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Analysis of electrical and pressure signals of the [redacted] human colon.

University — Université

U of Alberta

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

M.Sc. in Electr. Engg.

Year this degree conferred — Année d'obtention de ce grade

1980

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THE UNIVERSITY OF ALBERTA

ANALYSIS OF ELECTRICAL AND PRESSURE SIGNALS OF THE HUMAN COLON

by

'Cecil H. Bannister

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

ELECTRICAL ENGINEERING

EDMONTON, ALBERTA

SPRING, 1980

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Analysis of Electrical and Pressure Signals of the Human Colon.

submitted by Cecil H. Bannister

in partial fulfilment of the requirements for the degree of M.Sc. in Electrical Engineering.

Supervisor

Date April 24 - 1980

A mis padres.

A mi esposa.

ABSTRACT

Human colon pressure and electrical records are analysed to determine some significant features representative of the colonic activity.

A detailed description of the computer simulated process developed to generate these features is presented. The definitive feature computation can be achieved with a proposed dedicated microprocessor based machine.

The use of Pattern Recognition for the patient's disease identification by means of the evaluated features is suggested.

Acknowledgements

The author would like to thank Professor Y. J. Kingma who supervised this project, and Dr. K. L. Bowes for his support.

Thanks also to Mrs. Rita Lenhard and Mr. Donald McBride for the valuable help provided.

In addition the author would like to thank the University of Alberta for the financial support provided.

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I. INTRODUCTION

For years, investigators have been trying to understand the motor phenomena of the colon without conclusive results. Several factors have contributed to this, particularly the lack of uniformity in protocols, sensing devices and method of analysis, together with the complexity of the organ.

At present the Motility Group of the Faculty of Medical Sciences, University of Alberta, is using an arbitrary and time consuming method to evaluate the colonic motility from basal and post drug colonic pressure records. After the recordings are obtained, they are examined to see their relationship to the patient's disease or state, in an attempt to use them for diagnostic purposes.

The need arises to have rational figures of merit that are really representative of the colonic motility and an efficient and less time consuming way of computing them. Once these new figures are obtained, a method to systematically process them is needed to ensure unbiased results.

Some available pressure records will be used to test the validity of those figures. An automatic system for the computation of them and the use of pattern recognition with the purpose of disease identification are proposed.

II. PATTERN RECOGNITION

Pattern recognition is a term that refers to the process of recognizing an object and identifying it as a member of a certain class, or category. The characteristics, or features of the object constitute the pattern that is recognized. The pattern is then classified by comparing its features with those typical of different pattern classes and choosing the most clearly corresponding class [1,2,3].

An automated pattern recognizer takes a pattern as input and goes through a process designed to assign a classification to that pattern. This process may be broken down into three distinct subprocesses: measurments, processing and classification.

The measurement is usually accomplished by a transducer which accepts the original signal and converts it to a form acceptable by the computer. For example, in the case of a waveform, the transducer might digitize it. The input for the rest of the recognizer would then consist of a sequence of discrete measurements (i.e. numbers) representing the waveform.

The processor performs some sort of transformation on this set of measurements to generate a set of features, which is the input to the classifier. The procedures involved here are usually feature selection or feature extraction. Feature selection consists of choosing some of

the original measurements produced by the transducer to be the features used. To continue the previous example, the measurements for a digitized waveform might consist of a set of power values measured at regular period intervals from a power spectrum. If the power values for certain specified frequencies were to be used as features for classification, the processor would select those intensities and pass them to the classifier. Feature extraction involves more processing of the original measurement than a simple selection. In this case, the measurements are transformed in some way to yield more informative representations. For example, features such as average power, energy values, or number of peaks might be calculated from the power values of the waveform. Some additional information is extracted from that present in the original set of measures.

The features produced by the processor are used by the classifier to decide to which class the pattern belongs. The means by which this is accomplished usually is called a decision rule. A common example of a decision rule is the use of linear discriminant functions. There is a discriminant function for every class known to the pattern recognizer. Each function is calculated, using the features of the pattern, and the class corresponding to the maximum-valued discriminant function is chosen. There is a wide variety of pattern classifiers in use, which fall into the categories of mathematical, statistical, syntactic, and heuristic methods [1,2,3,4]. The kind of pattern classifier

to be used depends heavily on the characteristics of the features used, as will be seen later.

III. MOTILITY OF THE COLON

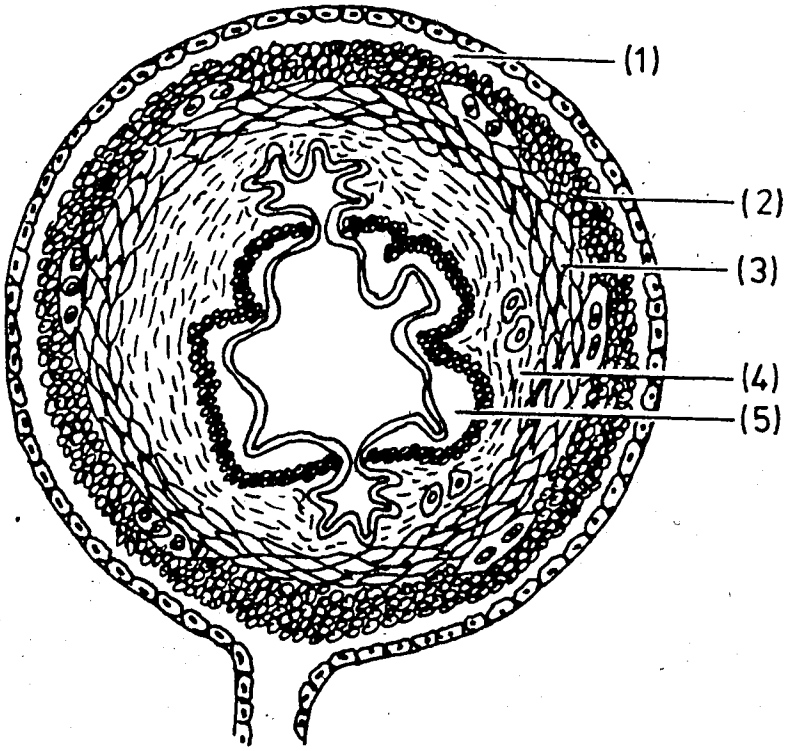
The primary function of the alimentary tract is to provide the body with a continual supply of water, electrolytes, and nutrients. In order to achieve this, food must be moved along the alimentary tract at an appropriate rate for the digestive and absorptive functions to take place.

A. CHARACTERISTICS OF THE INTESTINAL WALL.

The motor functions of the gut are performed by the different layers of smooth muscle. Figure 1 illustrates a typical section of the intestinal wall, showing the following layers from the outside inward: (1) the serosa, (2) a logitudinal muscle layer, (3) a circular muscle layer, (4) the submucosa, and (5) the mucosa. In addition, a sparse layer of smooth muscle fibers, the muscularis mucosae, lies in the deeper layers of the mucosa.

Electrical Activity and Contractions

In general, smooth muscle is composed of fibers far smaller than the skeletal muscle fibers, usually 2 to 5 microns in diameter and only 50 to 200 microns in length. In contrast, the skeletal muscle fibres are as much as 20 times as large in diameter and thousands of times as long. Nevertheless, many of the same principles of contraction



1 serosa
2 longitudinal muscle layer
3 circular muscle layer
4 submucosa
5 mucosa

Figure 1. Section of the human intestinal wall.

apply to both smooth muscle and skeletal muscle. The same chemical substances cause contraction in the smooth muscle similar to that in skeletal muscle, but the physical arrangement of smooth muscle fibers is entirely different.

The smooth muscle found in the gut is of the type called visceral smooth muscle. Visceral smooth muscle fibres are crowded together and lie in such close contact with each other that the cell membranes between adjacent cells either fuse or almost fuse. Measurments of ionic transport through these areas of close contact demostrate extremely low electrical resistance, so much so that intracellular electrical current can travel very easily from one smooth muscle fiber to another. Therefore, the smooth muscle of the gastrointestinal tract performs as a group of functional syncytium, which means that electrical signals originated in one smooth muscle fiber are generally propagated from fiber to fiber within a group.

The smooth muscle of the gastrointestinal tract undergoes electrical activity almost continuously. This activity is some times very irregular, but tends to have two basic types of waves, *slow waves* and *spikes*, both of which are ilustrated in Figure 2. The slow waves occur at frequencies between 3 and 12 per minute [5], and they represent a basic continuous oscillation that occurs in the membrane of the smooth muscle.

When the muscle is stimulated by stretch, by acetylcholine, or by parasympathetic excitation, the resting

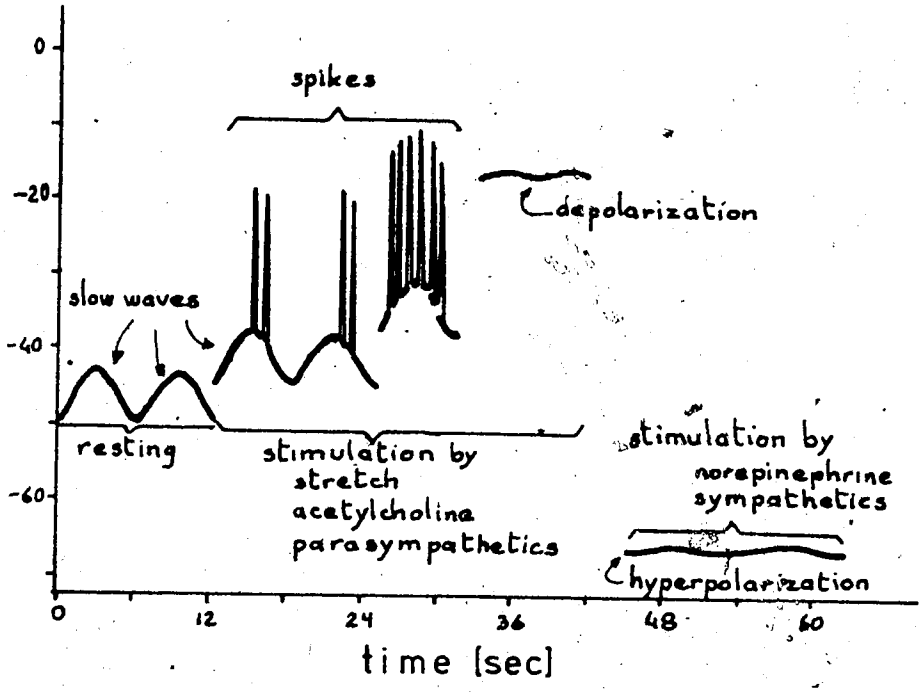


Figure 2. Slow waves of the smooth muscle.[6]

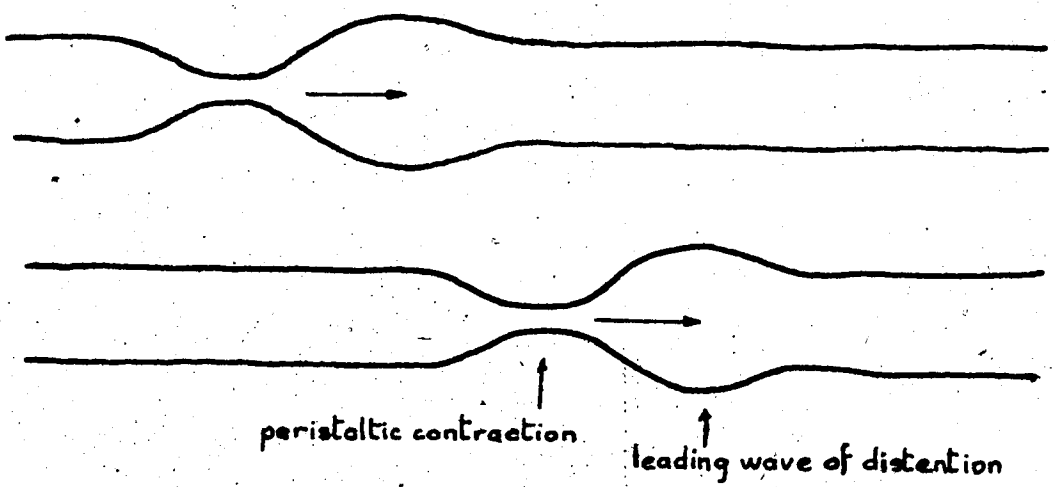


Figure 3. Peristaltic movements of the gut.

membrane potential of the fiber becomes more positive, which raises the entire potential level of the slow waves from their normal mean voltage of -50 to -40 millivolts up to some less negative value by the process of depolarization [6]. As the depolarization rises above -40 millivolts, spike potentials begin to occur on the peaks of the slow waves. The frequency of spikes increases progressively as the resting potential rises still further. However, with very strong stimulation, when the resting membrane potential rises to a value of -20 to -15 millivolts, the spikes disappear because the membrane potential now remains totally depolarized all of the time during stimulation.

Figure 2 also illustrates that stimulation of the smooth muscle by either epinephrine or sympathetic excitation will decrease the resting membrane potential to a hyperpolarized value approaching -70 millivolts, and the electrical activity as well as the mechanical activity of the smooth muscle approaches zero [6].

Most intestinal contraction occurs in response to the spike potentials. Indeed, there is ordinarily either no contraction or only very slight contraction in response to slow waves when these have no superimposed spikes [5,7] Thus, the spikes are comparable to action potentials in the skeletal muscle, and are responsible for the membrane changes that excite contraction. The contraction results mainly from entry of calcium through the cell membrane to the interior of the smooth muscle where it initiates a

reaction between the myosin and the actin of the smooth muscle.

The smooth muscle of the gastrointestinal tract exhibits both tonic contraction and phasic contraction. Tonic contractions are slow changes in tone, lasting minute after minute, sometimes increasing or decreasing in intensity but, nevertheless, continuing. It is believed to be caused by a series of spike potentials, the frequency of these[1] determining the degree of tonic contraction. The intensity of tonic contraction in each segment of the gut determines the amount of steady pressure in the segment.

In different parts of the gut the rhythmic contractions of the gastrointestinal smooth muscle occur at rates as rapid as 12 times per minute or as slow as 3 times per minute. These are also the frequencies of the respective slow waves in these segments; it is these slow waves that set the frequency.

Electrical Activity of the Colon.

Although the electrical activity of the colon presents some similarities to the electrical activity in the small intestine, the rectosigmoid electrical recordings have two characteristics distinct from other areas of the gastrointestinal tract [7]. First, it is claimed that the

---

[1] Duthie and Kirk [8] found the frequency of the spike activity "in vitro" to be 22±5 (s.d.) cycles per minute for a strip of taenia. In this case the myogenic activity had intermittent periods of regular spike activity, accompanied by tetanic contractions.

basic electrical rhythm (BER) is not present all the time, that is, that long periods of inactivity separate sequences of regular wave form [9,10]. However, there is a higher percentage electrical activity in the lower rectum than in the more proximal areas of the large bowel. Second, it is also claimed [7] that there are two different frequencies present in the rectosigmoid electrical activity, at about 3 cycles/min. and 6 cycles/min..

Innervation of the Gut.

The Intramural Plexus.

Beginning in the esophageal wall and extending all the way to the anus is an intramural nerve plexus. This is composed principally of two layers of neurons and appropriate connecting fibers. The outer layer, called the myenteric plexus, lies between the longitudinal and circular muscular layers as illustrated before in Figure 1, and the inner layer called the submucosal plexus, lies in the submucosa. The myenteric plexus is mainly motor in function and is far more extensive than the submucosal plexus which is mainly sensory, receiving signals principally from the gut wall.

In general, stimulation of the myenteric plexus increases the activity of the gut, causing increased tonic contraction or tone of the gut wall, increased intensity of the rhythmic contractions, increased rate

of rhythmic contractions, and increased velocity of conduction of excitatory waves along the gut wall.Inhibitory nerves are also present; these are both adrenergic and nonadrenergic.

The gastrointestinal tract receives extensive parasympathetic and sympathetic innervation that is capable of altering the overall activity of the entire gut or of specific parts of it, particularly altering the activity of the upper end down to the stomach, and from the distal end of the mid-colon region to the anus.

The postganglionic neurons of the parasympathetic system are part of the myenteric plexus, so that stimulation of the parasympathetic nerves causes a general increase in activity of the plexus. This in turn excites the gut wall and facilitates most of the intrinsic excitatory nervous reflexes of the gastrointestinal tract.

On the other hand, stimulation of the sympathetic nervous system generally inhibits the activity in the gastrointestinal tract, causing effects essentially opposite to those of the parasympathetic system.

B. FUNCTIONAL TYPES OF MOVEMENTS IN THE GASTROINTESTINAL TRACT.

Two basic types of movements occur in the gastrointestinal tract: *mixing movements*, which keep the

intestinal contents thoroughly mixed at all times, and propulsive movements, which cause food to move forward along the tract at an appropiate rate for digestion and absorption.

In most parts of the alimentary tract, the mixing movements are caused by either peristaltic contractions or local contractions of small segments of the gut wall. These movements are modified in different parts of the gastrointestinal tract for proper performance of the respective part.

The basic propulsive movement of the gastrointestinal tract is *peristalsis*, which is illustrated in Figure 3. A contractile ring appears around the gut and moves foward, moving any material in front of it. Peristalsis is an inherent property of any syncytial smooth muscle tube.

Movements of the Small Intestine

The movements of the small intestine, as elsewhere in the gastrointestinal tract, can be divided into the mixing contractions and the propulsive contractions. However, to a great extent this separation is artificial because essentially all movements of the small intestine cause at least some degree of both mixing and propulsion. Yet the usual classification of these processes is done between mixing contractions (segmentation contractions) and propulsive movements.

During mixing contractions, localized concentric contractions spaced at intervals along the intestine are generated when a portion of the small intestine becomes distended with chyme. These rythmic contractions proceed at a rate of 11 to 12 per minute in the duodenum and at progressively slower rates down to 9 per minute in the terminal ileum. The longitudinal length of each one of the contractions is only about 1 cm. so that each set of contractions causes "segmentation" of the small intestine, dividing the intestine at times into regularly spaced segments or "chambers". As one set of segmentation contractions relaxes a new set begins, but the contractions this time occur at new points between the previous contractions. Therefore, the segmentation contractions chop the chyme many times a minute, in this way promoting progressive mixing of the solid food particles with the secretions of the small intestine. The intensity of the segmentation contractions is increased by parasympathetic stimulation but decreased by sympathetic stimulation.

During propulsive movements, chyme is propelled through the small intestine by peristaltic waves. These occur in any part of the small intestine, and they move distally at a velocity of 0.5 to 5 cm. per second, much faster in the proximal intestine and much slower in the terminal intestine. However, they are normally very weak and usually die out after traveling only a few centimeters, so that movement of chyme is much slower. Very intense irritation of

the intestinal mucosa, such as occurs in some infectious processes, can elicit a so-called peristaltic rush, which is a powerful peristaltic wave that travels long distances in the intestine in a few minutes. These waves can sweep the contents of the intestine into the colon and thereby relieve the small intestine of either irritants or excessive distention.

Slow oscillatory electrical waves, as described earlier, occur at the membranes of the smooth muscle, at frequencies of 11 to 12 per minute in the duodenum and decreasing to 6 to 7 per minute in the terminal ileum. However, these electrical waves do not in themselves produce intestinal contractions. They merely set the background conditions for the contractions (hence are also called Electrical Control Activity, E.C.A.).

Movements of the Colon

The absorption of water and electrolytes from the chyme and storage of fecal matter until it can be expelled, are the main functions of the colon. The usual colon contraction is segmentation; peristalsis is uncommon.

During mixing movements, large circular segmental constrictions occur in the large intestine. At each of these constriction points, about 2.5 cm. of the circular muscle contracts, sometimes constricting the lumen of the colon to almost complete occlusion. At the same time, the

longitudinal muscle of the colon, which is aggregated into three longitudinal strips called the teneae coli, contracts. These combined contractions of the circular and longitudinal muscle cause the unstimulated portion of the large intestine to bulge outward into baglike sacs called *haustrations*. The haustral contractions or *haustral shuttling* [5], once initiated, usually reach peak intensity in about 30 seconds and then disappear during the next 60 seconds. They at times also move slowly analward during their period of contraction. After another few minutes, new haustral contractions occur in nearby areas but not in the same area. These contractions expose the fecal material to the surface of the large intestine, and help to move the fecal contents of the cecum and ascending colon into the transverse colon.

Some authors hold that peristaltic waves of the type seen in the small intestine do not occur in the colon. Others [11] indicate that they actually occur in the colon, and they are described as contraction waves moving down the colon at 1 to 2 cm. per minute, preceded by muscle relaxation. Contraction, in this case, is said to be sustained behind the tail of the fecal mass such that net movement of the contents does occur.

During propulsive movements, fecal contents are propelled toward the anus in a *mass movement*, which occurs only a few times a day, most abundantly for about 15 minutes during the first hour or so after breakfast.

Mass movements can be initiated by colon irritation.

For instance, a person who has an ulcerated condition of the colon (ulcerative colitis) frequently has mass movements that persist almost all of the time. Mass movements are also initiated by intense stimulation of the parasympathetic nervous system or simply by overdistention of a segment of the colon.

Intraluminal Pressure

Pressure waves recorded from the colonic lumen represent in general segmental non-propulsive, non-peristaltic contractions of the colonic muscle. Muscle contraction elevates intraluminal pressure when the lumen is obliterated by mucosal folds which form closed chambers, or when there is resistance to displacement of feces because of areas of contraction elsewhere in the bowel, or because of the high viscosity of the colonic contents. However, the most acceptable interpretation of pressure data from the colon is that most of the pressure waves represent segmental contractions [12].

C. DISORDERS OF THE LARGE INTESTINE

Constipation and diarrhea, cosidered common disorders of the large intestine, are no more than expressions of different diseases or states.

Constipation

Constipation means slow movements of feces through the large intestine, and it is often associated with large quantities of dry, hard feces in the descending colon which accumulate because of the long time allowed for absorption of the fluid. A frequent cause of constipation is irregular bowel habits that have developed through a lifetime of inhibition of the normal defecation reflexes.

Colonic motor activity is increased in patients with constipation [13]. Even though there is more motor activity, the net propulsive movement through the colon is slower than in normal subjects.

