to waveform analysis by coherent (or 'triggered') averaging techniques, to study the relation between e.g.g. waveforms and gastric contractile activity on the one hand, and the position of the cutaneous electrodes used to pick up the e.g.g. on the other. The trigger pulses used were picked up by electrodes applied to the serosal surface of the stomach. To make allowance for the influence of gastric contractions and the related electrical signals on the e.g.g. waveforms a computer program was developed to create a multicategory averager. Instead of adding all signal segments together, each segment was assigned to one of four categories, depending on the magnitude of the corresponding gastric contraction (as recorded by a force transducer applied to the stomach wall). The signal segments in each category were then averaged. The results of the analysis showed that both abdominal electrode position and magnitude of gastric contraction had a clear influence on e.g.g. waveforms. It was also concluded that, depending on the position of the abdominal electrodes, e.g.g. waveforms are related to either corporal or antral regions, or to both regions simultaneously.*

Keywords—*Coherent signal averaging, Dog, Electrogastrogram, Waveform*

1 Introduction

THE stomach can be considered as a generator of running signal sources (waves) originating somewhere in the orad corpus, which control the contraction of the gastric wall. Each wave consists of a fast potential change ('control potential', c.p.), followed by a slower potential change ('second potential', s.p.), which is related to the amplitude of the contractions. The c.p. travels along the stomach with increasing speed and amplitude until it vanishes at the pyloric end, about 25 s after the moment of generation (CODE *et al.*, 1968). In man the mean interval between successive c.p.s is about 20 s and in the dog 12 s (range 8–30 s) (SMOUT *et al.*, 1979). Obviously, in most cases at least two c.p.s will be travelling along the stomach wall simultaneously.

Electrogastrography may be defined as the recording of electrical phenomena originating from the stomach by means of abdominal surface electrodes. The interpretation of individual e.g.g. waveforms is very difficult. On the one hand, the signal is blurred by various kinds of noise (electrode-to-skin interface, contributions from the heart, respiration muscles, duodenum and other electrically active organs, and motion artefacts), while on the other hand the cutaneous signal generally results from two or more gastric signal sources. The lack of knowledge of the individual e.g.g. waveforms hampers, among other things, the understanding of the relationship between the electrical activity at different parts of the stomach and the recorded cutaneous signals and the construction of models for the generation of the e.g.g. that may be needed in the future to develop specialised filters and correlation methods to be used in online e.g.g. analysis. A great deal of work needs to be done to expand the possibilities of this noninvasive, atraumatic procedure as a diagnostic tool in gastric research.

The electrogastrogram (e.g.g.) has a dominant frequency equal to the mean repetition frequency of the c.p. SMOUT *et al.* (1980*a*) showed that the s.p., if present, is also reflected in the e.g.g., predominantly by an increase in the amplitude of the cutaneous signal. However, for the reasons indicated above, the waveform of the cutaneous e.g.g. is much less clear than the electrical activity recorded on the wall of the stomach; without some kind of statistical processing, hardly any meaningful patterns can be observed.

So far, workers in this field have therefore concentrated their attention mainly on the repetitive aspect of the signals, which they studied by means of frequency analysis (SMOUT *et al.*, 1980*b*) or phaselock analysis (SMALLWOOD, 1978*a*, 1978*b*). A considerable improvement in the representation of e.g.g. data in both the time and frequency domains was achieved by means of 'running spectrum analysis' (VAN DER SCHEE *et al.*, 1982). KENTIE *et al.* (1981) and VAN DER SCHEE *et al.* (1981) used an adaptive-filter technique in an

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attempt to manipulate the signals so as to bring out meaningful waveforms more clearly, thus permitting analysis of the 'form' aspect of the e.g.g. as well as its repetitive aspect.

It is known that the electrical activity of the stomach wall depends on the stage of digestion: during the activity fronts of interdigestive migrating complexes (i.m.c.) and in the postprandial state, the intervals between successive c.p.s picked up by serosal electrodes tend to be longer than in the normal fasting state, whereas c.p.s are followed by s.p.s of variable amplitudes when contractions occur (SMOUT *et al.*, 1979). We would hope to find some reflection of these patterns in the cutaneous e.g.g. signals. Furthermore, the shape of the e.g.g. depends on the position of the electrodes used to pick up the electrical signals in question.

The objectives of the present study were therefore threefold: first, to investigate whether use of a suitable averaging technique would allow meaningful waveforms to be derived from the crude e.g.g. recording, secondly, to study whether these waveforms depend on the position of the cutaneous electrodes and thirdly to determine whether the waveforms thus obtained could be correlated with the contractile activity of the stomach wall.

2 Materials and methods

Recordings were obtained from four healthy dogs (beagles), weighing 10–14 kg. Two strain-gauge force transducers and four bipolar electrodes, each comprising two Ag/AgCl conical tips with a length of 3 mm and mounted on a plate at a distance of 2 mm apart, were sutured on the serosal surface of the stomach under general anaesthesia. The wires were tunnelled to the animal's back, where they left the body via a hole in the skin. Two dogs could be kept in this condition without problems for a year and a half. Aureomycin was applied to the wound and the hole, the cable and the multipin connector were protected against violent rubbing and scratching by a canvas jacket. For cutaneous recordings two or six disposable Ag/AgCl e.c.g. electrodes were attached to the shaved abdominal skin after rubbing it with some electrolyte paste. The positions chosen for the serosal and cutaneous electrodes and the force transducers are indicated in Fig. 1. During the recording sessions, which lasted from 1 to 4 h, the conscious, unsedated dogs were standing in a canvas support mounted on a rack.

The signals from the electrodes and the force transducers were recorded on both curvilinear pen recorders (Van Gogh EP-8B) and magnetic tape

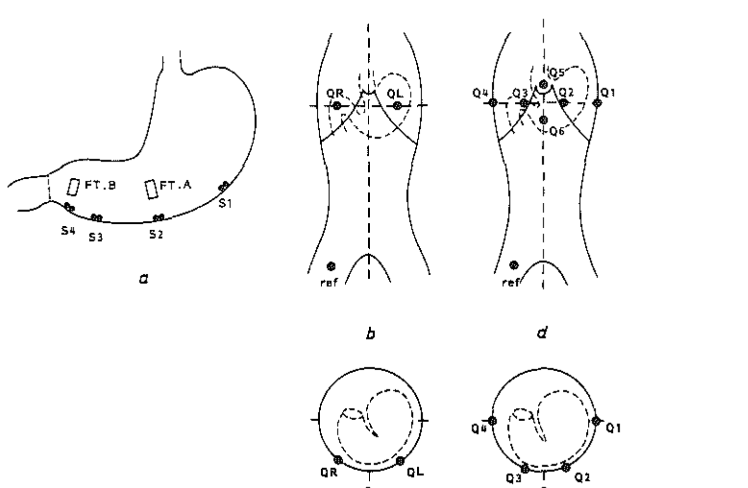

Fig. 1 *Positions of electrodes and force transducers on the stomach and the skin of the abdomen:*
(*a*) *Serosal electrodes (S) and force transducers (FT): S1 is situated 12 cm from the pylorus, S2 and FT.A 7 cm, S3 4 cm, and S4 and FT.B 2 cm*
(*b*) *Two cutaneous electrodes (QR and QL) 10 cm apart on Addison's line; reference electrode on the right hind leg; ventral view*
(*c*) *As (b) but shown in transversal section at Addison's line*
(*d*) *Cutaneous electrodes Q1, Q2, Q3 and Q4 8 cm apart on Addison's line and Q5 and Q6 on the midline 11 cm apart; reference electrode on the right hind leg; ventral view*
(*e*) *As (d), but shown in transversal section at Addison's line*

(Racal Store 14). Monopolar recordings were made with respect to the reference electrode attached to the right hind leg. Serosal recordings were made with cutoff frequencies provided by high-pass and low-pass filters at 0·012 and 15 Hz (6 dB/octave), respectively. For cutaneous recordings the corresponding filter settings were 0·012 and 0·46 Hz.