Diarrhea

Diarrhea, which is the opposite condition to constipation, involves decreased segmentation and consecuently, rapid movements of fecal matter through the large instestine. The major causes of diarrhea are infection in the gastrointestinal tract called enteritis, and excessive parasympathetic stimulation of the large intestine, which is called psychogenic diarrhea.

Psychogenic diarrhea is caused by excessive stimulation of the parasympathetic nervous system, which greatly excite secretion of mucus in the distal colon.

IV. RECORDING METHODS

Different methods are used to record colonic electrical and pressure activity. A short description of the most popular and common recording methods presently used is given.

A. COLONIC PRESSURE

The idea behind colonic pressure recording is to perform measurements with little or no perturbation in the area where measurements are performed. Systems using balloons and open-ended tubes are used most commonly because of this reason and because of their simplicity.

In general, balloons give good results, but have the disadvantage of altering the normal motility of the colon due to reflexes induced by mucosal or intramural stimulation. The size and complexity of the the probes, using balloons, limit their use in multiple simultaneous pressure measurements. This restricts them to use exclusively in single point colonic pressure measurements. The balloon is connected by a tube to an external pressure transducer. Usually the balloon, tube and pressure transducer chamber are filled with water to avoid compression and thus avoiding distortion. The stretching of the balloon however adds an extra pressure to that of the colonic pressure, making it difficult to obtain absolute pressure readings. Pressure noise can be generated by the

use of balloons, if the balloon is deformed by contact with the walls during colon movements, thus raising the internal balloon pressure without an actual rise of colonic pressure.

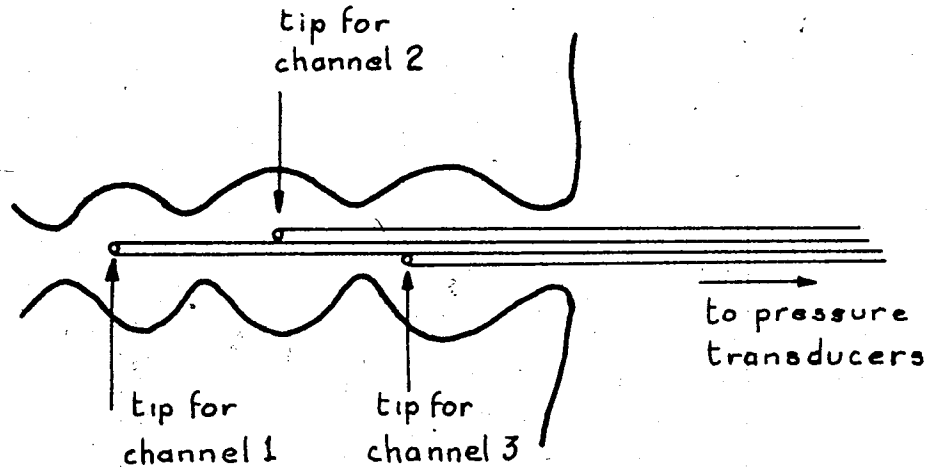
On the other hand, open-ended tubes allow sensing of colonic pressure simultaneuslly in several points. As shown in Figure 4, open-end tube arrays are formed by several small tubes with opened ends placed at different positions from the tip of the first tube. The other ends of the tubes are connected to pressure transducers. These open-ended tubes record true intraluminal pressures, but can be unreliable if air is present in the tube conecting the tip and the transducer. This is partially overcome by constantly bleeding fluid at a slow rate to maintain patency.

Other methods make use of local straingages, but their performance and reliability are questionable.

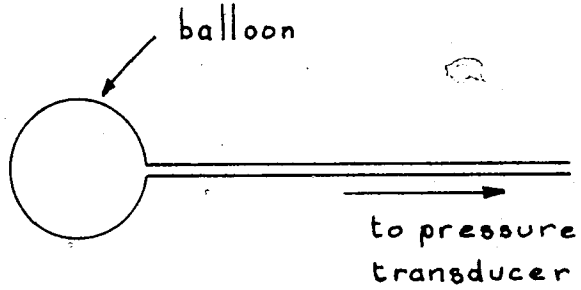
B. COLONIC ELECTRICAL ACTIVITY

"In vivo" recording

Some of the electrical activity recording in the literature cannot be interpreted because essential information about the recording featureswere not stated (features such as filter to cut off frequencies, filter orders, type of coupling, etc.). Although the type of electrodes used in some "in vivo" and "in vitro" recording are of the same type, their characteristics (impedance and frequency behavior) can be totally different from each other. Undoubtedly these factors are an important source of



(a)



(b)

Figure 4. a) Balloon and tube,
b) Multiple open-ended tubes.

discrepancies when they are not specified.

"In vivo" colonic electrical activity is recorded using local intraluminal bipolar electrodes. These electrodes, shaped as a hook, are inserted in the mucosa of the colon wall. A special system allows removal of the electrode with a minimum of discomfort to the patient when the recording is ended. The use of this take-off system does not permit the use of more than a few electrodes simultaneously.

Suction electrodes are also commonly used on the mucosal surface. The suction force brings electrodes tight against the mucosa, or pushes fine needle electrodes through the mucosa into the circular muscle, and maintains this as a stable contact.

Bipolar electrodes have also been implanted in patients when they undergo an operation. The wires from the electrodes are led out through the surgical drain and are removed after a few post-operative days. This method makes possible the continuous recording of electric activity during this period of time from several electrodes simultaneously implanted in the serosa.

Cutaneous electrodes, placed on the patient's skin, are claimed [14] to give good results, though they are not frequently used.

"In vitro" recording

Different kinds of methods and electrodes are actually used to record "in vitro" electrical activity. In general,

strips of colonic tissue are kept in a bath with oxygenated Krebs solution at a constant temperature during the recording, to keep the tissue alive. The different kinds of electrodes used in "in vitro" recording and some of their characteristics are discussed below.

Usually, "in vitro" recording is done by keeping the tissue strip pinned down in a fixed position to avoid movements, thus reducing the noise generated by changes in the electrode-tissue interface. Pressure electrodes can be placed by softly touching the tissue surface; micro-electrodes can be inserted intracellularly; wire electrodes can be implanted in the tissue, allowing the simultaneous recording of the electrical activity and the force generated. What is actually recorded with the different kinds of electrodes is still not clearly understood and is a present field of ongoing reseach.

C. METHOD USED IN PRESSURE RECORDING

Open ended tubes were used to record the colonic intraluminal pressure. As described above, constant bleeding is used to avoid blocking of the open tip. As shown in Figure 5, the constant flux is provided by a syringe driven by a electric motor at a constant speed. The flow rate is so low that the pressure drop in the small tubes is neglegible.

The actual system uses 5 tubes simultaneusly, with their tips 5 cm. apart, giving a total useful length of 25 cm. If two tips are too close to one another, both may end

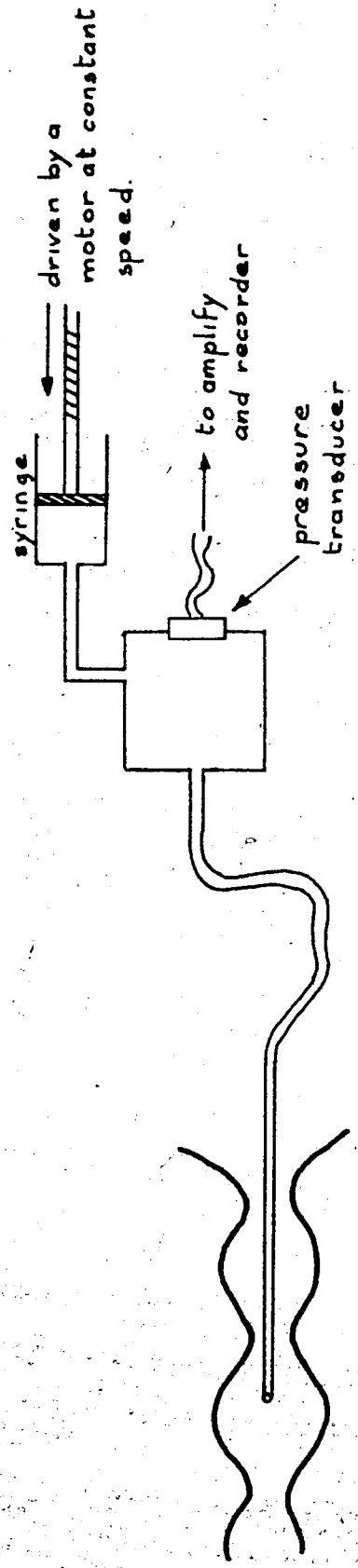


Figure 5. Recording system with constant bleeding.

up in the same luminal chamber, thus producing the same pressure record. On the other hand, if the tips are too far apart from each onother, correlation between channels is lost. The ideal situation is to have a tip distribution that allows the recording of the pressure from several successive chambers, as shown in Figure 4a.

V. DATA PROCESSING

The pressure and electrical activity data are stored on magnetic tape using frequency modulation (FM), by means of a Ampex FM tape recorder. Signals from different pressure transducers or electrodes are stored in different channels. The analog data of each channel is then low pass filtered and digitalized with a Hewlett Packard 2109MX computer and stored in digital form, again on magnetic tape, to be finally processed on the Amdahl 470V/7 computer.

The path the data follows untill it gets to the Amdahl computer, is shown in the block diagrams of Figure 6. The electrical signal from the pressure transducers passes through two variable gain amplifiers (VGA) to the Ampex FM tape recorder where the signal is stored. The signal for the FM recorder is taken from the output of the penmotor driver and before the ink recorder. The driver has a zero adjusting knob to allow the reference to be set at a given input pressure. The voltage required to set the pen motor needle at zero on the paper is -1.4 volts and for the full scale +1.4 volts. This procedure requires a permanent setting of the system for the "zero" and "full scale".

The zero reference is taken with the transducer's tip open at atmospheric pressure, at the level of the patient's rectum. This requires a zero calibration for each patient.

An evident disadvantage of this system is that changes in pressure can be generated if the patient moves or changes position during the recording. This is an important source

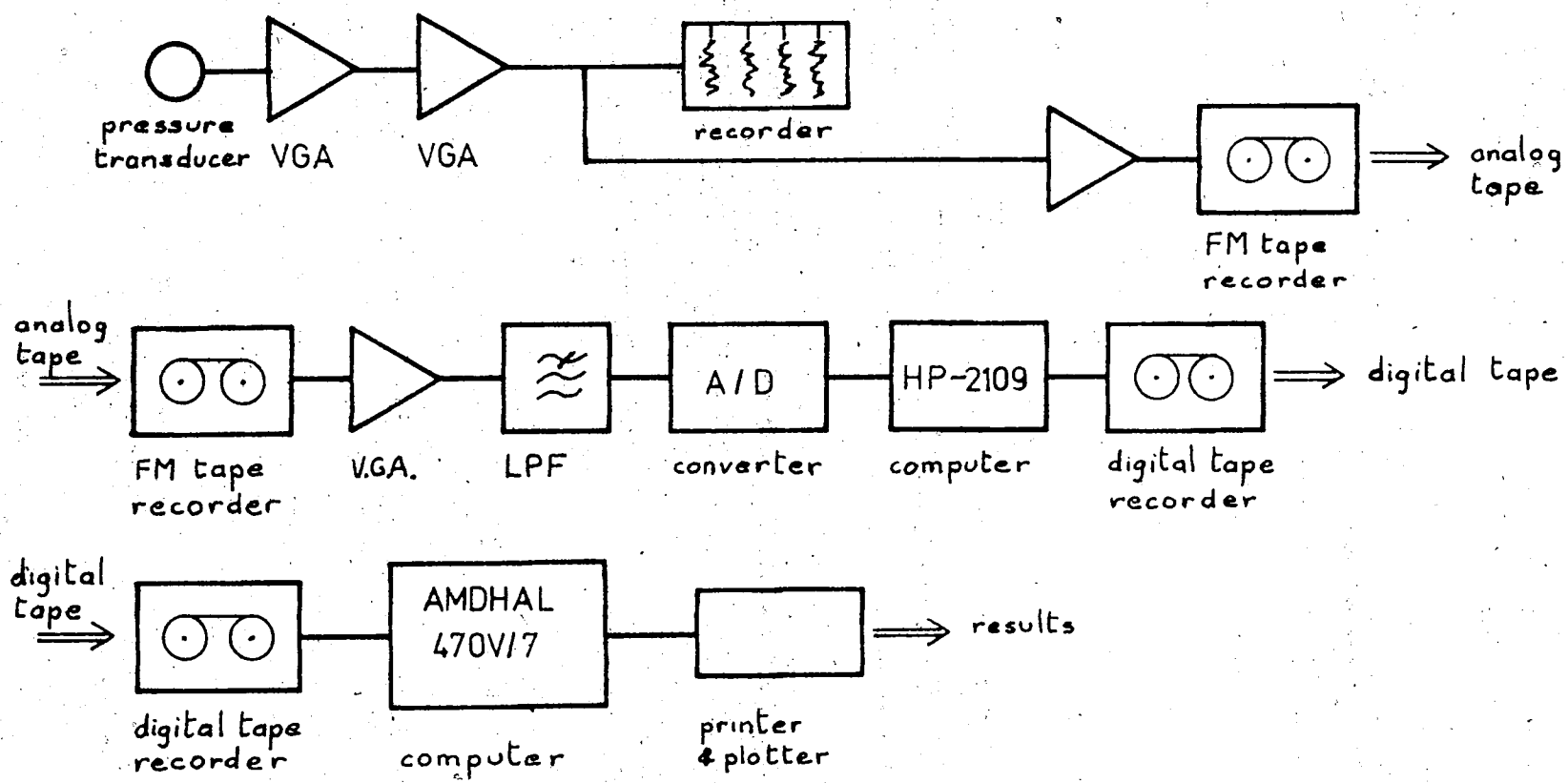


Figure 6. Data goes under this steps till it reaches the Amdhal computer to be processed.

of pressure 'noise' that will be discussed later. It is not necessary to gauge the full scale for every patient, if the gain of the VGA has not changed. Now, from the recording point of view, its zero input always corresponds to -1.4 volts and its full scale to +1.4 volts.

During the the analog to digital conversion, the FM tape is run at a speed 8 times higher than the one used in the recording. This permits the conversion to be performed in a shorter period of time than was used in the recording. The A/D converter has a VGA (with step setting) and a variable Low Pass Filter (LPF) to avoid aliasing. The actual A/D conversion was done with a sampling period of T =0.496/8=0.062 sec., which gives a real time sampling period for the data of T_s=0.496 sec..

The cut-off frequency for the LPF was set at 8 Hz which gives a real time cut-off frequency for the data of 1 Hz. The periods present in the colonic pressure records are longer than 6 sec.. The sampling period of 0.496 sec. is thus sufficient to avoid aliasing. The periods present in electrical activity are shorter than the ones present in pressure activity, and the highest frequency components have negligible power compared with the maximum power. In any case these components are filtered out by the LPF before the A/D conversion, so no significant aliasing effect will exist.

The digital data is stored on magnetic tape. Every file has data from the patient and particulars of the record

session. Each file is formed by one or more blocks, the total number of blocks being a function of the record length. Each block has a length of 256 words per channel digitalized. Each word is 16 bits long.

Preceding each data file, a heading file is placed containing information related to the data file, such as identification, including patient name, recording date, sensor position, recording conditions etc. This information file has a block length of 72 words.

The data stored in this tape is then processed on the Amdahl 470V/7 computer. The data files, before being used, have to be reorganized so that Fortran formats can handle them. This process involves the contraction of the data-file lines into lines of 340 characters, where two characters form an original word. During the A/D conversion, the channels are multiplexed in such a way that corresponding words are separated in the file line by a number of words equal to the number of channels being multiplexed.

The complicated method used to produce the required data makes the process difficult to use and extremely time consuming. Also the many variable gain amplifiers subjected to involuntary or unnoted changes make the process unreliable.

The principal purpose of our procedure is to test some features and to analyse the frequency spectrum of the signals by using the data processing and plotting capability of the Amdahl computer. If care is not taken during the

complete procedure, the final results can become extremely questionable.

Discusson

The cumbersome process the data goes through was necessary to achieve a proper data processing with the Amdahl computer. The process is intended to be performed later by a microprocessor-based system. This independent processing system will have excellent reliability and relative speed in processing the colonic pressure signals. Despite all the care that was taken in this cumbersome process, some data proved unreliable.

VI. PRESSURE RECORD ANALYSIS

Some features repesentative of the colonic motility, together with some other features, can be used in pattern recognition for disease identification.

Though the colonic pressure does not have a one to one relation with the colonic movements, it is an easily measurable variable.

A. USE OF FFT

To find the distribution of signal power as a function of frequency for the colonic electrical and pressure data, the Fast Fourier Transformation (FFT) method [15,16] was used and implemented on the Amdahl computer. This metod reduce the processing time considerably. In Appendix 1.1 the FFT Fortran program is given, which was used as a subroutine (SUBROUTINE FFT).

Data processing

The data, before going through the DFT, went through some changes to avoid undesired effects in the resulting power spectrum (PS). Pressure data has a large dc component compared with the ac component. If this dc is not previously removed, in the corresponding PS the dc will dominate and the ac will be abased by its presence. The electrical data however is recorded using ac coupling which eliminates the dc component directly.

To achieve the dc removal, the average value for the record of N samples to be used in the PS evaluation is determined, and substracted from each one of the N samples. This gives a negligible component at zero frequency in the PS. This average value is stored, since it is used in the later feature evaluation.

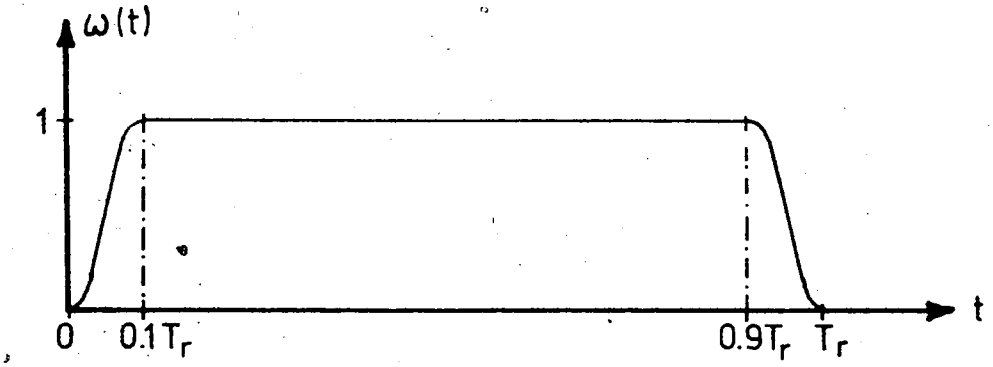
Each record-section used to evaluate the PS also goes through a transformation to avoid leakage effects. The leakage effect is generated by the use of a finite record in the FFT; the data record-section is chosen looking through a finite rectangular window. The leakage effect is reduced by the use of a more appropiate window, with small or non-existent spectrum side-lobes. The rectangular window is the most well known one which corresponds to the direct truncation of the data before specific processing. This rectangular window is defined by

$$w(t) = A\ [\ u(0) - u(T_r)\ ] \qquad (1)$$

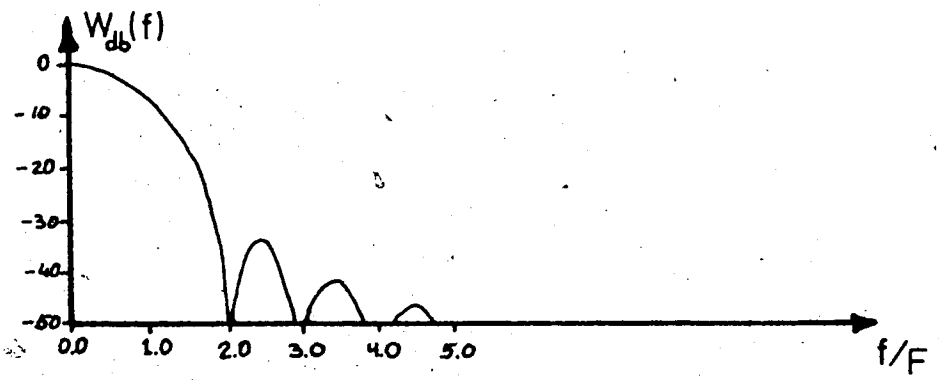
and the Fourier transform of this window is given by

$$W(f) = A\ T_r\ \mathrm{sinc}(\pi \cdot f \cdot T_r) \qquad (2)$$

The use of the rectangular window gives a periodogram with excessive side lobes. Instead, a Hanning window was selected and used as shown in Figure 7a. This window is easy to implement and gives good leakage reduction (Figure 7b).



(a)



(b)

Figure 7. a) Hanning window used.
b) Hanning window spectrum.

The Hanning window used is given by

$$\omega(t)=\begin{cases} 1/2\left[1-\cos\frac{\pi\cdot n}{0.1\cdot N}\right] & 0\leq n\leq 0.1\,N \\ 1{,}0 & 0.1\,N\leq n\leq 0.9\,N \\ 1/2\left[1-\cos\frac{\pi(N-n)}{0.1\cdot N}\right] & 0.9\,N\leq n\leq N \\ 0 & \text{otherwise} \end{cases}$$

The Hanning window gives a good leakage reduction. In Appendix 1.2, the Fortran implementation for this window is given (SUBROUTINE TAPER).

Limitations of the use of the FFT

As indicated before, the colonic pressure has almost all its power in the frequency band below 10 cycles per minute. A sampling frequency of 1.0081 sam/sec. (60.48s/min.) becomes acceptable to avoid aliasing, since it is about six times the highest frequency component of the sampled signal. This gives a folding frequency on the periodogram of

$$f=f_s/2=60.484/2=30.24 \text{ s/min} \qquad (4)$$

Now, a compromise has to be found between the record length and the periodogram resolution. Colonic frequency components change with time both in frequency and in power. This suggests the use of a short record of N samples to capture the instant frequencies, but on the other hand if N is small the resolution achieved in the periodogram becomes poor.

The actual number of samples N used to evaluate the pressure periodogram was N=256 which gives a record length of 4.23 minutes with a sampling period of $T_s'=0.992$ sec. (every other normal samples). All data was sampled with a sampling period of $T_s=0.496$ sec., referred to as the normal sampling period.