The signals were fed into a computer (Nova-2, Data General) from tape with a speed up to eight times real time, digitised and processed by a 'coherent' (or 'triggered') averaging technique, full details of which are given in the Appendix.

At this point, we will only give enough details to facilitate understanding of the results and discussion presented below.

Coherent averaging is based on the idea that the signal to be analysed comprises a number of signal segments with arbitrary time shifts (intervals) between the individual segments. To bring out the underlying waveform, the individual segments are first shifted in time (made 'coherent') with the aid of trigger pulses from a suitable source, and then averaged. In the present study, the sharp c.p. peaks of the serosal waves (picked up by the serosal electrode S4) were used as trigger pulses. A c.p. is normally generated somewhere in the orad corpus about 20 s before it is picked up by electrode S4, and continues to move on down the stomach for a number of seconds after this instant. The signal segment from the cutaneous e.g.g. recording picked out for averaging always starts 35 s before the trigger pulse, and extends up to 15 s after this pulse (see Fig. 2).

An essential addition introduced into the present study, to throw light on the influence of gastric contraction on the e.g.g. waveform, was that instead of averaging all signal segments together after they had been made coherent, each signal was assigned to one of at most five categories, depending on the strength of

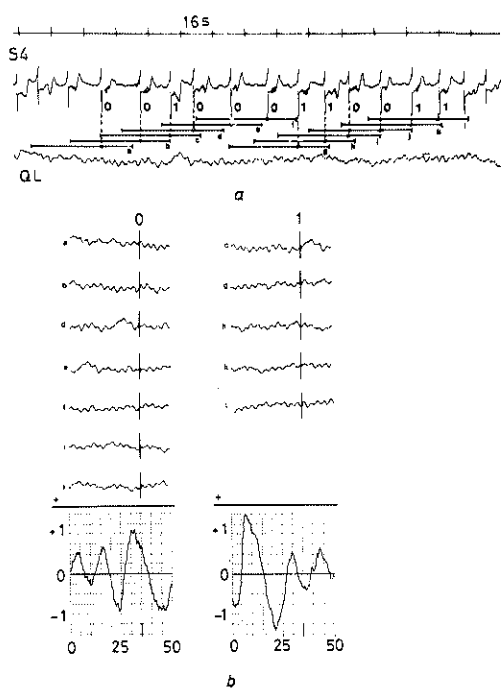

Fig. 2 *Principle of coherent averaging using two categories:*
(*a*) *Upper trace: serosal signal S4 used as the trigger signal; appropriate category numbers are assigned to the control potentials. Lower trace: cutaneous signal QL to be averaged. The lines a to l indicate the parts of QL which are fed to one or other of the averagers on the basis of the category numbers assigned.*
(*b*) *The contents of the two averagers are shown; the vertical bar on each signal segment indicates the trigger instant. The bottom trace represents the output of the two averagers*

the gastric contraction at the moment in question (picked up by serosal force transducer FT.B.). (The categories used were: 0, no contraction; 1, weak contraction; 2, strong contraction; and 3, outliers not subjected to further analysis (e.g. artefacts). An example of how these categories were assigned—restricted to categories 0, 1 and 2 for the sake of simplicity—on the basis of the recorded signals from the various electrodes is given in Fig. 3.)

The signal segments collected in each category were then averaged. The computer program used for processing the experimental data had one buffer (called an 'averager') for each category.

3 Results

Data of four dogs from 13 recording sessions with a total length of 28 h were processed. Typical results are shown in Figs. 4 and 5. Each graph in these two figures represents the output from one of the averagers. The moment of occurrence of the trigger pulse is indicated in each case by a vertical bar on the time axis.

Fig. 4 gives the results obtained from recordings on dog 1 in the interdigestive state. Three categories of gastric contraction were discerned, as indicated by the signals from force transducer FT.B (top row): 0, no contractions; 1, weak contractions; 2, strong contractions. The results for each category are given in one column: from top to bottom, successive rows show averager outputs derived from signals from the serosal electrodes S1 and S4 and the cutaneous electrodes QL and QR.

Arrows in the averager outputs for S1 indicate the c.p. of the wave, which gives rise to the trigger pulse when it passes S4, about 13 s later. The graphs for S4 show this c.p. coinciding with the trigger instant, as it must by definition. In these S4 graphs the amplitude of the s.p. following the c.p. will be seen to depend strongly on the magnitude of contraction. The fact that the fast c.p. peaks in the preceding and succeeding waves are attenuated to a greater extent than the slow s.p. components is an inherent feature of the averaging process.

The averager outputs for QL and QR show different dependences on contraction amplitude. Whereas the amplitude of the QR output will be seen to depend on the magnitude of contraction, QL does not. As we saw in connection with the S4 graphs, only the s.p. amplitude (and not the c.p. amplitude) is influenced by contractions. Hence the correlation between QR output and contraction amplitude may be due to the effect on the s.p.

The outputs for QL and S1 do not show such a relationship. When we compare the steep negative slope at (and after) time 35 s in the QR graphs with the corresponding segments of the S4 output, we are forced to the conclusion that the signal seen by electrode QR is predominantly that traversing the part of the antrum in the vicinity of electrode S4.

Fig. 5 shows the averager outputs for different electrode positions derived from data for a recording session on dog 2 in the interdigestive state. The various graphs are shown here in the same configuration as the cutaneous electrodes used during the measurements, as viewed from the ventral side. The coherent signal segments were not classified here.

The averager outputs for the serosal electrodes S1 to S4 are given by way of reference.

The mean outputs for Q2 and Q5 are quite similar and resemble that for S1 (with a time shift of 3 s), whereas those for Q3 and Q6 resemble that for S3. The

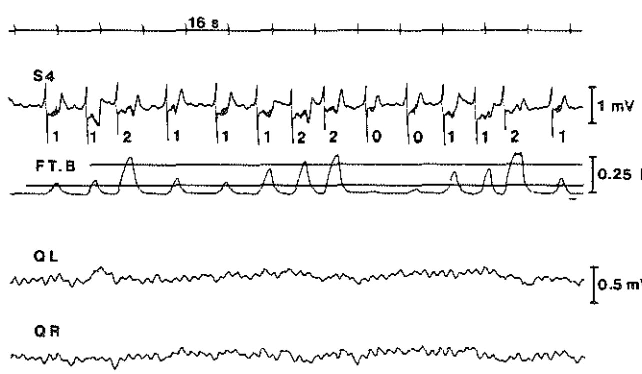

Fig. 3 *Typical chart recording for dog 2, showing the time markers and the signals from S4, FT.B, QL and QR. The numbers under trace S4 indicate the category numbers assigned to the various trigger pulses on the basis of the gastric contraction levels determined from trace FT.B (0 = no contraction, 1 = weak contraction, 2 = strong contraction)*

outputs for Q1 and Q4 seem to be inverted with respect to those for Q3 and Q6. In our opinion, however, this is not really the case: it is more meaningful to consider that all graphs show a more or less sharp downward-pointing peak at about 35 s. In the Q1 and Q4 outputs, however, this peak coincides with the crest of the S4 basic signal, whereas in the Q3 and Q6 outputs it coincides with the trough. Q2 and Q5 also exhibit such a sharp negative peak at 35 s.

The three principle waveforms mentioned above (those for the Q2–Q5, Q3–Q6 and Q1–Q4 groups) were also found in the averager outputs in other recording sessions. In general it may be said that almost all the electrodes 'see' the c.p. fairly well as it passes the antrum, but the extent to which they pick up signals from other parts of the stomach depends quite strongly on their location.