In special cases 512 samples were used with a record length of 8.46 minutes or N=256, using every second sample which gives a sampling period of $T_s'=1.984$ sec. Also record-section lengths of 6.35 min. and 256 samples were used, with a sampling period of three times normal or $T_s'=1.488$ sec. This last case allows a better resolution at low frequencies if the record lacks high frequency components. For electrical data, a normal sampling period of $T_s=0.496$ sec. was used with a record-section of N=256 and 512 samples.

The use of the FFT in this case obviously has some limitations. Since frequency components change with time, short records have to be used, and by doing this very low frequency components are missed or compressed into a few

spectral lines. The PS's fundamental frequency $f_0 = f_s/N = 1/T_s * N$ gives the distance between spectral lines. This is of the order of $T_0 = 4.23$ min. for a sampling frequency of $f_s = 60.48$ s/min. and a record of N= 256 samples. This limitation can be partialy ovecome by the use of a padded record. To an actual record of N samples, N more points are added with a value equal to zero, as shown in Figure 8. This produces a virtual record with a total number of 2N points. This yields a fundamental frequency in the spectrum that is half of what it would be if only N points were used. The addition of these extra points has the effect of interpolating the spectrum. The original record-section used is still the same one, so the information is also the same. The padded records were used only in those cases as it became advisable.

On the other hand, the colonic electrical activity has frequency components higher than the colonic pressure, for which the normal sampling frequency of $f_s = 1/0.496$ s/sec. was used (double that usually used in the pressure).

As mentioned before, electrodes generally have a long term drift which can be seen as a low frequency noise. To avoid this "noise" ac coupling is used in the first stages, before the FM recording, thus getting rid of the dc and very low frequency components. Since dc and very low frequencies were removed, there was no need to use a long record to determine the periodogram. What is more, a short record was needed to have good spectrum resolution at higher

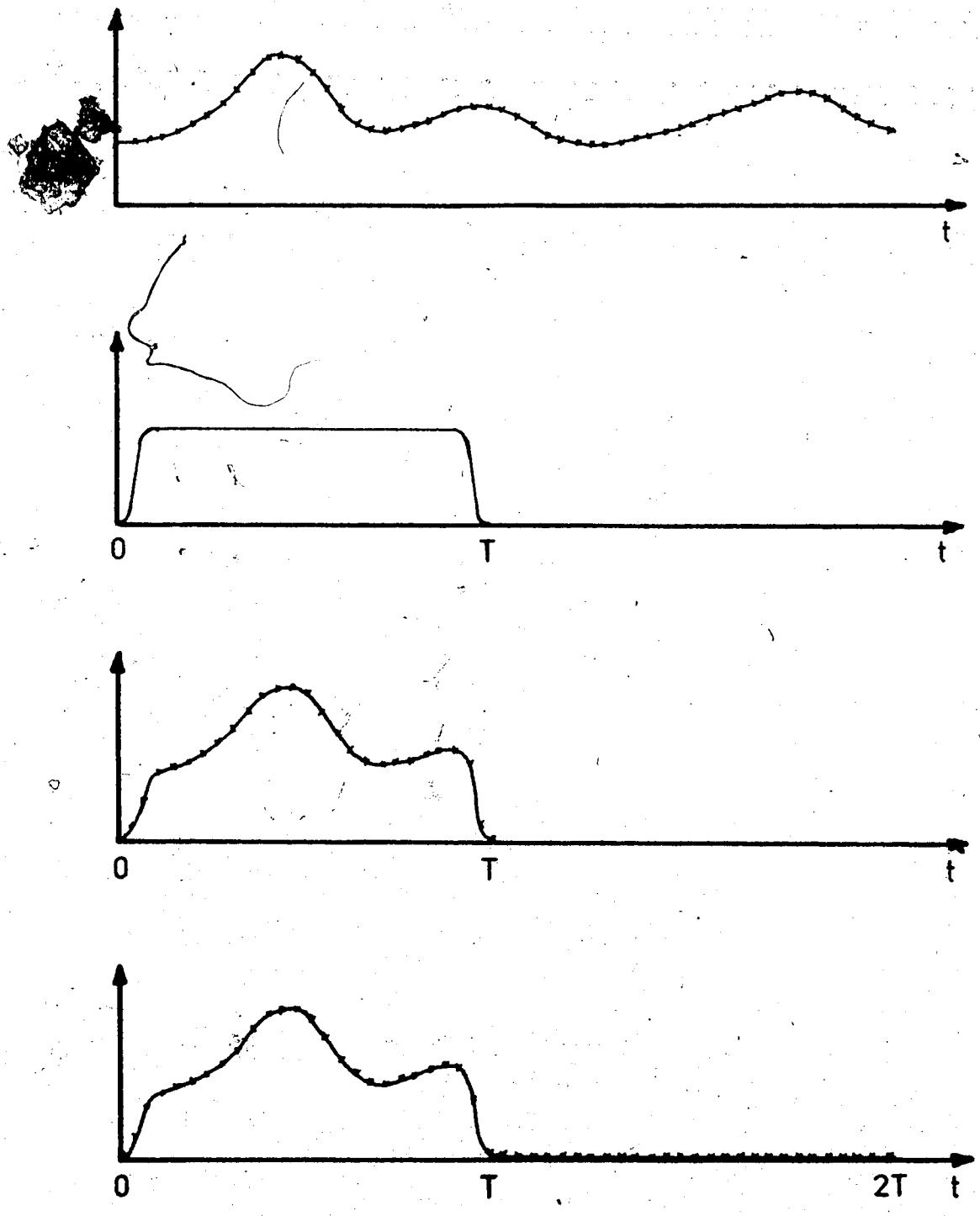


Figure 8. a) Original sampled signal. b) Window used.
c) Data after the window. d) Final padded record.

frequencies, but the sampling frequency limits the maximum number of samples that can be used for a fixed record length.

B. A NON-STATIONARY PROCESS

It was mentioned before that frequency and power distribution of pressure and electrical signals change with time. Since that a nonstationary process is present, the choice of a record segment that is representative of the whole signal is a difficult decision. This record segment will be used later to generate aperiodogram, and hence to obtain some features representative of the colonic activity.

Figure 9 shows the power spectrum of the colonic pressure recorded in channel 1 (tip location: 15 cm.). The data used to evaluate the periodogram corresponds to 256 samples with a fs=1.0081 s/sec. Figure 10 shows an average of several successive overlapped periodograms of the same data used in Figure 9.

It becomes evident from Figure 9 that a single periodogram gives a precise picture of the frequencies present in the record-section used, while the averaged periodogram gives a picture of the complete record but the frequencies present are also to some extent averaged frequencies. In the last case the precise frequencies can not be obtained, since they are changing with time generating lobes placed near their own central frequencies. In the case where frequency components remain constant,

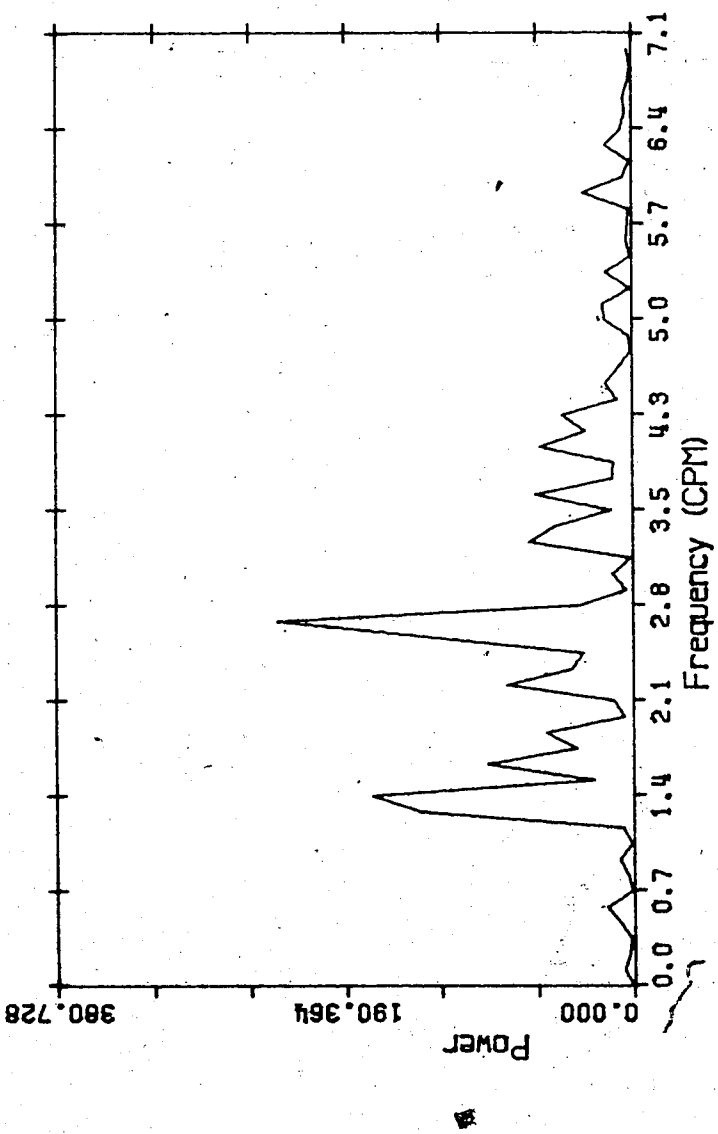


Figure 9. Periodogram(file D61-ch1).

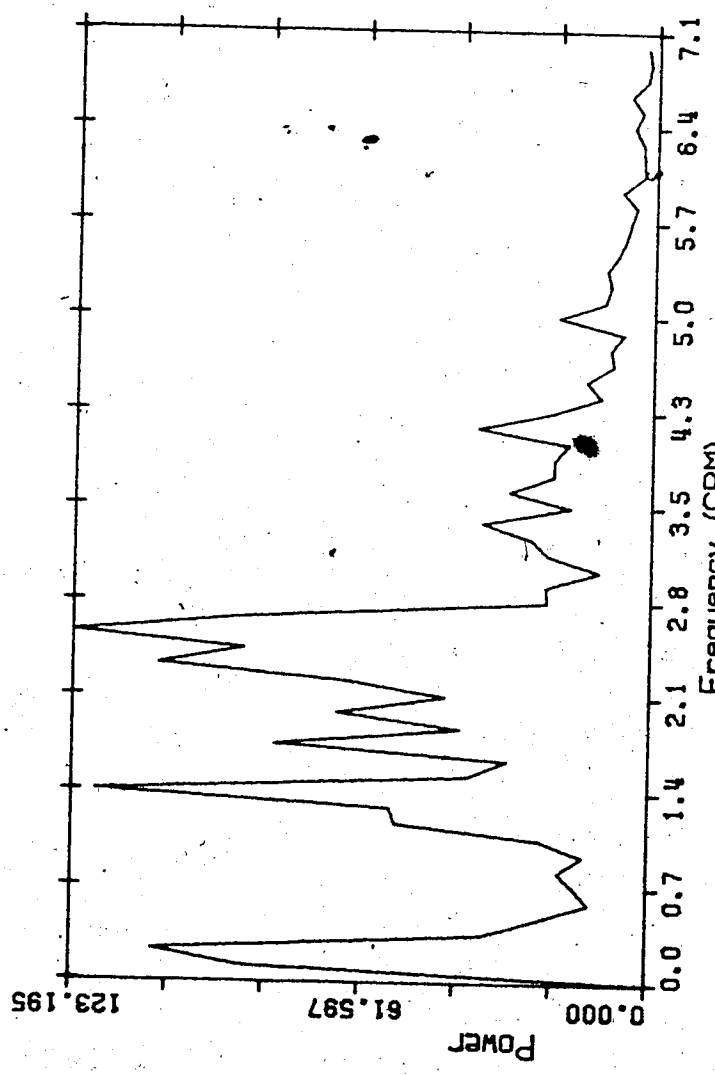


Figure 10. Averaged periodograms (file D61-ch1).

changing only their power with time, a considerable difference between the averaged PS and the single PS will still exist. It is evident that the use of the maximum power in the averaged PS is useless as a feature for pattern classification. This will be considered later.

C. THREE-DIMENSIONAL PLOTS

A better approach to this time varying process is the use of successive PSs to form a three-dimensional plot (3-DP). The coordinates for the 3-DP are power, frequency and time.

Figure 11 shows a three-dimensional power spectrum plot (3-DPSP) for the same data as in Figure 9 and Figure 10. The PSs used in the 3-DPSP are generated by record-sections overlapped (in time) by 1/4 of the record-section length.

A schematic representation of the successive overlapped record-section is given in Figure 12. Since the shape changes of two successive PSs is considerable, interpolation of two PS between successive PSs was done. This interpolation in time was carried out between two successive spectrum line components of two successive PSs. New PSs can be determined and placed instead of the interpolated PSs. Due to the considerable time and cost required to evaluate each PS, interpolation of PSs is an acceptable alternative to use. The nearest power spectra, determined using entirely different data, will lie 12 PSs apartin the 3-DPSP. The interpolated power spectra are included in this number.

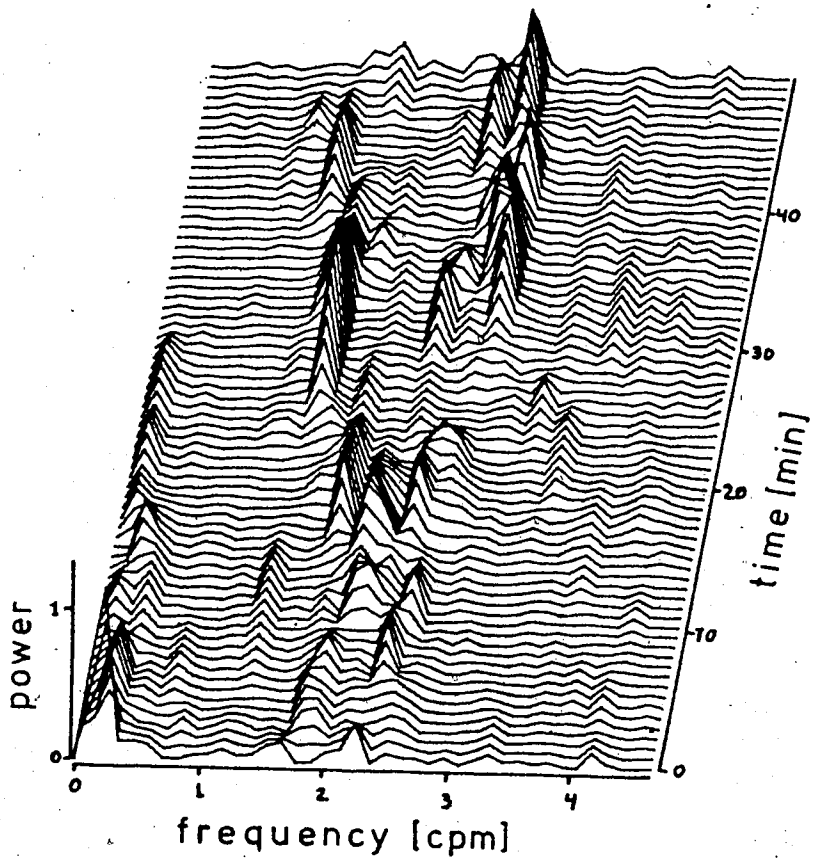


Figure 11. 3DPSP (file D61-ch1). Frequency components can be followed as a function of time.

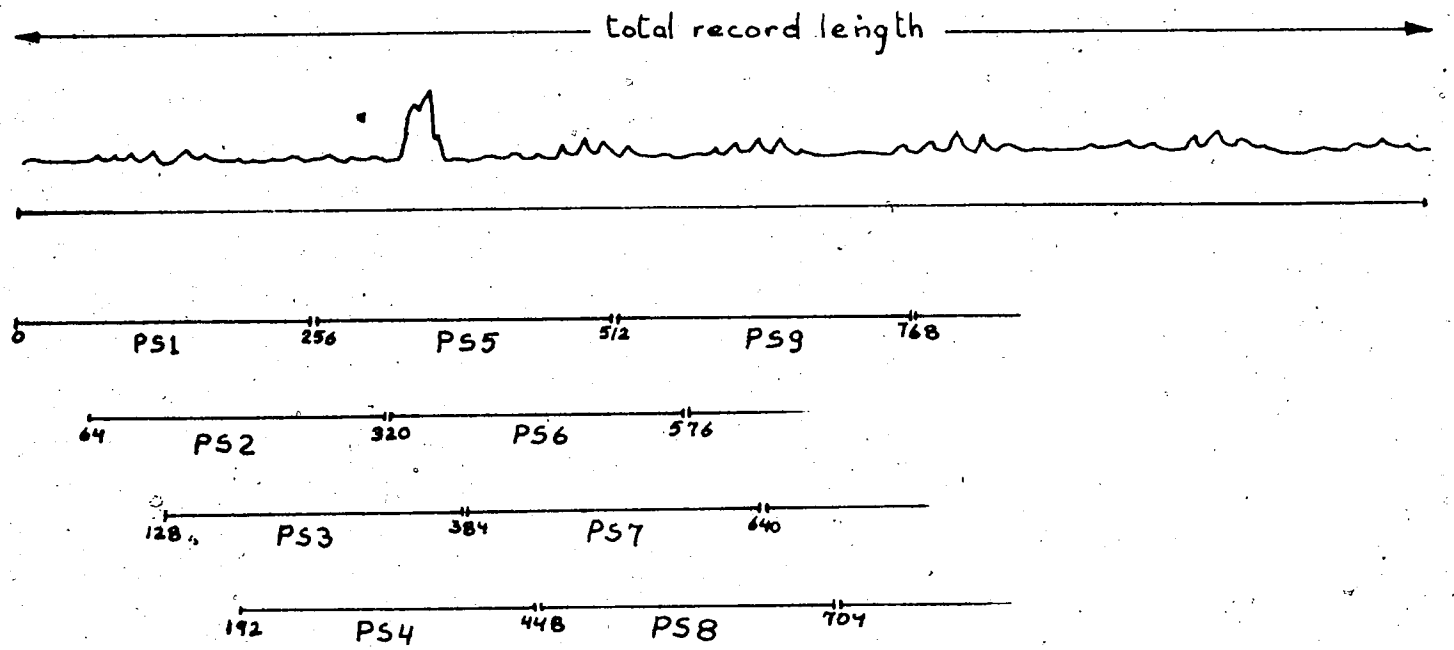


Figure 12. Sucessive overlaped record sections used to evaluate the corresponding power spectrum.

The 3-DPSP has a time coordinate. This time indicates the instant at which the record-section for the given PS starts. Using Figure 12 as example, the first PS is placed at 0 minutes, but it actually uses the first 4.23 minutes of the record to be evaluated; the second PS is placed at 0.2 minutes, and so on.

Interpretation of 3-DP has to be done with caution. For example, in the 3-DP there is a maximum for a given frequency and time, this time is the time where the record-section for that particular PS starts, and not that forwhich the frequency has a maximum power at that particular time. Rigorously, that peak in power is the average power of that frequency during the record-section starting at that particular time.

Usually in pressure records there is some noise caused by movements of the patient, coughing, etc. This noise is characterized by a burst in pressure of short duration, generally present simultaneously in all channels. The appearance of this burst in the 3-DPSP is confusing, since it shows up with considerable energy for a long period of time, usually in a wide frequency band. That is, the burst energy is present in at least twelve successive PSs of the 3-DPSP, which in time can be much longer than the real burst duration. This can be explained using Figure 11. This figure illustrates a record with a burst at sample number 350 and the successive record-section used to evaluate the PSs. The interpolated PSs are not considered here. The burst of

energy will be included in four PSs, namely, PS3, PS4, PS5 and PS6. If the interpolation is now included, the burst will be included in the 12 successive PSs. Figure 13a and 13b show two 3-DPSP of pressure data of the same patient taken at the same time but from different channels. Allthough the signals are clearly different, the noise is present in both channels generating the same spectrum. Figure 14a and 14b show the presence of noise in electrical 3-DPSP, where the noise is in the two channels generating the same spectrum. The causes for electrical burst or noise were already analyzed.

The same data, using different lengths of record section lengths to evaluate the PSs, give different 3-DPSP in power and to some degree in frequencies. This will hold true for data originated by a nonstationary process. As will be shown later, for stationary processes, the number of samples (N) or more precisely the length of the record-section, affects the frequency and to some extent the power of the PS.