4 Discussion

Coherent averaging techniques are in principle designed to eliminate 'noise' of three different types from the signal to be processed:

(*a*) random noise

(*b*) signals from other sources, noncoherent with that from the source of interest (in our case, this means electrical signals from organs other than the stomach)

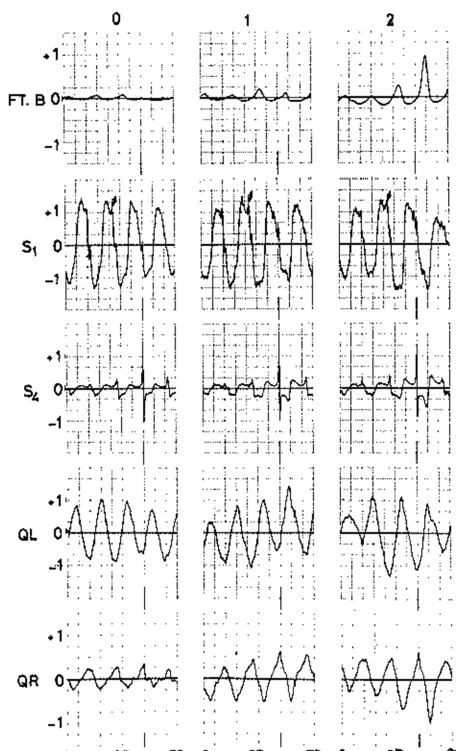

Fig. 4 *E.g.g. signals averaged in three categories according to the magnitude of contraction on the basis of recordings of dog 1. Each column corresponds to one contraction-related category: 0 = no contraction (241 samples), 1 = weak contraction (111 samples), 2 = strong contraction (97 samples). The successive rows show the averaged signals from FT.B, S1, S4, QL and QR, respectively. The amplitudes are in arbitrary units, which are the same for each row*

(*c*) signals from the source of interest, coming before or after the component which is related to the trigger pulse.

It may be assumed that the coherent averaging program used by us will be effective in dealing with the first two types of noise, but the effectiveness of the technique in dealing with preceding and succeeding waves is perhaps more open to doubt. To test the effectiveness of our program in this latter respect, we applied it to a synthetic e.g.g. waveform (shown in Fig. 6*a*), presented with a repetition time which was varied at random with a certain spread around the value of 12 s. The averager outputs obtained with various spreads in the repetition-time distribution are shown in Fig. 6*b*–*e*. It will be seen that when the spread is zero our coherent averaging method does not succeed in attenuating preceding and succeeding waves. This is understandable, and does not matter since such precise repetition is never found in practice. In a more realistic

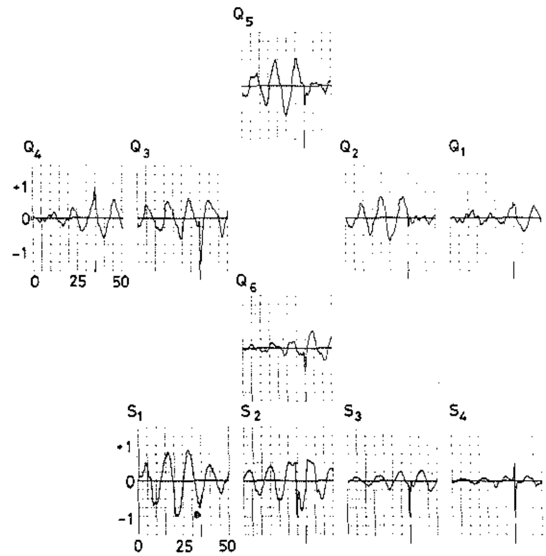

Fig. 5 *Averaged e.g.g. signals as functions of electrode position (650 samples each). Q1 to Q6 are cutaneous signals; the various graphs are arranged in the same way as the electrodes themselves on the abdomen of the dog, when viewed ventrally. Amplitudes are in the same arbitrary units throughout. S1 to S4 are serosal signals. Amplitudes are in arbitrary units (1 unit corresponds to 0·7 mV for S1, 2 mV for S2, 5 mV for S3 and 3 mV for S4*

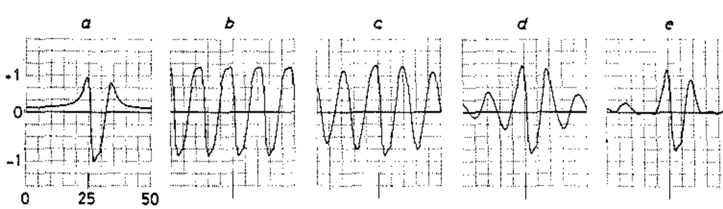

Fig. 6 *(a) Synthetic e.g.g. waveform. (b–e) Results of averaging 200 samples of trace A with repetition times distributed at random within the range. (b) 12 ± 0 s, (c) 12 ± 2 s, (d) 12 ± 4 s and (e) 12 ± 6 s. All amplitudes are in the same arbitrary units*

situation, where the spread of the repetition time is ±4 s (Fig. 6*d*), the preceding and succeeding waves are attenuated considerably.

The results obtained with these synthetic signals thus confirm—as we have already seen in Figs. 4 and 5—that the averager output tends to be dominated by the wave that is related to the trigger pulse. However, it is worth while inspecting the results of Figs. 4 and 5 in greater detail, to see just how this works out in practice.

Because of propagation of the c.p. + s.p. wave along the stomach wall, there is a time shift between the observed e.g.g. waves and the corresponding trigger pulses. When a serosal signal, proximal to S4, is averaged with S4 as trigger signal, then the trigger instant will come some time after the peak of the averaged signal. We see from Fig. 5 that the passage of the c.p. + s.p. along S1 occurs between 17 and 28 s (i.e. between 18 and 7 s before the trigger pulse), whereas the corresponding passage times for S2, S3 and S4 are approximately between 27 and 38 s, 33 and 44 s and 33 and 44 s, respectively.

The averaged outputs for the cutaneous electrodes Q1 and Q4 show maximum amplitudes between about 35 and 46 s. When we compare this pattern with the corresponding parts of the serosal signals, it seems clear that the averaged signals from Q1 and Q4 are dominated by waves travelling along the antrum somewhere near S4. The signal from QR in Fig. 4 seems to show the same effect.

This finding may be explained on the assumption that the part of the stomach 'seen' by electrodes Q1, Q4 and QR is predominantly the antrum.

Similarly, comparison of the dominating parts (between 19 and 31 s) in Q2 and Q5 with S1 (Fig. 5), strongly suggests that Q2 and Q5 'see' the wave travelling along the orad corpus, somewhat after the c.p. of that wave passes electrode S1. The preceding wave is attenuated and the succeeding wave seems to have disappeared completely. On the other hand, the presence of a peak at 35 s in both Q5 and S4 suggests that what we are 'seeing' here is mainly a wave travelling along the antrum. Q2 shows a similar effect, albeit less pronounced. It seems clear from these observations that cutaneous electrodes Q5 and Q2 'see' the antrum as well as the orad corpus.

The averaged signal from electrode Q3 might be expected to show the same phenomenon. In fact, inspection of Fig. 5 shows that this signal has its main wave between 29 and 40 s, which would seem to correspond to a c.p. + s.p. wave travelling along the stomach somewhere between serosal electrodes S2 and S3, whereas the sharp negative spike at 35 s may be owing to the c.p. of the same wave travelling along the antrum. The rest of this wave is not visible in the averaged signal; it may be cancelled out by the signal from the other part of the stomach 'seen' by Q3. The averaged signal from Q6 also shows the same negative spike as in Q3 (although less sharply), but no other dominant wave.