Very low frequency components (periods longer than the record-section used) will show up in the PS together with the dc components of the signal. Consequently, their specific frequency can not be determined fr m a single PS, but they do show up in the 3-DPSP w th double the frequency. The derivative of these component will appear as dc power in the direction of the time axis. The derivative appears in the 3-DPSP with half the period of the original signal (for

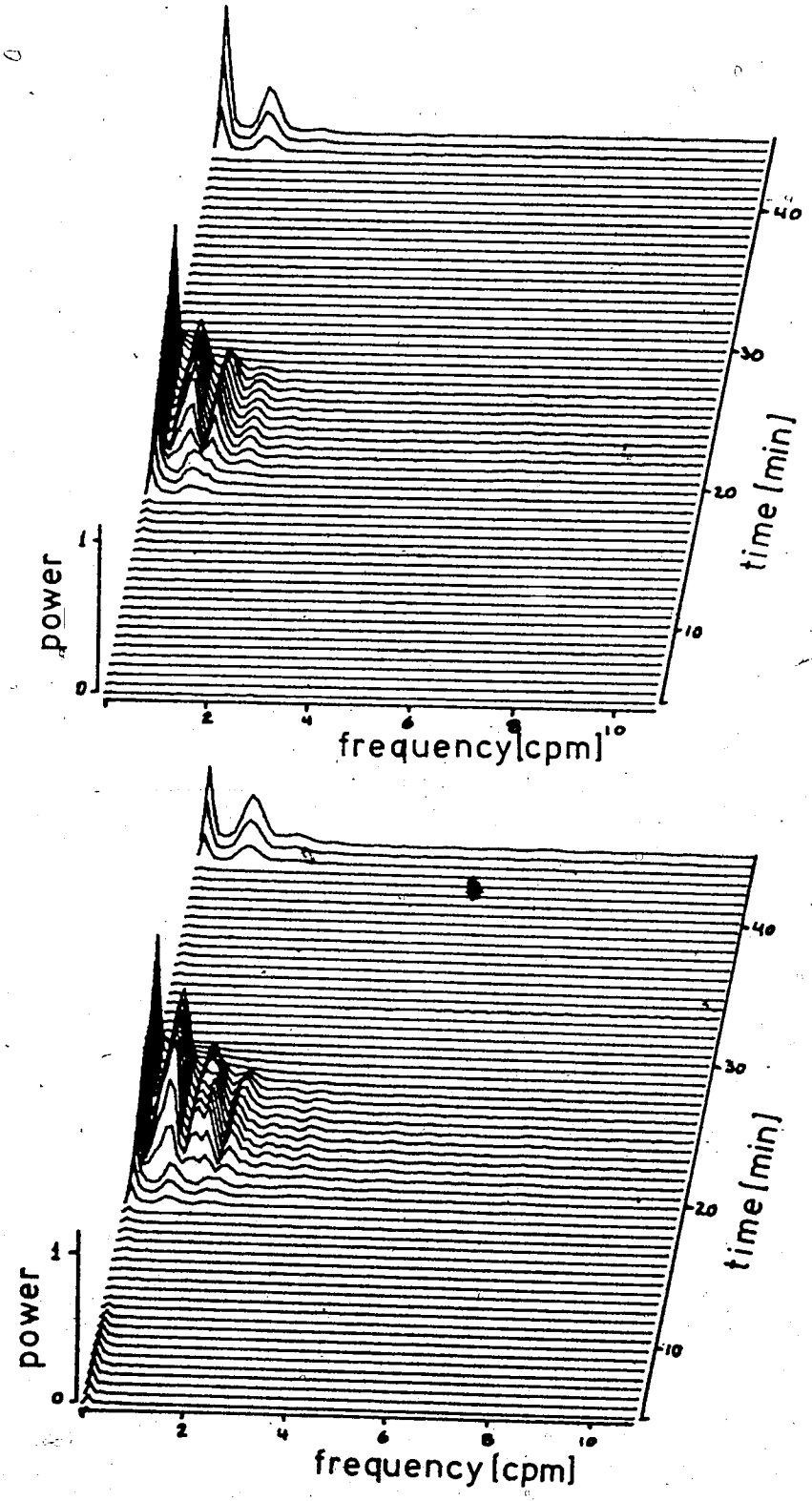


Figure 13. a) Presence of a noise burst on pressure channel 1.
b) Presence of a noise burst on pressure channel 2.
(file D36).

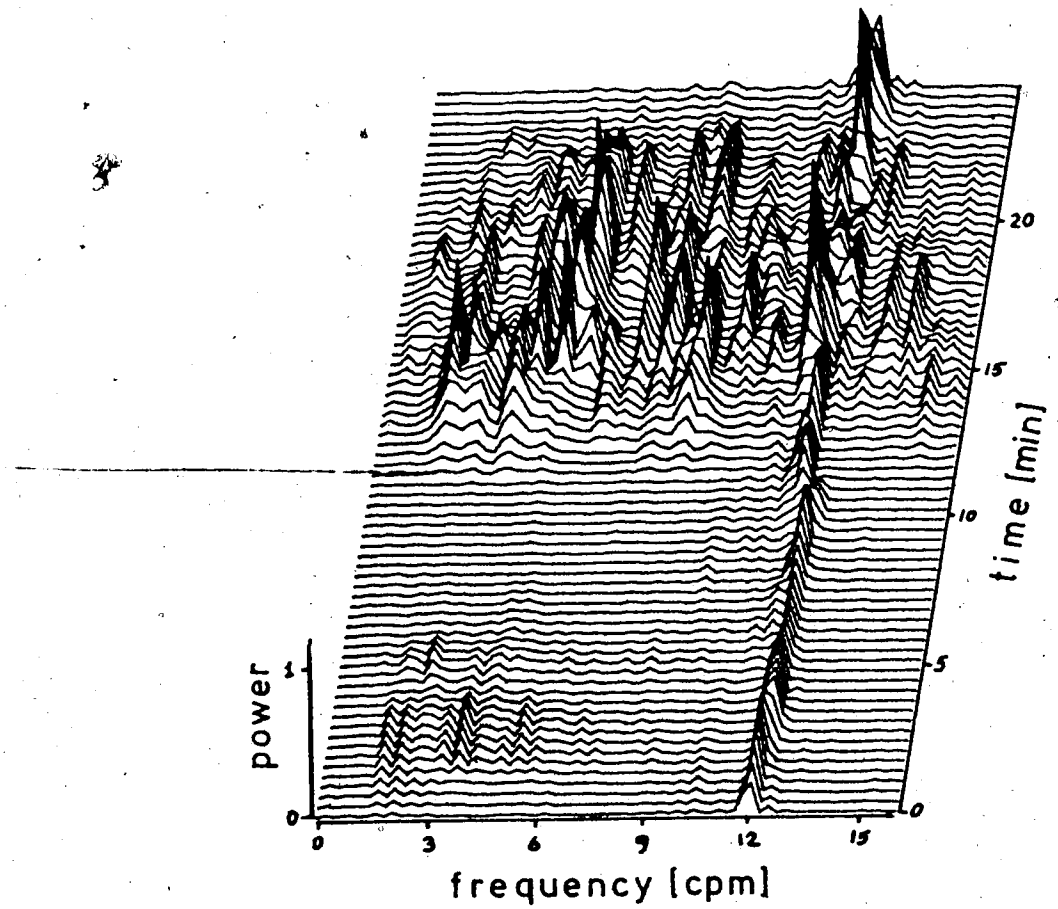


Figure 14. a) Presence of noise on electric channel 1. (file D60).

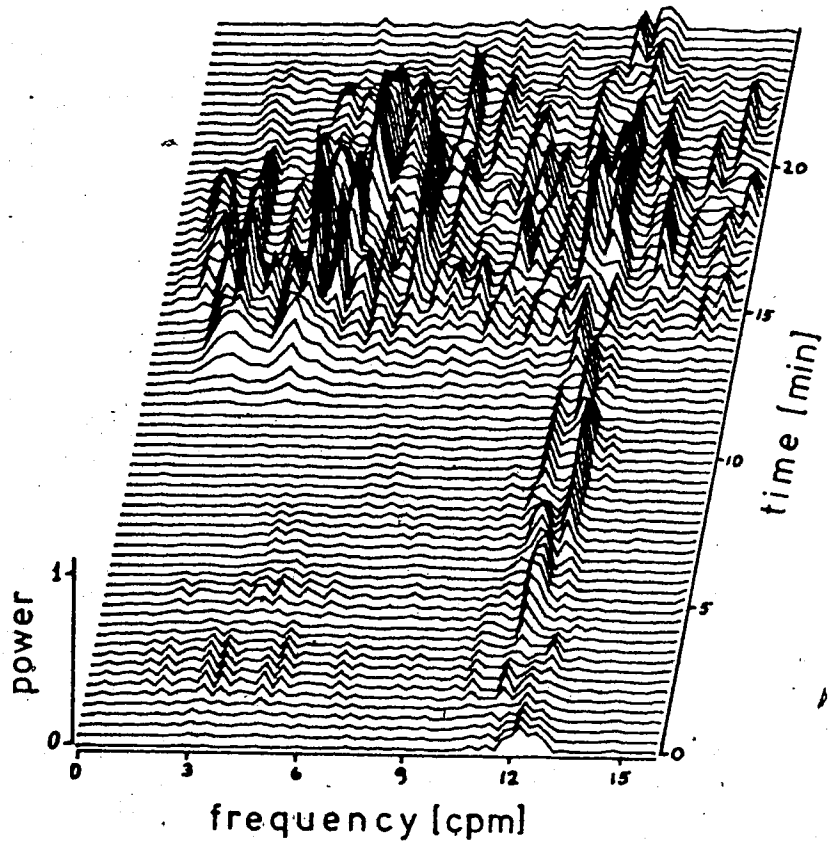


Figure 14. b) Presence of noise on electric channel 6. (file D60).

a single very low frequency), but its power will not be the true power.

The 3-DPSP allows a simple and fast analysis in one picture of the power and frequencies present on records of 1 or 2 hours duration.

D. USE OF CORRELATION

At first sigth, the use of cross-correlation seems promising when used with electrical and pressure records. In fact, the determination of the relative signal phase or phase shift by using cross-correlation can give inconsistent results when dealing with time varying signals. For two signals in phase, zero phase shift and variable amplitude, cross-correlation maxima will not be necessarily at zero phase.

Phase computation can be consistent, using cross-correlation only, if it is done with a simultaneous visual inspection of the record used to choose a convenient record-section. And still in this case where the phase shift is φ, it can not be decided if it is realy φ or $\varphi+2n$, where n can be any integer. Nevertheless, auto-correlation gives good results in determining the fundamental period of signals by averaging its zero crossings. This fundamental period usually becomes very close to the one found by using DFT. Correlation is a simple technique to be implemented with a dedicated microprocessor, compared with the implementation of the DFT from where the fundamental

component can also be obtained.

The use of auto-correlated band-pass-filtered data gives better results than unfiltered data. Higher and lower frequency components than the fundamental one produce "noise" when a zero crossing count is being performed. It is proper to do a zero crossing count of filtered and auto-correlated data, when the fundamental frequency component of the signal does not go out of the filter's band and all channels are filtered identically.

E. USE OF BAND PASS FILTERS

As was mentioned before, filtered data is useful to determine the fundamental frequency component of the signal. Also, as will be discussed later, it is important to evaluate the average signal power in a certain frequency band. This can be done in two ways. First, by computing the power in the frequency band from the PS, or second by computing the RMS of the band pass filtered data. If the computations are done with a dedicated microprocessor, the RMS value of filtered data is a practical method to use.

IRR BP Filter Design

A digital band-pass filter was designed using the Infinite Impulse Response method [15,16]. The bilinear transformation allows the design of a BPF with a frequency response similar to a reference analog filter. The bilinear transformation operates on an analog LPF to generate a

discrete BPF as shown in Figure 15.

If s is the digital final Laplace variable and p the analog low-pass prototype Laplace variable, the desired digital transfer function H(z) is obtained by replacing p in terms of z.

The bilinear transformation relating the prototype variable p and the discrete variable z is given [15,16] by

$$p = D\left[\frac{1 - Ez^{-1} + z^{-2}}{1 - z^{-2}}\right] \tag{5}$$

where

$$D = \Omega \cdot \cot\left[\frac{T}{2}(w_3 - w_1)\right] \tag{6}$$

$$E = 2\,\frac{\cos\left[\frac{T}{2}(w_3 + w_1)\right]}{\cos\left[\frac{T}{2}(w_3 - w_1)\right]} \tag{7}$$

where:

Ω = analog low pass reference radian frequency (cut off frequency in analog LPF)

w_1 = lower radian frequency of digital band-pass filter corresponding to $-\Omega$ in the analog low-passfilter

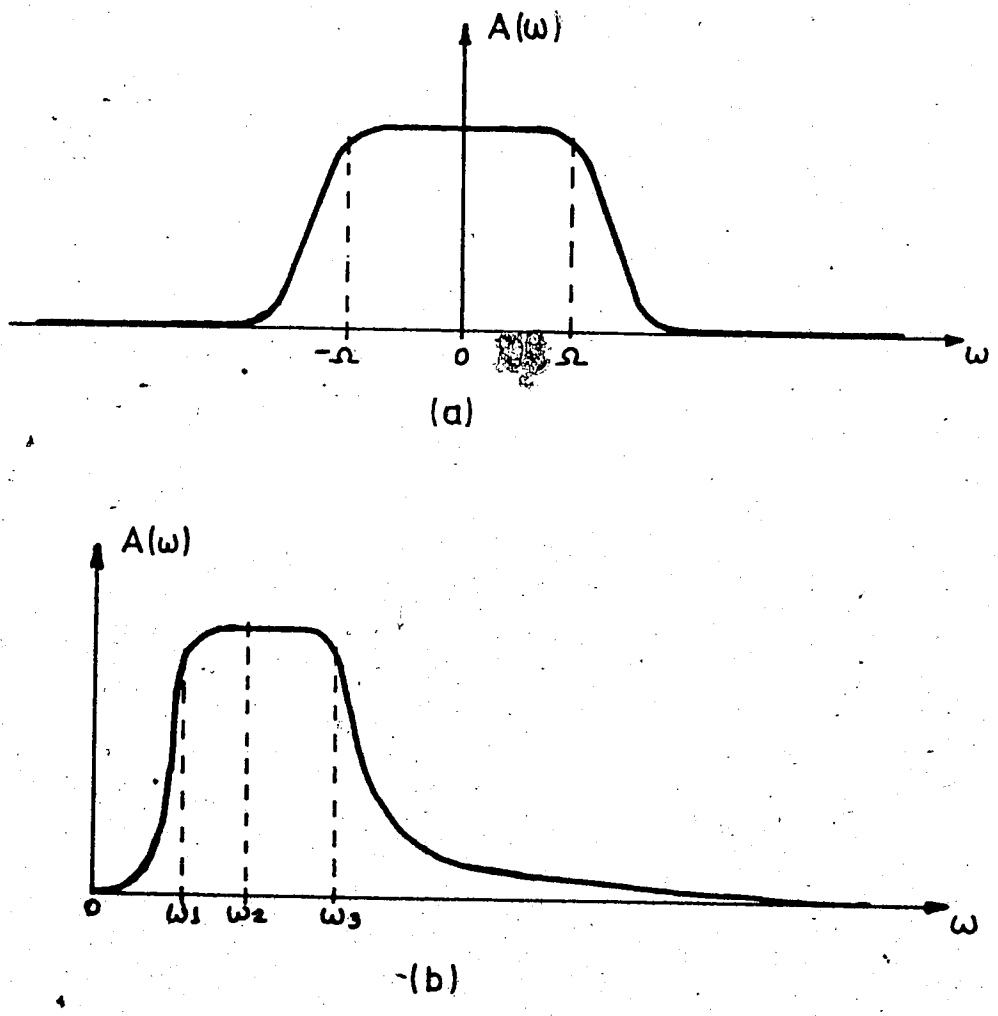


Figure 15. a) Analog LP filter frequency response.
b) Digital BP filter frequency response.
The bilinear transformation of IIR filter design method relates the analog LPF prototype with the digital BPF.

w_2 = radian central frequency of digital band-pass filter.

w_3 = upper radian frequency of digital band-pass filter corresponding to Ω_{min} in the analog low-pass filter.

Once the bilinear transformation is computed, the digital band-pass transfer function H(z) is determined from the analog low-pass filter function G(p) by the relationship

$$H(z) = G(p)\Big]_{p=D\left[\frac{1 - E z^{-1} + z^{-2}}{1 - z^{-2}}\right]} \qquad (8)$$

which gives a number of poles (or filter order) for the band-pass filter that is twice that of the low-pass filter.

A third order Butterworth LPF was used as the analog prototype filter. Third order was needed to compensatethe distortions in the resulting digital filter, introduced by the bilinear transformation. This distortion show up as different roll-off slopes, the steepest one at low frequencies. The LP third order Butterworth filter is given by

$$G(p) = \frac{1}{1 + 2p + 2p^2 + p^3} \qquad (9)$$

with a normalized cut-off frequency of Ω= 1 [rad/sec]. For a sampling frequency of f_s=1/0.496=2.016 s/sec, a center frequency of 0.053Hz=3.18c/min and a band-width of 0.056Hz = 3.36 c/min, eq. 6 and 7 yield the values of D= 11.4308 and E= 1.9730.

As defined in Eq. 5, the analog low-pass prototype Laplace variable becomes

$$p = 11.4308 \left[\frac{1 - 1.9730\, z^{-1} + z^{-2}}{1 - z^{-2}} \right] \qquad (10)$$

The desired digital BP filter transfer funtion H(z) is computed by Eq.8 where G(p) is given in Eq.9 for a third order LP Butterworth filter, and by replacing p in G(p), which gives

$$H(z) = \frac{5.62187 * 10^{-4} \quad (1 - z^{-2})^3}{1 - 5.575\, z^{-1} + 13.029\, z^{-2} - 16.338\, z^{-3} + 11.591\, z^{-4} - 4.4156\, z^{-5} + 0.70507\, z^{-6}} \qquad (11)$$

This H(z) has 6 poles located at

P1 = 0.912559 + j 0.214281

P2 = 0.974819 - j 0.077281

P3 = 0.974820 + j 0.077281

P4 = 0.912559 - j 0.214281

P5 = 0.910504 + j 0.100462

P6 = 0.910504 - j 0.100462

Filter implementation

The filter implementation is intended to be done on a microprocessor-based machine using a word length of either 8 or 16 bits. If the filter is realized in the direct or canonical form, an 8 or 16 bit word is not enough to avoid sensitivity problems. Therefore an equivalent cascade configuration of second-order filters was chosen which improves this sensitivity problem. In this specific design the z-plane poles lie very close to the unit circle, therefore the sensitivity problem can be severe if it is not carefully considered.

The cascade form yields

$$H(Z) = A*H1(z)*H2(z)*H3(z)$$

where $A_0 = 5.62187\ 10^{-4}$ (13)

$$H1(z) = \frac{1 - z^{-2}}{1 - 1.825117\, z^{-1} + 0.878680\, z^{-2}} \quad (14)$$

$$H2(z) = \frac{1 - z^{-2}}{1 - 1.949638\, z^{-1} + 0.956246\, z^{-2}} \quad (15)$$

$$H3(z) = \frac{1 - z^{-2}}{1 - 1.821007\, z^{-1} + 0.839109\, z^{-2}} \quad (16)$$

Figure 16 shows the cascade realization of the digital BP filter. The pole location in the z-plane is shown in Figure 17. Since the pole location is symmetrical with respect to the real axis, only the positive imaginary half of the z-plane is plotted. In this half z-plane lie three of the six poles.

The amplitude and phase response of the filter as a function of frequency are shown in Figures 18a and 18b respectively. The digital BP filter is a distorted image of the analog LP filter, as was mentioned before; it has a good and sharp rolloff at low frequencies but a poor one at the high frequencies. However, the filter is sufficiently narrow to warrant the band power evaluation.

F. ZERO CROSSING

For pressure and electrical activity of the colon, it is interesting to determine if the signals from different channels are phase-locked, and to know the relative phase shift between the these signals. As discussed before cross-correlation is not a reliable method to use for this purpose, if the two signals are "time varying". Zero-crossing [17] will give good results as long as the frequency component with the main power is the same during the whole intervalwhere zero-crossing is being performed. The other frequencies contribute only with "noise", from the zero-crossing point of view.

The use of BP filtered data introduces some errors in

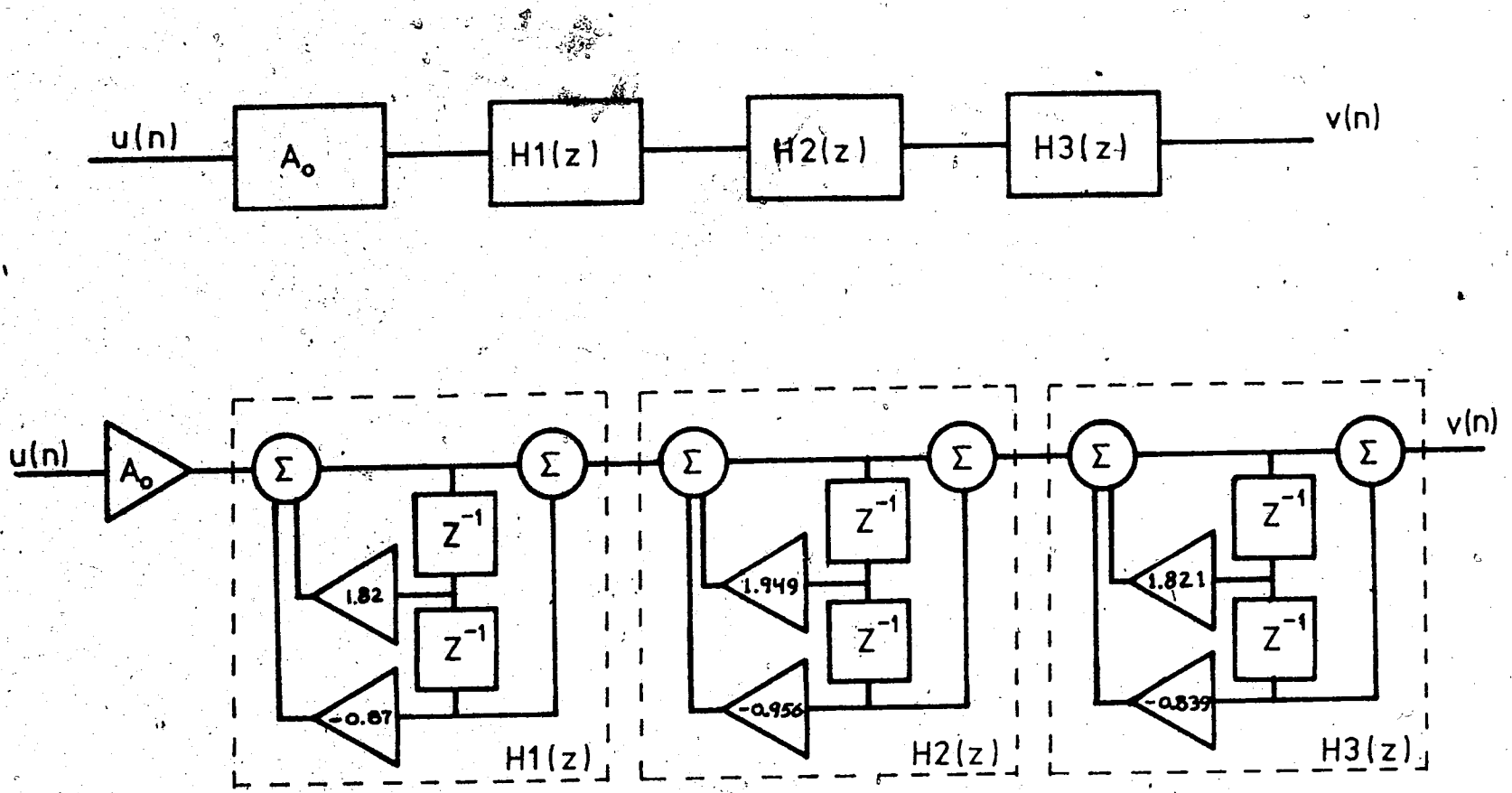


Figure 16. BP digital filter cascade realization.

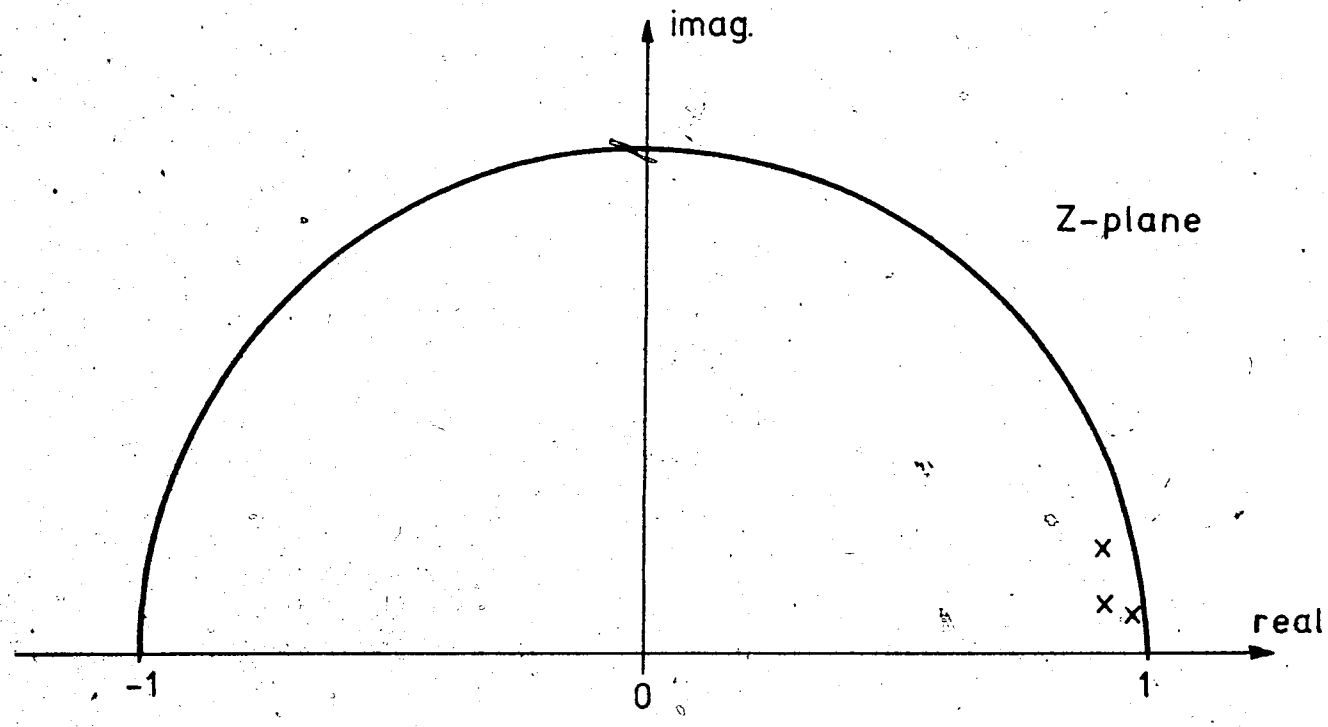


Figure 17. BPF pole location in the z-plane.

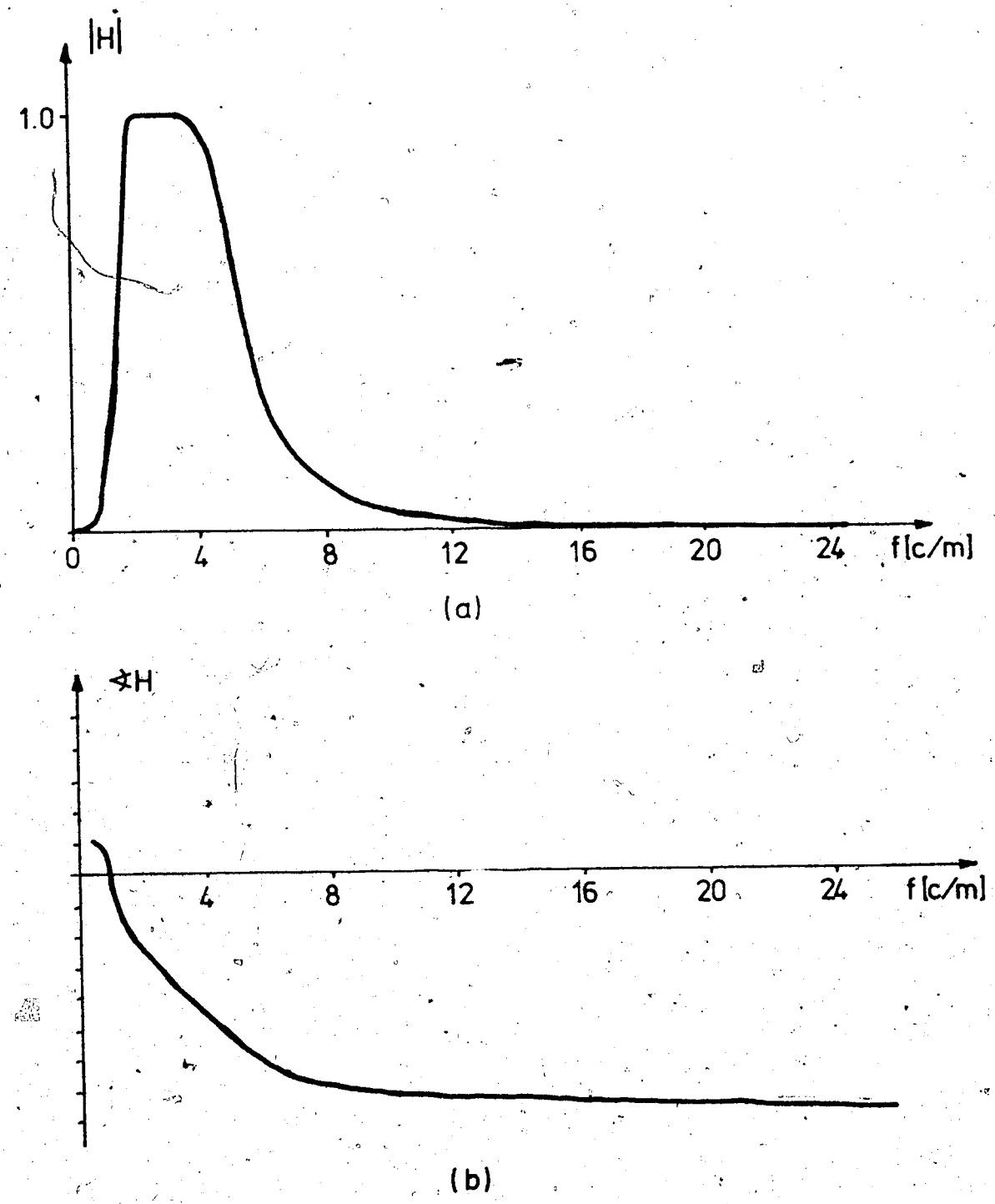


Figure 18. a) BP digital filter amplitude response.
b) BP digital filter phase response.

the computation of the phase shift between two signals when the zero-crossing method is used. A BP filter eliminates the dc components, which is necessary when the data is used for zero-crossing analysis. Also the filter abases the undesired frequencies leaving only the ones in the band that are of interest to the computation of the phase shift. However, if the signal has time-varying "noise" added to it with frequency components within the filter's band, the zero-crossing would yield erroneus phase information due to the phase response of the filter. On the other hand, the use of unfiltered data will also produce distorted zero-crossing readings. The use of the zero-crossing method with filtered data can be reliable, providing that the signal is constant in frequency components, which means frequency components with constant relative amplitudes and constant phase. This condition is seldom satisfied completly for the amplitudes, as can be seen in different 3-DPSPs throughout this work.

VII. ELECTRICAL RECORD ANALYSIS

The mechanical motion of the smooth muscle in the colon is closely related to its electrical activity. The interpretation of the colonic electrical activity is of great importance to understand the mechanical behavior of the colon. With this purpose in mind, "in vivo" and "in vitro" electrical colonic activity have been recorded largely while the specimen or the patient was under the effects of drugs. Drugs alter the normal electrical and mechanical activity of the smooth muscles, and they are used widely as a powerful tool to study muscle behavior. "In vivo" and "in vitro" recording procedures were mentioned in earlier chapters.

Electrical activity frequency components also change in amplitude and frequency with time. This demands special care in the signal analysis using FFTs. The result of averaging successive overlapping FFTs reduces the effects of noise but the changes in time can not be seen. Rather they produce lobes, the width of which depend on the magnitude of their changes.

In the case where the signal power spectrum has harmonics, generally these harmonics also change with time as the fundamental does and generate lobes too. These extra lobes may be centered at the harmonics frequencies, but not necessarily, since the center depends on the changes of the individual harmonics. This can lead to a missinterpretation of the lobe as if there were other frequencies present not

related to the fundamental component. The average of several successive overlapped power spectrums of electrical signal is shown in Figure 19. Here the small lobes can not be easily associated with harmonics.

The use of three-dimensional power spectrum plots (3-DPSP) allows visualization of the frequency changes (fundamental and harmonics) with time. The same data used for Figure 19 is used now to generate the3-DPSP of Figure 20. In this figure, it can be seen clearly that the harmonic "follows" the fundamental component in its changes, and that it is not an "independent" frequency (independent in the sense that it has a different frequency behavior as a function of time, so its origin is in a different source).

A simulation of the actual electrical signal waveform was done to help the identification of harmonics and understand their behavior.

A. SIGNAL SIMULATION

Single source

Figure 21a shows a typical electrical record. In the simulation of this signal an approximation was done by successive sinusoidal cycles followed by a silent period, as shown in Figure 21b.

$$G(f) = \sum_{-\infty}^{\infty} C(nf_0)\, e^{j2\pi nf_0} \qquad (17)$$

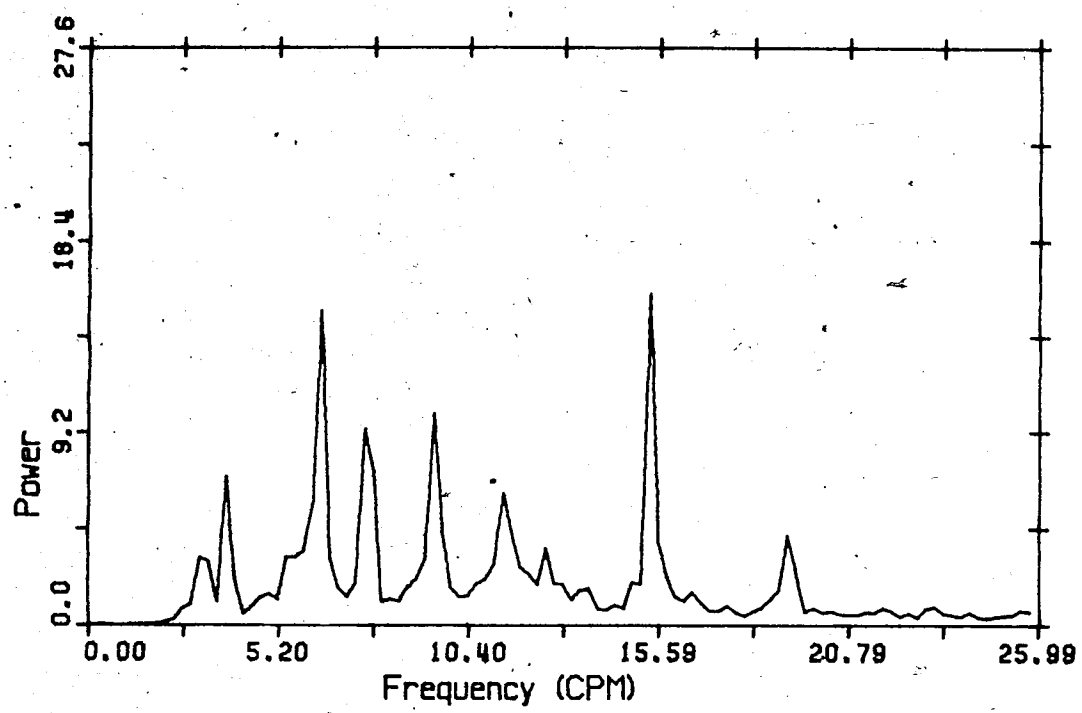


Figure 19. Average of successive power spectrums. Because of the averaging, the lobes are not clearly associated with harmonics (file D48 ch2).

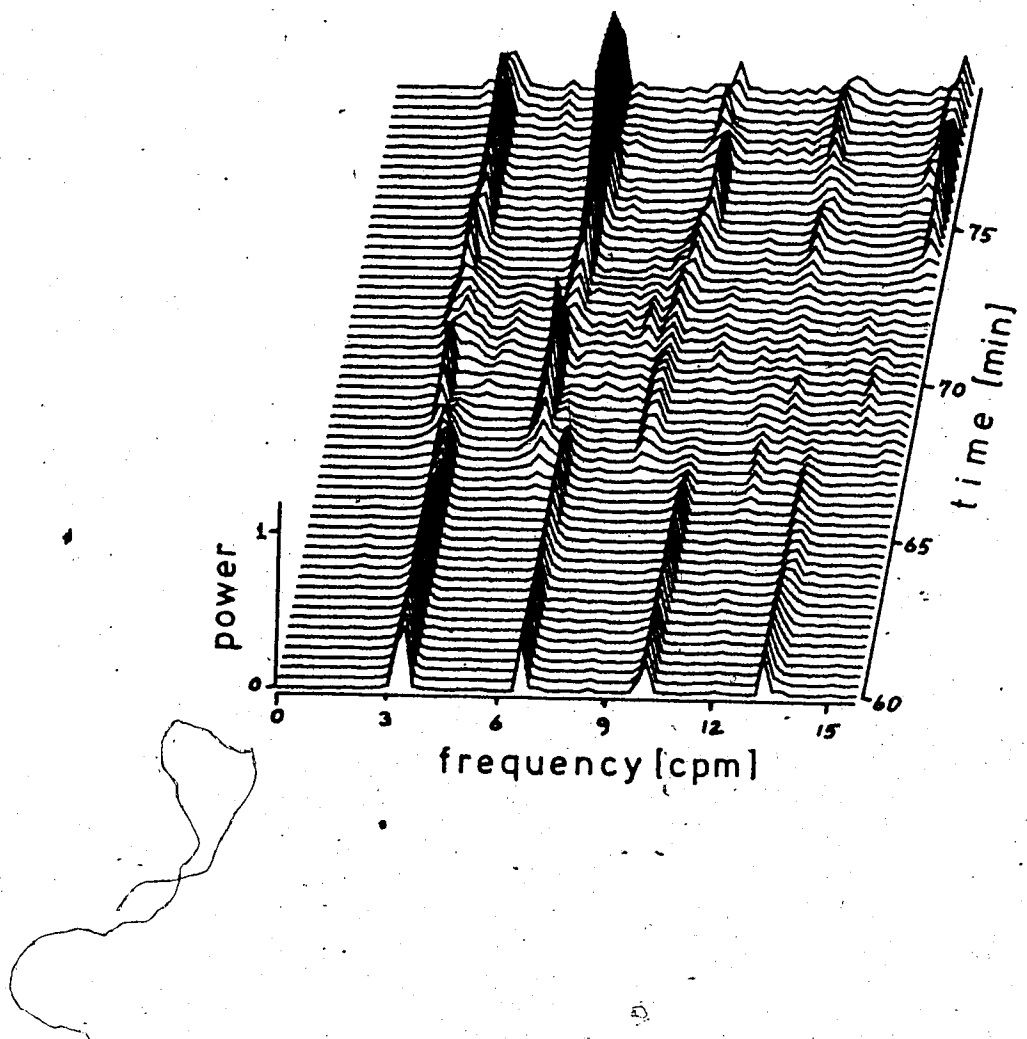


Figure 20. 3DPSP for the same data used in Figure 19. The harmonics "follow" the fundamental changes. (file D48 ch2)

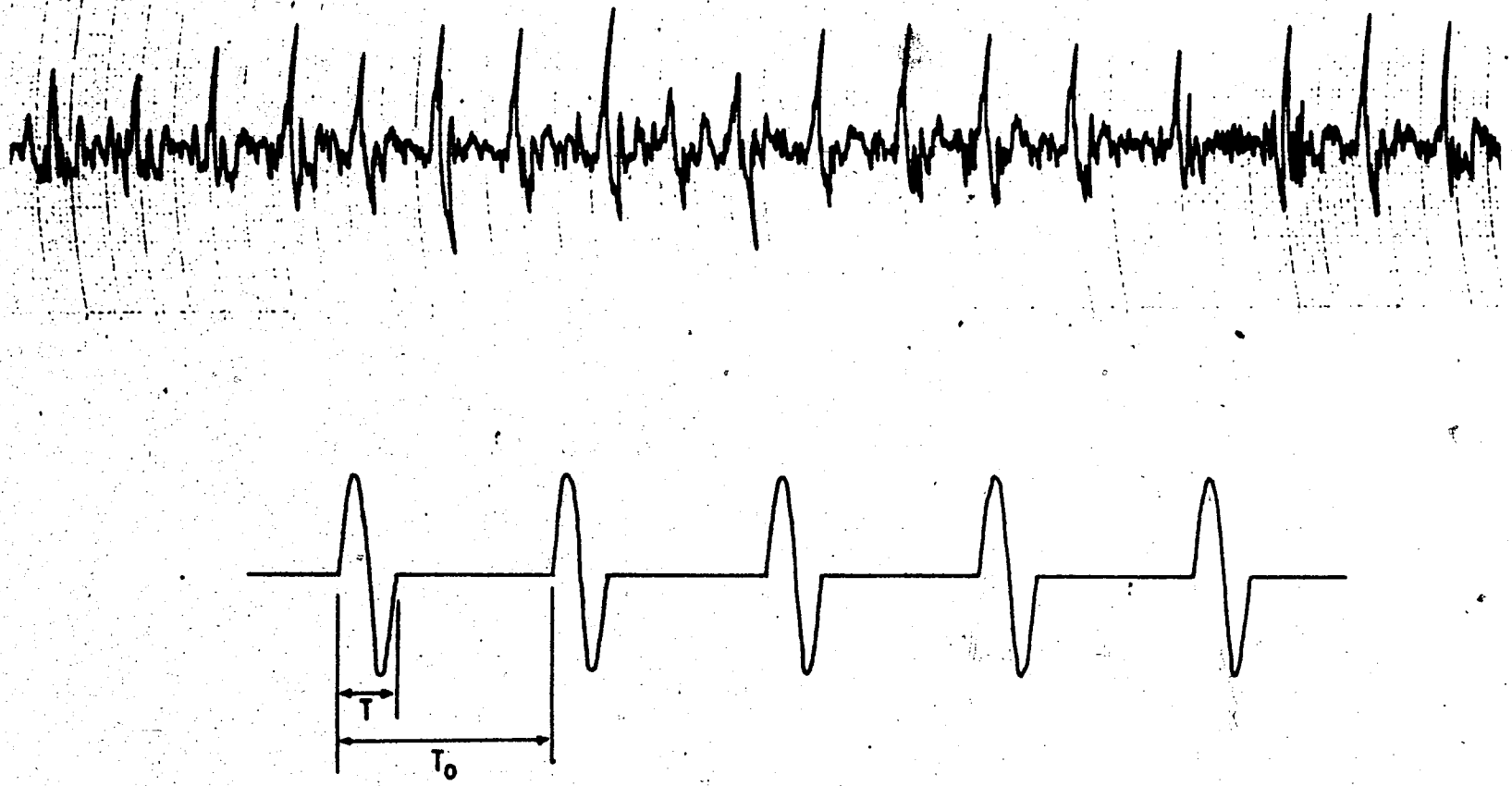


Figure 21. a) Typical electric signal.
b) Simulation of the electric signal.

$$C(nf_0) = \frac{1}{T_0}\int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} v(t)\, e^{-j2\pi n f_0 t}\, dt \qquad (18)$$

$$= \frac{1}{T_0}\int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} A \sin\left[\frac{2\pi t}{T}\right] e^{-j2\pi n f_0 t}\, dt$$

$$= \frac{A}{2}\left[\frac{\sin\pi(2f - nf_0)T}{2\pi(2f - nf_0)T_0}\right] - \frac{A}{2}\left[\frac{\sin\pi(2f + nf_0)T}{2\pi(2f + nf_0)T}\right]$$

$$= \frac{A}{4}\frac{T}{T_0}\left[\operatorname{sinc}(2f - nf_0)T - \operatorname{sinc}(2f + nf_0)T\right] \qquad (19)$$

In the simulated signal (Figure 21b), the period of interest is T_0. The period T varies from record to record and depends largely on the characteristics of the tissue-electrode interface. Different values of T with respect to T_0 yield different spectrum patterns, given by Eq. 19. A common relation for T and T_0, found in most of the electrical records is $T=T_0/2$. The simulated spectrum for this relation is shown in Figure 22, where the fundamental frequency becomes smaller in power than the harmonics. For

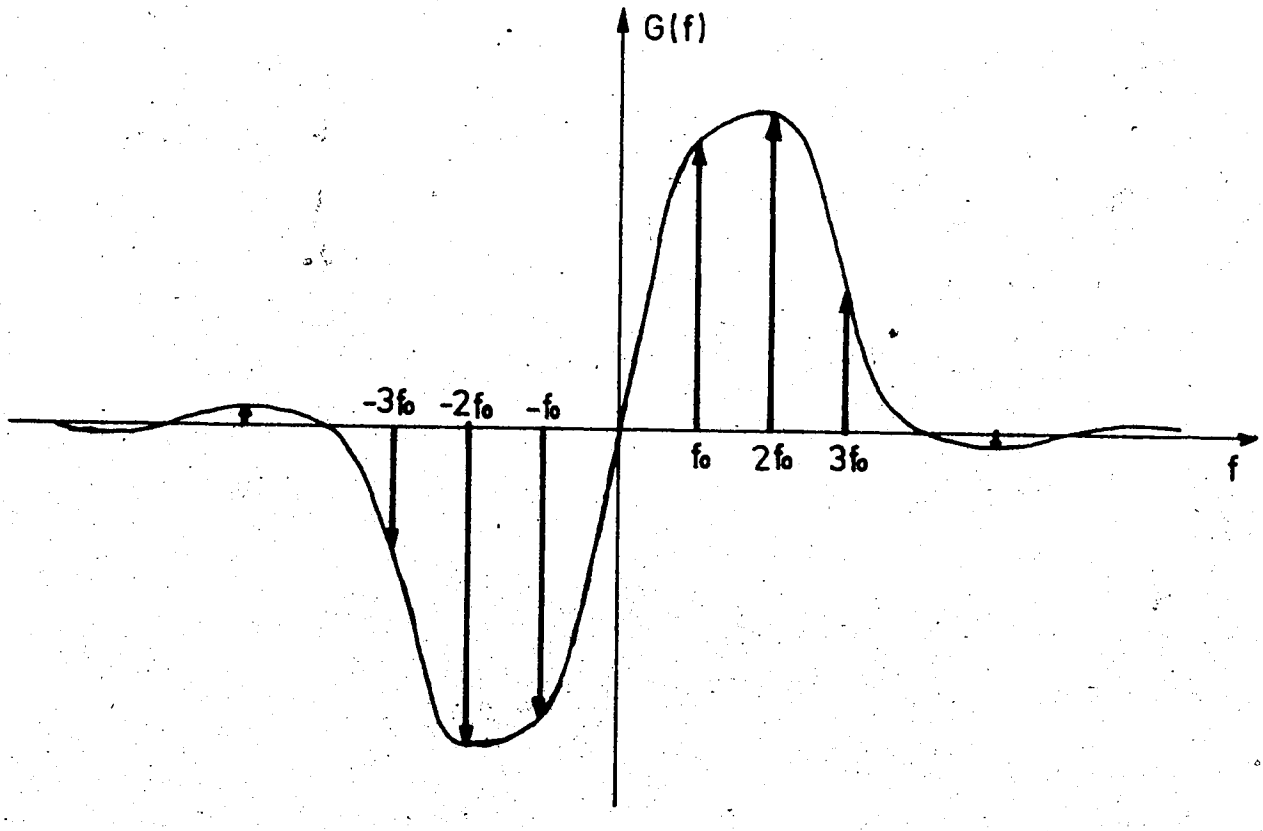


Figure 22. Spectrum for the simulated signal with $T=T_0/2$, given by Eq. 51.