Why do most of the cutaneous electrodes used in our study seem to be able to 'see' waves travelling along the antrum, whereas only some can detect waves travelling along the corpus? At least two reasons can be proposed for this. First, the stomach lies crooked in the body, and so two different parts of the stomach can both be more or less at the same distance from one electrode. Secondly, the amplitude of the waves increases with distance down the stomach: our measurements showed that the c.p. amplitude of the waves on the antrum was about four to five times that on the corpus, a finding in agreement with that of other workers, e.g. KELLY *et al.* (1969). This suggests that an electrode which is closer to the corpus than to the antrum might pick up waves from both these parts of the stomach with roughly equal amplitudes. It is not known what effect the disappearance of the electrical activity in the pyloric region has on the cutaneous signals.

The coherent averaging technique presented in this paper only gives clear e.g.g. pictures, i.e. high signal-to-noise ratios, when a large number of signal segments are averaged. When the signal segments are not classified according to any criterion, about 200 signal segments have to be averaged to give decent results. When classification is used and no successive segments fall into the same category, it is sufficient to average about 80 signal segments per category. To produce the results of Fig. 4, some 900 trigger pulses were needed to give at least 80 signal segments in each category. This took 3 h of recording. It will thus be clear that it is difficult to use this technique to obtain information about changes in e.g.g. waveforms with time. Further research is required to determine whether coherent signal averaging could be used with fewer trigger pulses when signals are pretreated by adaptive filtering, thus permitting repeated averaging of successive signal segments (by analogy with the 'running spectrum analysis' described by VAN DER SCHEE *et al.* (1981*b*)), so that e.g.g. variations with time might be more easily detected.

5 Conclusions

(*a*) Waveforms in cutaneous e.g.g. signals are correlated with the strength of gastric contractions.

(*b*) Waveforms derived from cutaneous electrodes are related to the site on the abdomen where the electrodes are placed.

(*c*) Some cutaneous electrodes, especially those placed over the orad corpus, seem to have both the corpus and the antrum in their 'field of vision'; almost all the cutaneous electrodes we used can 'see' waves travelling along the antrum.

(*d*) Coherent averaging tends to give strong attenuation of waves before and after the one which corresponds to the trigger pulse, although not to eliminate them completely. This attenuation effect increases with increasing spread in the repetition time of the signals under investigation.

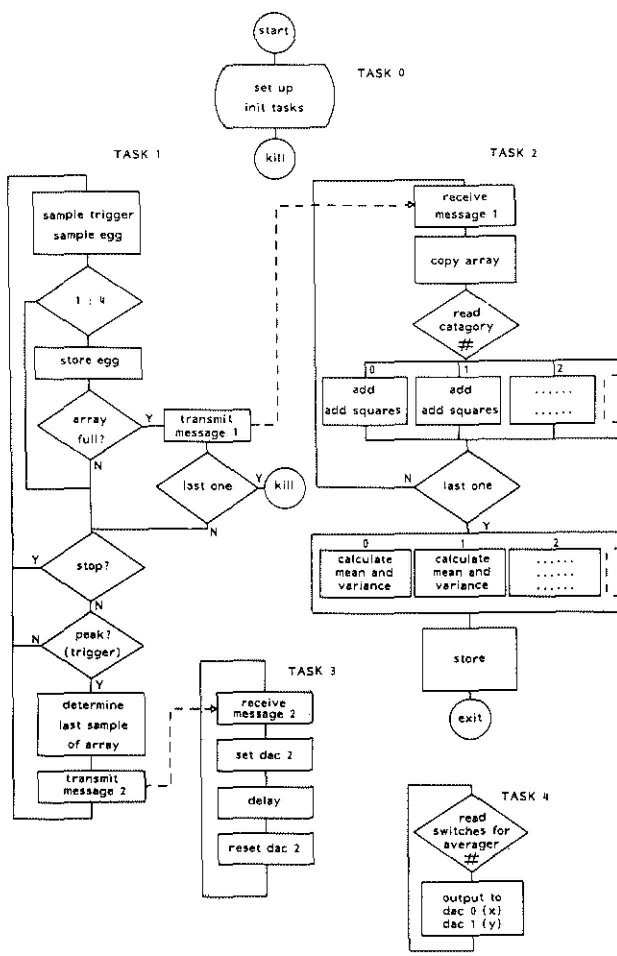

Fig. 7 *Flow diagram of computer program for coherent averaging of the e.g.g. recordings*

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Appendix: principle of the coherent averaging technique used in this study

Coherent averaging techniques are used widely to enhance the quality of biological signals with a high noise content. The signals to be averaged must be related to some event which can be used to provide a trigger pulse for the averager.