$T=T_0$ its the case of a perfect sinusoid of frequency f_0, without harmonics. If T changes as a function of time, the spectrum of w(t) also changes, as shows the 3-DPSP of w(t) in Figure 23, where T at t=0 min is about $T_0/5$ and goes to $T=T_0$ at t=21 min. For this plot the factor $AT/4T_0$ af Eq.19 was left fixed.

Other records of colonic electrical activity such as the one shown in Figure 24a, have a wave form that can better be simulated by two sinusoidal cycles followed by a silent period as shown in Figure 24b. The spectrum components given by Eq.18 yield Eq.21 for this simulation.

$$C(nf) = \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} A \sin\left(\frac{2\pi t}{T/2}\right) e^{-j2\pi n f_0 t}\, dt \qquad (20)$$

$$= \frac{A}{2}\left[\frac{\sin\pi(2f - nf_0)\,T}{2\pi(2f - nf_0)\,T_0}\right] - \frac{A}{2}\left[\frac{\sin\pi(2f + nf_0)\,T}{2\pi(2f + nf_0)\,T_0}\right]$$

$$= \frac{A}{4}\frac{T}{T_0}\left[\mathrm{sinc}(2f - nf_0)T - \mathrm{sinc}(2f + nf_0)T\right] \qquad (21)$$

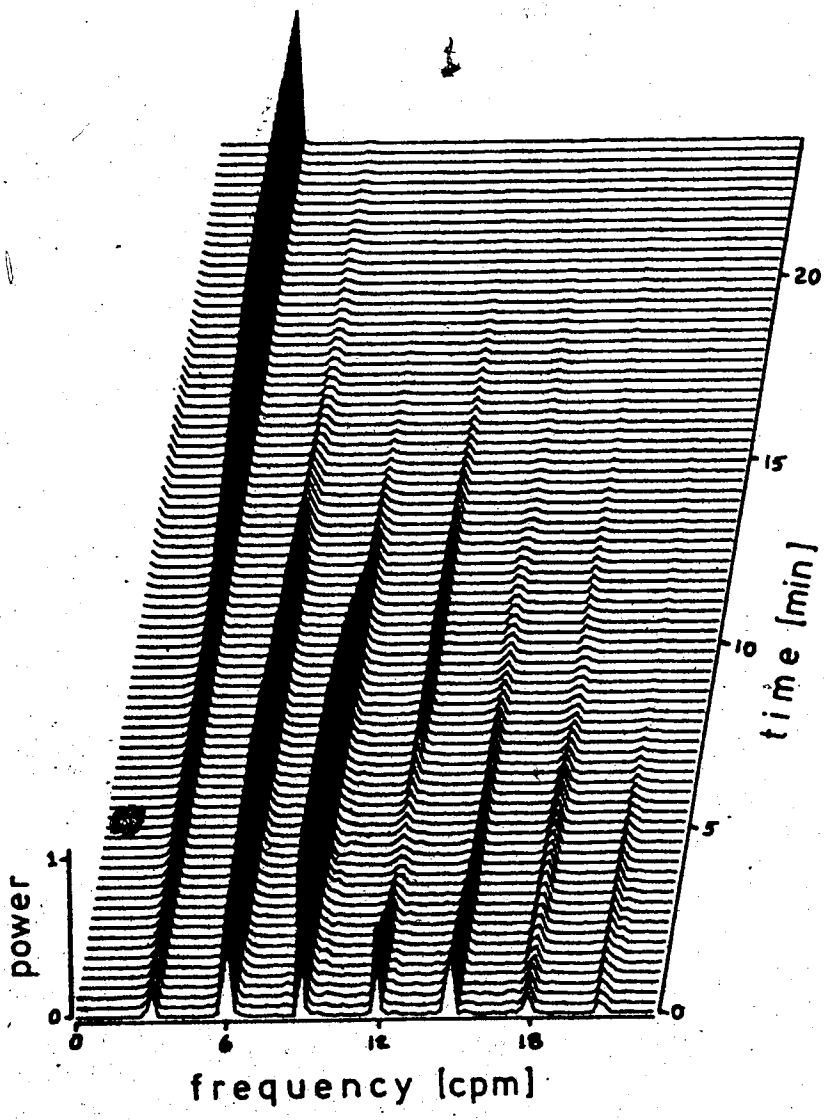


Figure 23. 3DPSP for the simulated signal with increasing value of T as a function of time.

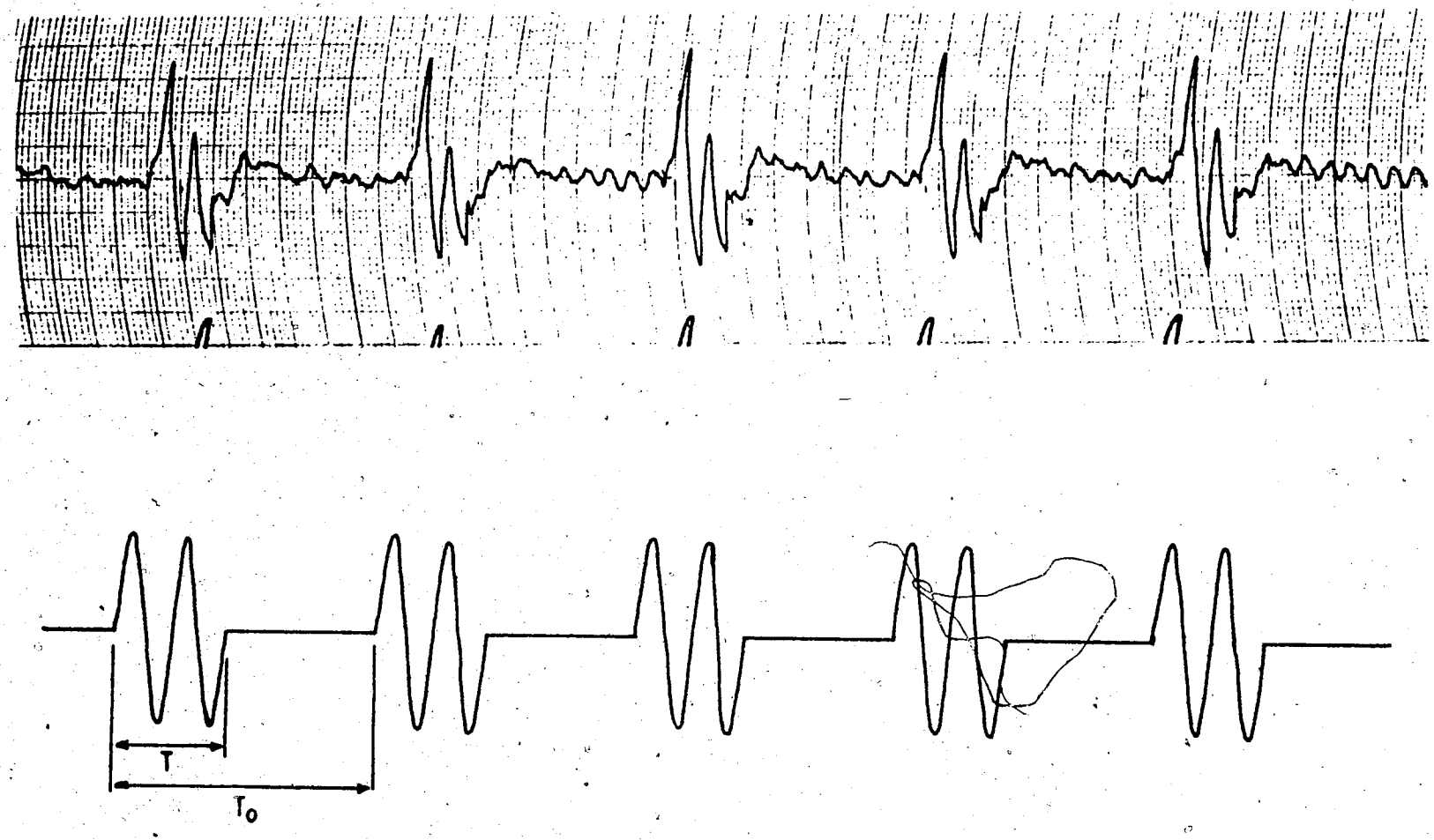


Figure 24. a) Colonic electric signal.
b) Simulated signal for a).

A value of $T=T_0/2$ ($fs=4f_0$), Eq. 21 gives the spectrum component plotted in Figure 25b. In the extreme case when $T=T_0$, the signal is again a clean sinusoid of frequency $2f_0$ (Fig. 25a). The 3-DPSP of this signal is shown in Figure 26, where T changes with time starting with $T=T_0/8$ at t=0 min. and ends with $T=T_0$ at t=21 min. It can clearly be seen that in some cases, as in this last simulation, the fundamental frequency component is not necessarily present in the PS, but it can be determined from it. Since the harmonics are positioned at a distance f_0 from each other, f_0 can be read from here instead of from the fundamental if it is not present. Later, records with all these characteristics will be analyzed.

Multiple-oscillators.

In some cases electrodes simultaneously record from independent oscillators. In these cases it is necessary to distinguish between two signals that can be of the same frequency or very close using PSs. In some cases these two signals are of the same frequency with a fixed phase shift but they can not be distinguished in the PS, since the signal phase is not well defined. The phase can be determined with the FFT but the results are useless if the frequencies involved are not perfectly stable.

What could happen in the case of fixed phase shift is to have a PS that looks like the one in Figure 27. Here the signal is similar to the one shown in Figure 21b. Now, this

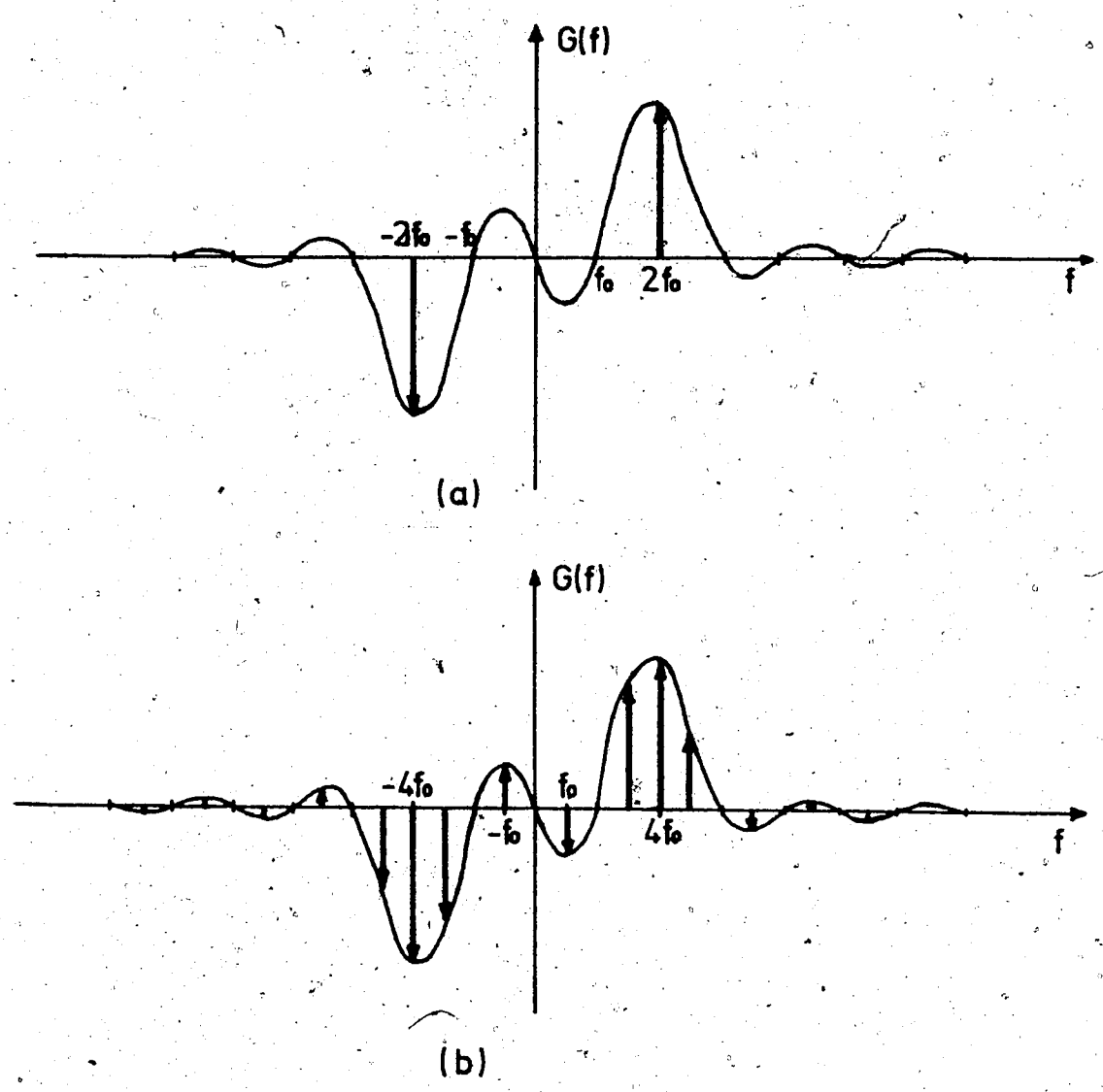


Figure 25. Spectrums of the simulated signals.
a) Signal with $T=T_0$ ($f=2f_0$)
b) Signal with $T=T_0/2$ ($f=4f_0$)

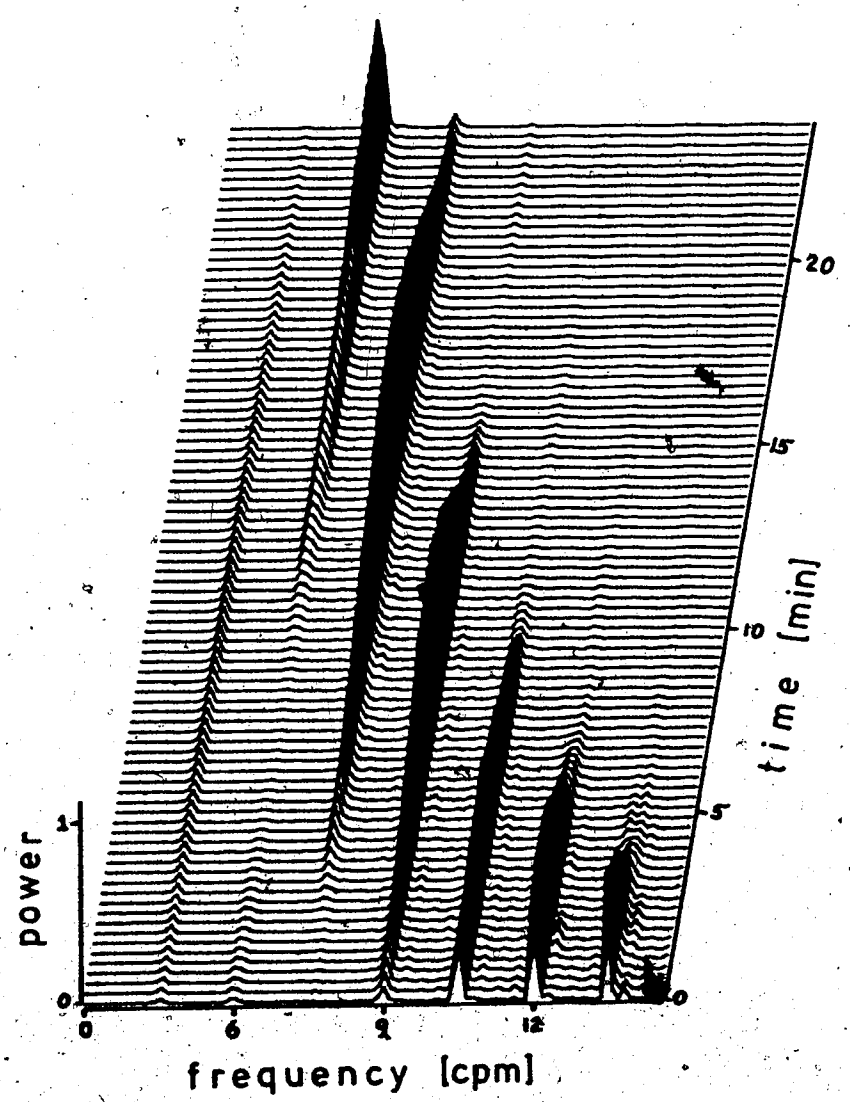


Figure 26. 3DPSP for the simulated signal with variable value of T as a function of time, and a fixed T_0.

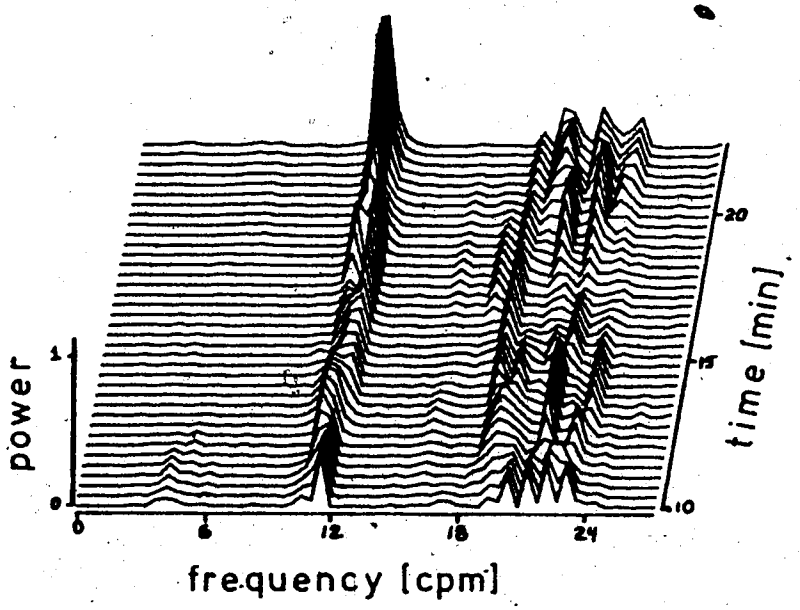


Figure 27. 3DPSP for two signals very close in frequency. (file D49 ch4).

kind of signal can be generated either by electrode distortion of the signal of a single oscillator or by recording from two adjacent oscillators that are phase-locked and have a constant phase shift. In cases like this nothing can be concluded from PS inspection. In other cases, when the electrode is recording signals that are generated in two oscillators of close frequency, other problems arise.

We will suppose that the signals generated by each of the oscillators are of the form simulated in Figure 21b. Figure 28 shows an electric record that looks as if it actually had two independent signals combined in a single record. The 3-DPSP shown in Figure 29 corresponds to the simulated signal, where the two frequencies are very close together. This graph was obtained by using sufficiently long record-sections for each PS which allows the two frequencies to "appear" as independent frequencies.

If the record-section used to evaluate each PS is less than the period of time it takes for the two signals to be in phase again, the 3-DPSP changes to that illustrated in Figure 30. If the actual oscillator's frequencies are very close together, the normal PS of the total signal would look very much like Figure 30. This effect is found in some actual electrical 3-DPSPs.

What the electrodes record from two oscillators would be not only the addition of their signals, but also some other relationship. The relationship will depend largely on

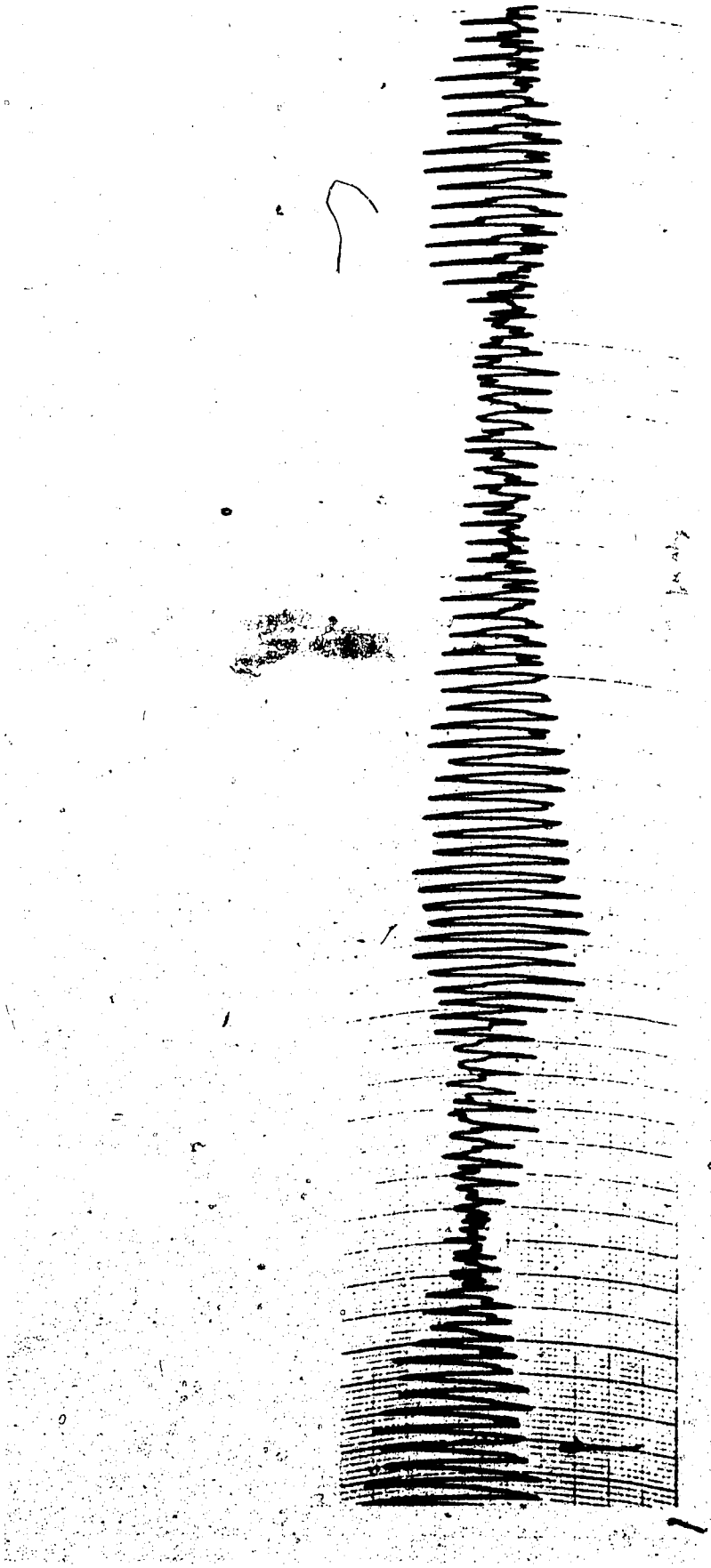


Figure 28. Electric record for two close frequencies.

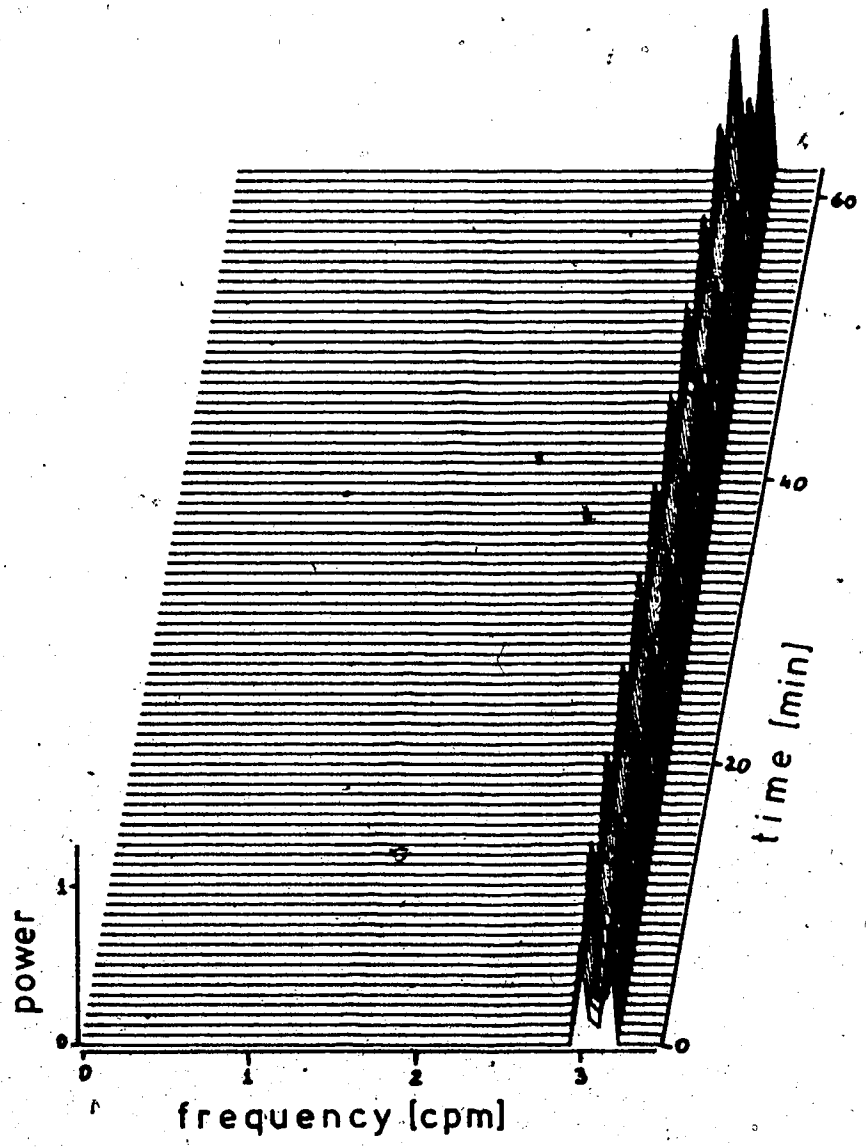


Figure 29. 3DPSP for a simulated signal formed by two close frequencies, using short records for the PS evaluation.

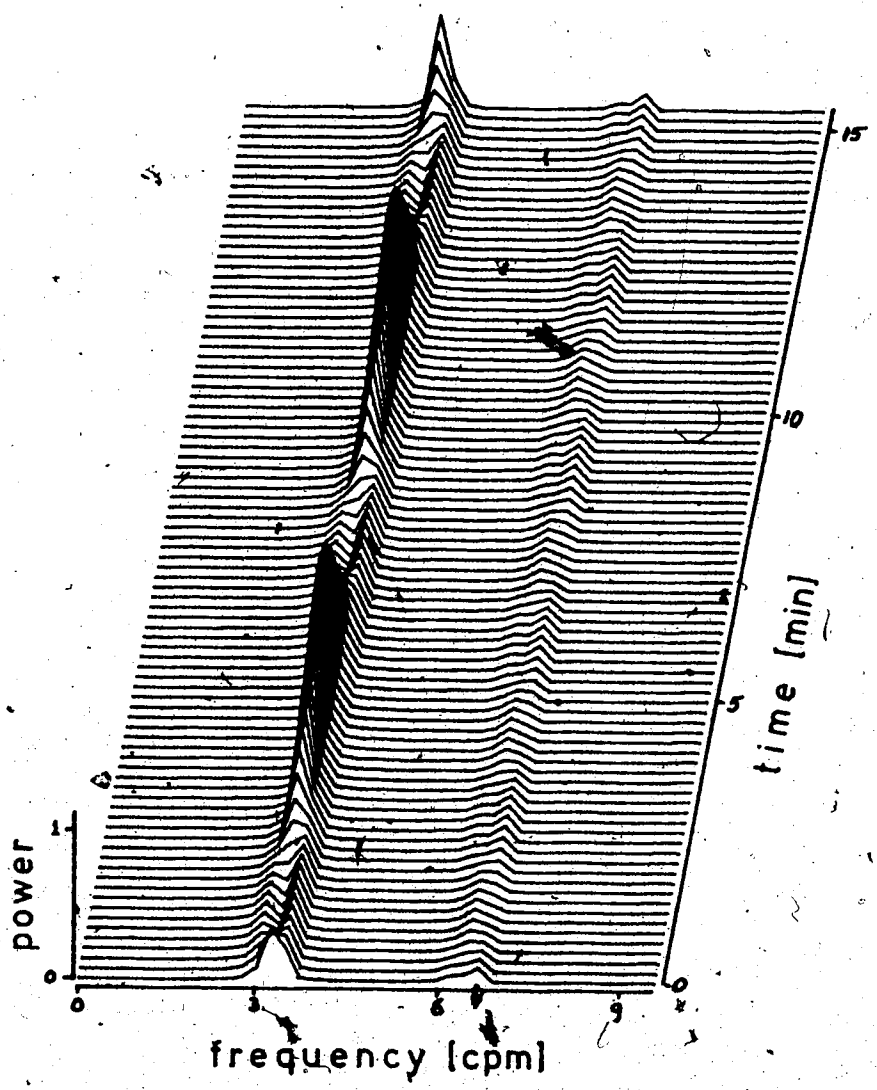


Figure 30. 3DPSP for two close simulated signals, using long records for the PS evaluation.

the electrode-tissue interface. This allows one to model of the resulting signal by

$$F(t)=aF1(t)+bF2(t)+cF1(t)F2(t)+dF1(t)F2^2+eF1(t)^2F2(t)+....$$

where the second and higher order components are deleted because they became insignificant. F1(t) and F2(t) are the signals generated by the two different oscillators.

We have already seen the simulation of F(t)=F1(t)+F2(t) and their 3-DPSP. Now if we look at the term F1(t)*F2(t), it generates different 3-DPSPs depending on the record-section length used. If the record-section is long enough the resulting PS is what one expects for a signal product. The 3-DPSP for the simulation of a product is shown in Figure 31, using a signal model as shown in Figure 21b. As expected, there are no frequency components at the original frequencies of F1(t) or F2(t), but some power appears near zero and other frequencies.

In the recording of the electrical signal, the dc and very low frequency components are removed by a BPF (ac coupling) so if in the PSs some power appears at dc or very low frequencies it means that the actual power at these frequencies is much larger. These frequencies can be generated by either the dc drift or the effect of multiplication of signals of different frequencies. The filtering makes it difficult to identify any component of

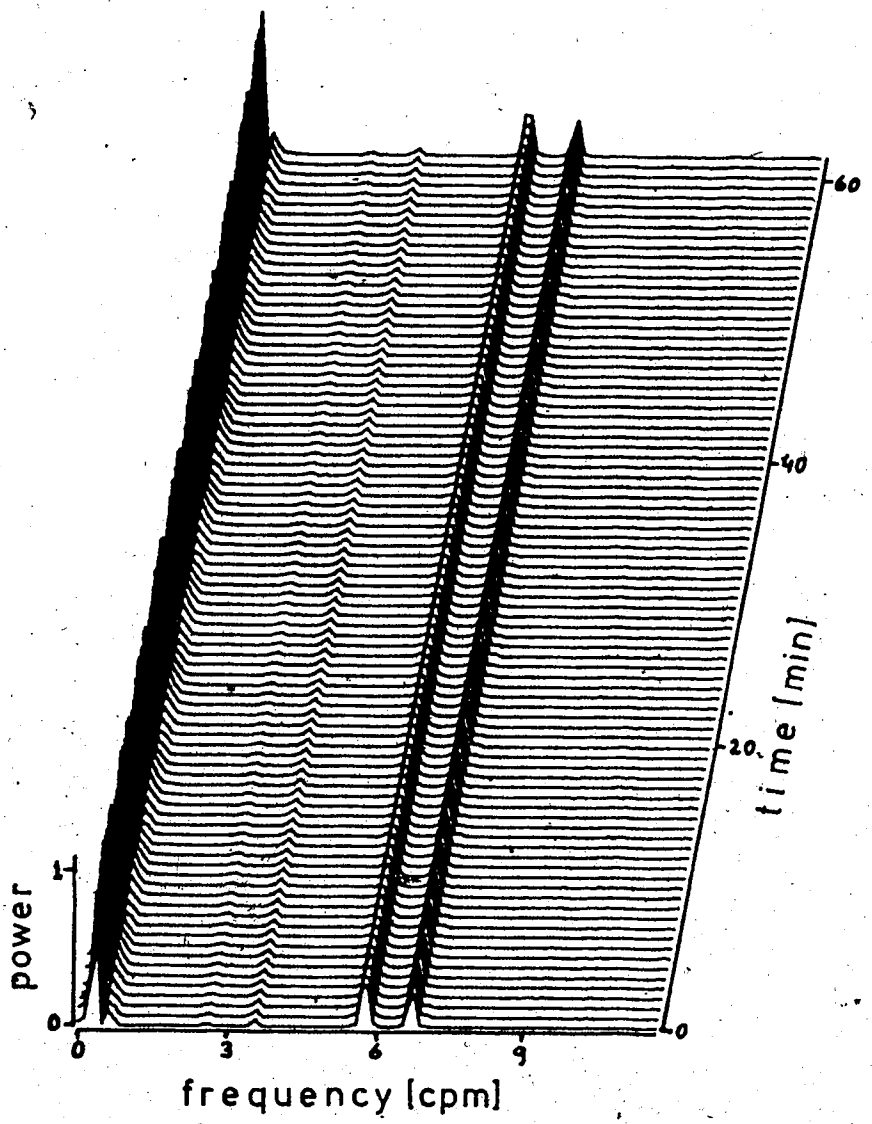


Figure 31. 3DPSP for the simulated product of two close frequencies, using long record sections for the PS evaluation.

this kind in the PSs. If a short record-section is now used to evaluate the PSs of the 3-DPSP, the result is different than Figure 31, as shown in Figure 32. The changes in the PSs as a function of record-section length can be used as an indicator to determine the presence of a product.

Simulated and actual signal relation

The simulated signal, as indicated before, was of the form $F(t)=F1(t)+F2(t)+F1(t)*F2(t)+...$ where the terms $F1(t)+F2(t)$ are the most likely to be present. It was seen that the PS is extremely sensitive to the record-section used to evaluate it.

Some of the actual records used in the following analysis correspond to colonic electrical activity obtained using the recording method previously described, and others correspond to electrical activity recorded in different points of the stomach and intestine. This last data was recorded from electrodes placed during operation on a patient. Figure 33 shows the point where the electrodes were fixed. Figure 34 is a 3-DPSP for the electrical activity recorded by the electrode placed in the antrum of the stomach. In this plot the fundamental frequency and its harmonics can be seen to be similar to the ones in the 3-DPSP for the simulated signals. As the fundamental changes in frequency with time, the harmonics "follow" these; the first harmonic doubles the changes of the fundamental, the

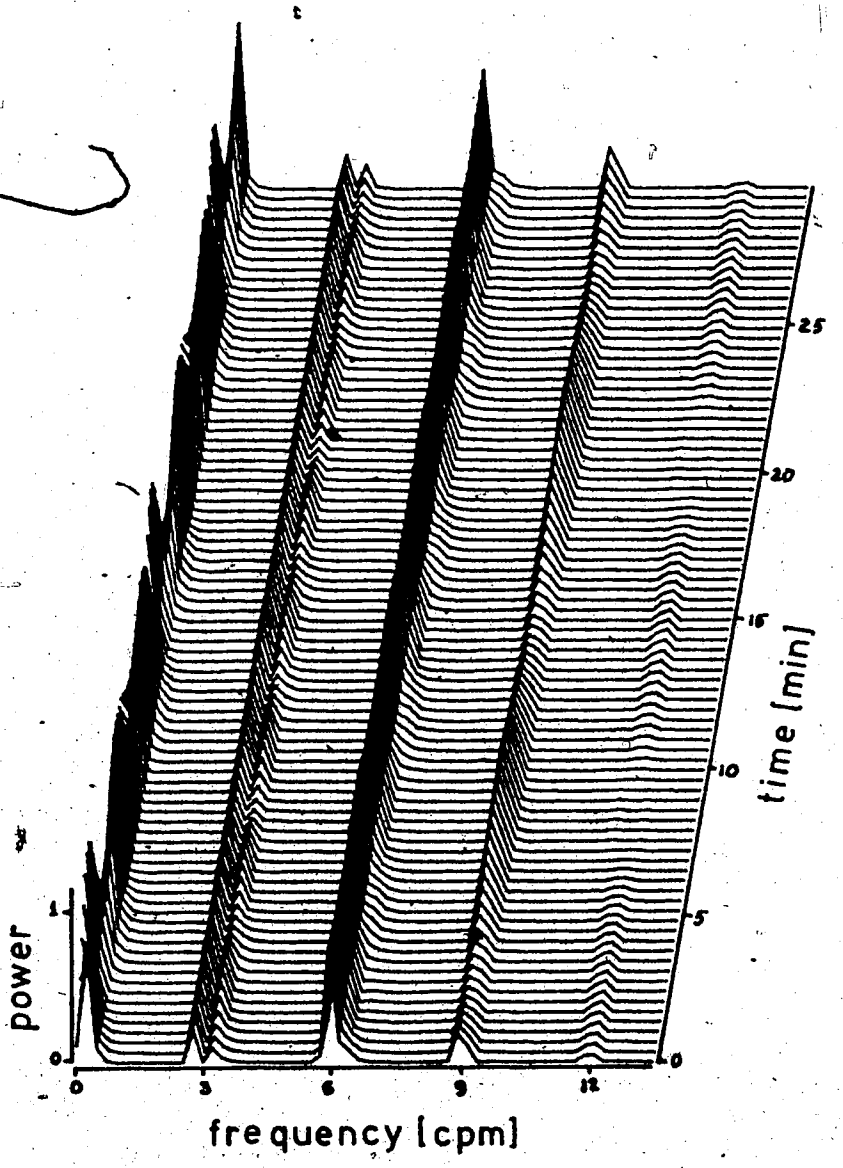


Figure 32. 3DPSP for the simulated product of two close frequencies, using short record sections for the PS evaluation.

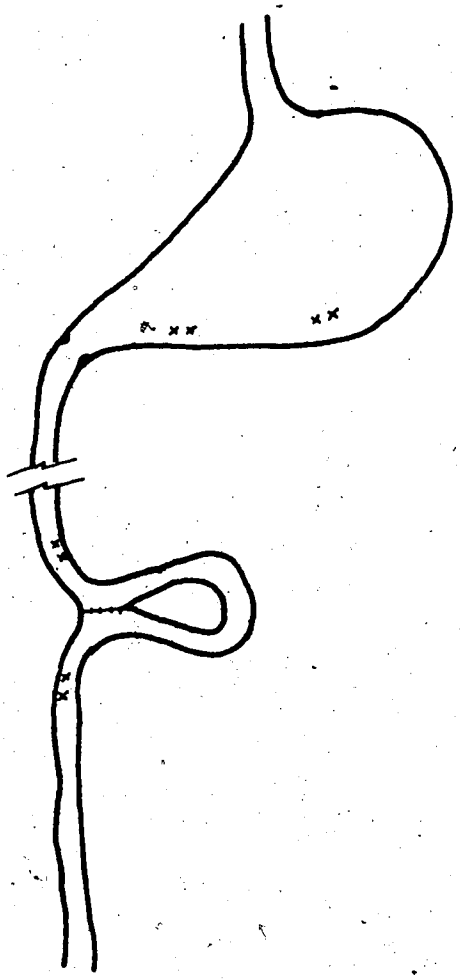


Figure 33. Electrode location in the stomach and small intestine

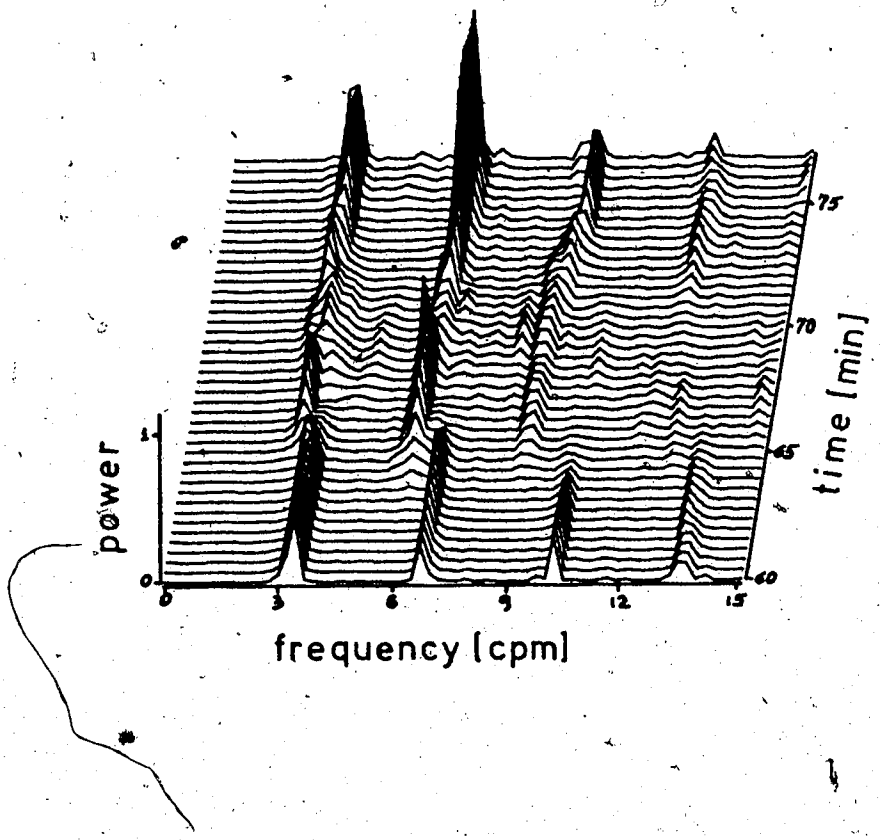


Figure 34. 3DPSP of the antrum electric activity. Presence of the fundamental frequency and its harmonics. (file D48 ch2).

second one triples the changes etc. Clearly they are harmonics generated by the signal wave form and not frequencies independent of the fundamental, as can be claimed from the averaged PS analysis. Also the powers given in the averaged PS are distorted values, while the power given in the 3-DPSP is a better approximation of the real instantaneus power.