The electrogastrogram (e.g.g.) can be considered as the summation of time-shifted waveforms, each one being generated by a control potential (c.p.) and its associated second potential (s.p.) propagated along the stomach wall. The c.p. picked up anywhere on the stomach wall can be used as the event that triggers the averaging process to obtain the waveform corresponding to this c.p.

A coherent averager used for processing e.g.g. recordings should satisfy the following three requirements:

(*a*) The duration of the signal segments sampled before and after the trigger pulse should be fairly long (of the order of 30 s), because we do not know exactly how long it takes for a c.p. to travel from the corporal area where it originates to the pyloric region where it vanishes.

(*b*) In view of the relative long interval between c.p.s (about 12 s), each c.p. must be used as a trigger pulse with not one being lost, so as to keep the overall recording time within reasonable limits.

(*c*) Different signal segments may be related to different phenomena on the stomach, and so it may be necessary to classify the signal segments sampled on the basis of some appropriate criterion (e.g. the degree of gastric contraction associated with each c.p. used as a trigger).

The requirements mentioned under (*b*) and (*c*) could not be met by any commercial averager, which is why we developed a special computer program for this study.

The following four tasks are run concurrently in this multitasking program (see flow diagram of Fig. 7):

(*a*) The highest priority task samples the trigger pulses and the signal to be averaged. The latter are stored in a rotating buffer. Although it is sufficient for our purposes to use a simple peak detector for trigger sampling (each peak in the trigger signal which exceeds a certain adjustable level is used as a trigger pulse), more sophisticated criteria could be incorporated. The sampling frequency for the trigger pulse can be chosen as a multiple of that of the signal to be averaged, because of the higher frequency content of the former.

(*b*) After reception of a message a specified time after detection of a trigger pulse in the first task, the second task copies the appropriate part of the signal stored in the rotating buffer in the first task, and feeds it to one of five available averagers according to the classification criteria described below. The squares of the signal samples are also generated, added and stored to permit calculation of the variance of the averaged signal as well as the mean.

(*c*) Each time a trigger pulse is detected in the first task, a message is sent to a third, low-priority task to output a pulse which can be used to confirm detection of the trigger pulse.

(*d*) The fourth, lowest-priority task, which uses the remaining computer time, outputs the contents of one of the averagers to digital-to-analogue convertors for display on an oscilloscope. The choice of averager can be made at run time by means of the console switches of the computer.

The overall averaging procedure is as follows:

(*a*) First a primary run is made to check which triggers are detected. In this run the trigger signal, the signal to be averaged and the trigger detection pulses generated by the third task are recorded on a multichannel pen recorder, to show explicitly which peaks are detected as trigger pulses and which are not. In addition, the signal from one of the strain-gauge force transducers is recorded as a basis for classification of the signal segments; an example of such a recording is shown in Fig. 3.

(*b*) A classification number 0–4 is now assigned to each trigger pulse, on the basis of the classification criterion chosen. In our case, we could choose the amplitude of the contraction wave following the c.p. used as trigger pulse (judged on the basis of either the force-transducer signal or the amplitude of the corresponding s.p.) or the length of the succeeding or preceding time interval as classification criterion. For the present study, we actually chose the force-transducer output as criterion. It should be noted that with this procedure any classification criterion can be used.

(*c*) A list of the classification numbers determined is entered in a file in the computer, to be read out by the second task.

(*d*) During the main run, the classification numbers are read out (task 2) and whenever a trigger pulse is detected, the corresponding signal samples and their squares are added to the appropriate averager.