In the 3-DPSP of Figure 34, the signal wave form changes can be recognized by the changes in the harmonics power. As was suggested before, the number and the power of the harmonics are a function of the ratio T/T_0 for the simulated signal. A 3-DPSP of a signal that generates harmonics almost without power at the fundamental, is shown in Figure 35. Again in this case the number of harmonics of a certain or greater power present in the 3-DPSP, depends on the ratio T/T_0, as the simulated signal does.

Figure 36 shows the 3-DPSP for the electrical signal recorded with the electrodes placed in the jejunum as shown in Figure 33. Here the frequencies are much higher (10 c/m.) than in the stomach (3 to 4 c/m.). In this case it seems there are two independent frequencies very close to one another. Also the position of the harmonics reveals the presence of the two close frequencies. In some cases there are two frequencies present but the harmonic power is too small to decide on their simultaneous presence.

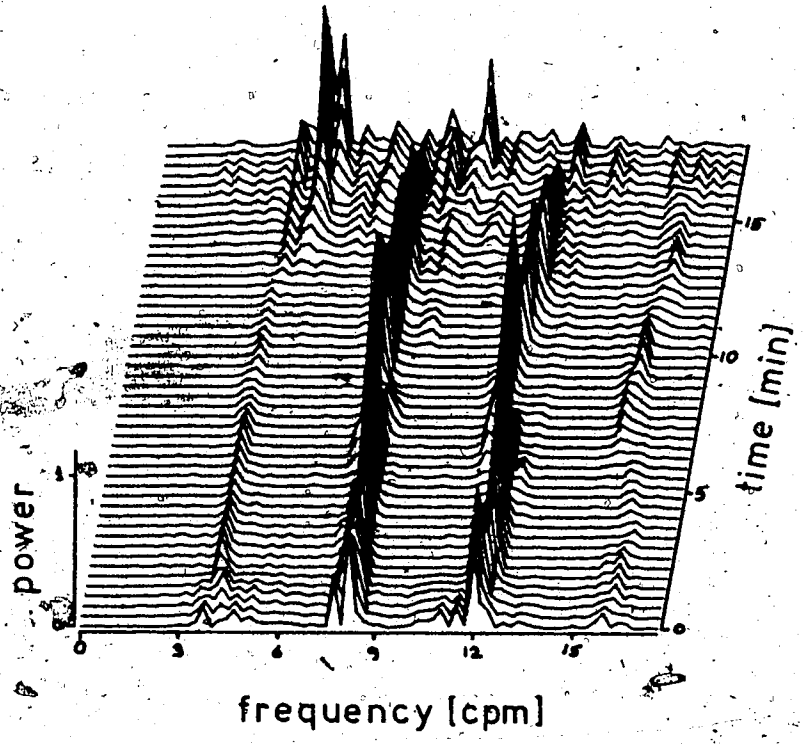


Figure 35. 3DPSP for the electric activity of the stomach. Only the harmonics are present (file D60 ch4)

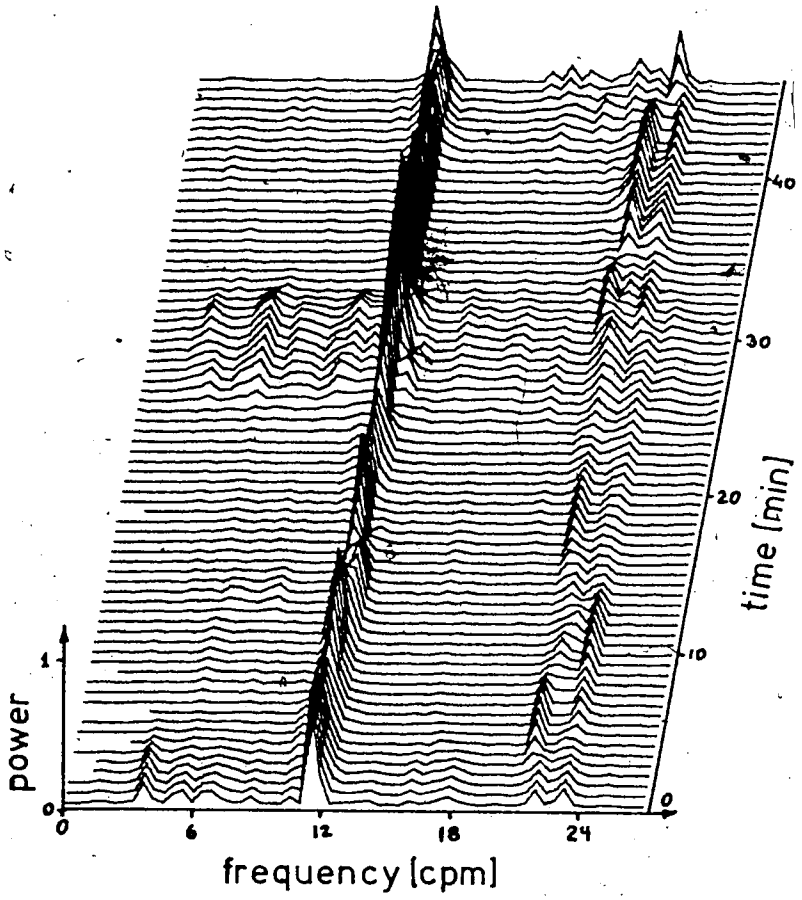


Figure 36. 3DPSP for the jejunum electric activity. Two close frequencies seem to be present simultaneously. (file D49 ch4).

Discussion

A good approximation to real electrical signals has been achieved by the various simulations done. However there is much more in the records to be analysed.

In these records, there is a considerable amount of "noise" generated by external sources. The most common "noise generator" is the patient's movements, for example due to a cough, change of position etc. Although the "noise" is produced by a mechanical source, it also appears in the electrical records because it alters the electrode-tissue interface. Generally an important noise burst is present in all channels simultaneusly, generating a similar spectrum in all channels. This observation can be used to decide if a burst is "noise" or not. An averaged PS of a record with a noise burst gives completely distorted information to the original signal frequency components. These components can become completely masked by the noise power. In electrical records the electrode-tissue interface accounts for most of the signal distortion. These distortions generally are a function of time. If it had been possible to record the electrical activity without filtering the dc and low frequencies, a better analysis of the signal and PSs could have been possible. 3-DPSP helps in the data analysis, but by itself it is not enough. 3-DPSP also has its limitations, as was pointed out before, therefore it must be used with care in these applications.

VIII. FEATURES TO BE USED

To be able to identify automatically a patient's illness, some features have to be extracted. By means of these features and the use of pattern classification a good approach to the identification of the illness may beattempted. These features have to be properly selected to make possible a reliable pattern classification.

It is thought that the colonic pressure can provide significant information when dealing with patients suffering from chronic diarrhea or constipation. A method already described to measure and record the colonic pressure was used to generate the necessary data. From this data suitable features can be computed and selected.

Colonic activity

The term *colonic activity* has been used extensively in a qualitative form in this work and in most related reports, but there is no standard definition for this term that allows it to be used quantitatively. Although some definitions of *activity* have been attempted [18], defining it as the ratio of the sum of the duration of all waves during a given period of observation to the total duration of the observation seems inappropriate.

This definition does not include the wave's amplitude nor its frequency, so two records with the same *activity* percentage can be quite different. It becomes clear that this is not a complete definition for activity.

Other authors have tried to classify the wave forms and use that classification to compare different records. Tempton and Lawson [19] were the first to attempt a rational approach to the variable patterns of activity recorded from the distal colon. Four types of pressure patterns were defined as follows. Type I waves are isolated spontaneous monophasic waves of small amplitude; their function is unknown. Type II waves are similar in form to type I but are greater in amplitude (approximately 10 mm of Hg.) and are of somewhat longer duration. These seem to correspond to the haustral shuttling movements of the colon. Type III waves are frequently observed elevations of the base line pressure superimposed upon which are seen type I and II waves. The function of type III waves is not clear. Type IV waves are peristaltic waves but are very infrequently observed.

This classification has been applied to man and is still being used in recent texts [19] (1978), although previous writers have readily agreed that, in view of the very irregular patterns of activity often observed, it is inadequate [20,21]. Today, a rational classification of colonic pressure waves still does not exist.

Rigorously, given the characteristics of the pressure activity, it does not seem likely that a clear

classification of colonic pressure waves would become a useful tool in colonic motility studies. Instead, some features can be extracted from the pressure records that can be used together with other features in the classification of diseases instead of the individual pressure record waveforms. Some of these convenient features are considered below.

Feature Extraction

The features selected will be used in the classification of specific diseases or of patient states. Since no study has been done about the relation of the feature proposed with specific diseases or whether these features are relevant or not, all the ones were extracted that in some way related to different particularities of the pressure records. However, the minimum number of features that will finally be significant has to be determined later through a feature selection process, and the useless or redundant ones discarded.

The extracted features have to be somehow representative of the colonic motility from the basal or post-drug recordings. They have been extracted from one hour long records of basal pressure, and from records of the first one hour after the drug has been administered. These two records, basal and post-drug, must be recorded in a close successive way so there is consistence in the later

comparison of their features. The features extracted from 1 hour records are referred to as "total".

To have normalized procedures, the amount of drug administered should be determined in a rational way to ensure consistensy. The kind of drug can be included as a feature, since the motility response is a function of the specific drug being used.

A response to the drug usually becomes evident during the first 10 to 30 minutes after it is administered, and its peak response is reached within the first hour. From this peak response some features are extracted within a small fixed period of time of 4.4 min., centered at the peak. These features are refered as "partial".

Since the dc component of the pressure does not contribute directly to the colonic motility, the greater weight is given to the ac components of the colonic pressure.

If N is the number of samples in 1 hour, M the number of samples in 4.4 minutes and X_i the pressure value in cm. of water at sample i, then the features were defined as:

Total Average Pressure (TAP)

is the average pressure of a one hour record

$$TAP = \frac{1}{N} \sum_{i=1}^{N} X_i$$

Total ac Pressure (TACP)

is the "area under the curve" (during 1 hour) per sample, after the TAP has been subtracted.

$$TACP = \frac{1}{N} \sum_{i=1}^{N} | x_i - TAP |$$

Total ac power pressure (TACPP)

is the total power of the ac pressure component per sample.

$$TACPP = \frac{1}{N} \sum_{i=1}^{N} (x_i - TAP)^2$$

Partial Average Pressure (PAP)

is the average pressure during the peak 4.4 minutes.

$$PAP = \frac{1}{M} \sum_{i=1}^{M} x_i$$

Partial ac Pressure (PACP)

is the "area under the curve" (at the peak 4.4 min.) per sample, evaluated after the PAP has been subtracted.

$$PACP = \frac{1}{M} \sum_{i=1}^{M} | x_i - PAP |$$

Partial ac Pressure Power (PACPP)

is the power of the ac component during the peak 4.4 min.

$$PACPP = \frac{1}{M}\sum_{i=1}^{M}(x_i - PAP)^2$$

Other features

The features previously defined are to be obtained from basal and post-drug records. These two kinds of records are obtained, one immediately after the other, to evaluate the effects of drugs on the colonic motility. The ratio of some features can be used as new features, such as TACP ratio (TACPR), TAP ratio (TAPR), PAP ratio (PAPR), and PACPP ratio (PACPPR).

Other features can be defined that involve the pressure of different channels. The intraluminal pressure from a single channel depends strongly on the amount of colonic contents and its characteristics. Increase on intraluminal pressure does not necessarily involve movements of intraluminal contents or marked wall movements. The differential pressure from two channels can be more closely related with the actual content movements. The same features used for basal and post-drug records can be used for the differential pressure. These features can only be relevant and

significant if they are obtained in a normalized procedure, that is, obtained from channels that have their open-end tips at a constant distance. Unfortunately, the pressure records available differ in the channels used, wich makes the evaluation of the differential pressure features inconsistent. However, with the use of the automatic feature computation machine proposed, these features can be reliably and consistently evaluated.

Discussion

The features were defined considering every characteristic of the pressure signal. Obviously some of these features will turn out to be without significance during their selection, before they are used by the pattern classifier.

All these features were extracted from 46 records, each record with several channels. The results obtained showed some inconsistency, specificaly the features where the absolute pressure was used directly. This corroborates the previous conclusion that, after the cumbersome process the data goes through until it reaches the Amdahl computer, it becomes unreliable principally due to uncontrolled gain or zero changes. However, good results were obtained from spectrums where absolute pressures were not used.

These features can be used by the classifier together with other features related to the intestine motility to

decide to which class or disease the patterns belong. These other features as bowel habits, stool consistency, colonic transit times of radioopaque markers, and rectoanal reflexes have been already determined and quantified for normal man [22]. The class corresponding to normals can be directly defined from these normal features. The other classes remain to be defined, depending on the features obtained from ill patients.

IX. PROPOSED AUTOMATIC FEATURE COMPUTATION

For the feature computation, a microprocessor based machine is proposed, which can achieve the data acquisition and data processing in a reliable form.

A. SYSTEM DESCRIPTION

The system performs two different functions, data acquisition and data processing.

During data acquisition, the pressure transducers and preamplifiers are shared by the Beckman recording system and the acquisition system, as shown in Figure 37. The analog signals are converter by the analog to digital converted and stored in random access memory (RAM) and simultaneously or later, stored in a (cassete) magnetic tape. Once the data acquisition is finished, the data stored in RAM can be processed to compute the desired features. If the feature evaluation algorithms are later changed, they can be reevaluated from old data by transfering back this data from the magnetic tape in to the RAM.

The pressure transducers use strain-gages, and a Beckman 9803 strain-gage coupler is used to interface them with the Beckman amplifiers. The amplifier output is then sampled at 1 sample per second in a multiplexed manner and then converted to a digital form. If four pressure channels are used, there will be four samples per second generated, and with one hour long records 15 kilobytes of RAM are required. The data acquisition and processing is performed by

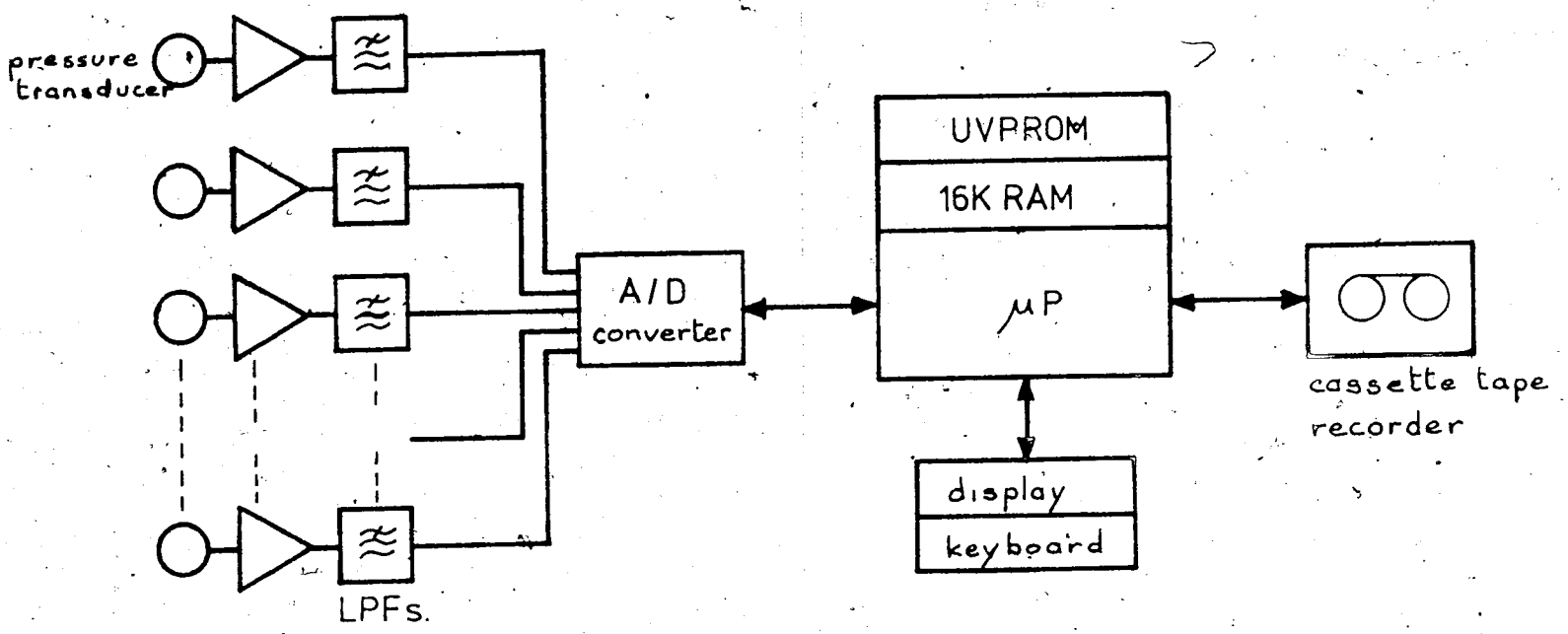


Figure 37. Data acquisition and processing system block diagram.

the same microprocessor, and the results are displayed and or printed out. If it is decided to implement the three-dimensional power spectrum plots (3-DPSP), then additional circuitry is necessary to be used in the FFT evaluation. The 3-DPSP can be plotted on a X-Y recorder.

The program used in the feature evaluation can be stored in ultra violet erasable read only memory (UVPROM), wich makes possible later program changes.

The number of pressure channels can be increased by adding extra RAM memory (3.6 kilobytes per channel) to store the data.

Up to 49 kilobytes (bytes of 8 bites) can be stored in a 1 hour cassete by using 110 boud rate (bites per second).

B. FEATURE COMPUTATIONS

The feature proposed previously can be efficiently computed by a microprocessor, since there are no time limitations.

The algorithm to be used in the evaluation of each of the features will depend strongly on the microprocessor used, thus algorithms will not be analysed. However, additional special circuitry must be used if 3-DPSPs are desired.

X. CONCLUSIONS

Several features representative of the colonic motility were defined. These features were evaluated using the Amdahl computer to test their validity, but most of the data turned out to be unreliable giving rise to unreliable features. The defined features depend on the gain settings, which changed from record to record so they could not be compared or used in a normalized manner.

Nevertheless, extensive frequency component analysis were made for the colonic pressure data, mainly using the 3-DPSPs. 3-DPSPs were done for 46 colonic pressure records[2], which in general revealed an absence of significant and consistent frequency components. With the exception of 3 or 4 patients that presented some post-drug rhythmic pressure waves, they changed in frequency and amplitude with time. Therefore, features representative of some frequency component of the motility were difficult to define without ending in inconsistent features.

The 3-DPSP gives a very good "picture" as a function of time of the frequency components, so it can be used together with the proposed features. 3-DPSPs of the colonic electrical activity "in vivo", "in vitro", and of simulated signal were done. It was found that the electrical activity frequency components depend on the electrode-tissue interface, which is exposed to changes with time due to the

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[2]A total of 161 pressure records corresponding to different channels were analyzed by using the 3-DPSP.

patient movements or movements of the gut wall. Abrupt movement, as the ones caused by cough, generates strong periods of noise generally of high power in relation to the signal, which can be easily detected in the 3-DPSPs. The simulated signal showed that some of the high frequency components are only harmonics and not independent frequencies, as some authors claim[3] [10,14,24].

The way of overcoming the problem of unreliable data is through the use of a direct automatic data acquisition and processing machine, as was proposed, which can perform a reliable and efficient feature computation. This microprocessor based machine permits changes in the feature evaluation algorithms, by changing the program stored in UVPROM. This flexibility is essential when the features, as in this case, have been extracted in excess and are liable to be deleted or changed by other more significant ones during the feature selection process. The use of the features by the pattern classifier will disclose their usefulness.

The use of pattern recognition makes possible rational feature selecting and processing. With the use of a statistical pattern classifier implemented with a computer, different classes corresponding to specific states or illnesses can become defined. This classification can be used later for a simple, fast and reliable diagnosis.

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[3]Bardakjian *et al.* [23] dispute the excistence of these two frequencies and state that electrical slow waves in the ascending colon are omnipresent and have only one rhythm at a frequency of approximately 0.006 Hz. (3.5 c/min.)

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APENDIX

1.1 Discrete Fast Fourier Transform program.

```
      SUBROUTINE FFT(X,Y,M)
      DOUBLE PRECISION X(512),Y(512),ARG,TWF,C,S,T1,T2
      INTEGER REP,DISP
      CALL ORDER(X,Y,M)
      PI=3.1415926535
      N=2**M
      DO 10 I=1,M
      REP=2**I
      DISP=REP/2
      ARG=2*PI/REP
      DO 10 J=1,DISP
      TWF=(J-1)*ARG
      C=DCOS(TWF)
      S=DSIN(TWF)
      DO 10 K=J,N,REP
      J2=K+DISP
      T1=C*X(J2)+S*Y(J2)
      T2=-S*X(J2)+C*Y(J2)
      X(J2)=X(K)-T1
      Y(J2)=Y(K)-T2
      X(K)=X(K)+T1
      Y(K)=Y(K)+T2
10    CONTINUE
      RETURN
      END


      SUBROUTINE ORDER(X,Y,M)
      DOUBLE PRECISION X(512),Y(512),T1,T2
      N=2**M
      ND2=N/2
      NM1=N-1
      J=1
      DO 30 I=1,NM1
      IF(I.GE.J)GO TO 10
      T1=X(J)
      X(J)=X(I)
      X(I)=T1
      T2=Y(J)
      Y(J)=Y(I)
      Y(I)=T2
10    K=ND2
20    IF(K.GE.J)GO TO 30
      J=J-K
      K=K/2
      GO TO 20
30    J=J+K
      RETURN
      END
```

1.2 Subroutine TAPER

```
      SUBROUTINE TAPER(Y,NS)
      DOUBLE PRECISION Y(512),F
      M=NS/10.
      F=3.1415927/M
      Y(1)=0.0
      DO 10 I=2,M
      Y(I)=Y(I)*(1.-DCOS(F*(I-1)))/2.
10    Y(NS-I+2)=Y(NS-I+2)*(1.-DCOS(F*(I-1)))/2.
      RETURN
      END
```