Extracting quantitative information from digital electrogastrograms

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Abstract—*Cutaneous recordings of gastric electrical activity (electrogastrography (EGG)) could become a valuable non-invasive tool for recognising gastric electrical abnormalities. Although signals obtained with internally implanted electrodes deliver quantitative information, this technique cannot be used for diagnostic purposes because of its invasive nature. On the other hand, the objectivity of electrogastrography is still in question. The aims of this work are to develop computer techniques for extracting quantitative information from digital electrogastrograms, and to evaluate quantitatively EGG recordings from healthy volunteers. The dynamics of all four EGG parameters are studied: amplitude, frequency, time shift between different channels, and waveform. Four separate two-dimensional computer plots are developed using specially designed digital signal-processing procedures. Each parameter is evaluated in a study of 20 healthy volunteers. Frequency is found to be the only EGG parameter that shows quantitative consistency and merit.*

Keywords—*Electrogastrography, Gastric electrical activity*

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1 Introduction

GASTRIC ELECTRICAL abnormalities recorded *in vivo* with electrodes implanted on the stomach wall have been extensively studied (SZURSZEWSKI, 1981; SMOUT, 1980; DANIEL and CHAPMAN, 1963) and can be related to certain gastric motility disorders (SMOUT, 1980). However, such techniques are rarely used because they are invasive and uncomfortable (SMOUT, *et al.*, 1980).

Cutaneous recordings of gastric electrical activity (GEA), known as electrogastrography (EGG), would seem to be an avenue for the non-invasive assessment of gastric motility. Although Alvarez recorded electrogastrographic signals in 1921 (ALVAREZ 1922), only recently has the technique shown practical promise. Unfortunately, the diagnostic value of this method is still uncertain, and much new knowledge is required before clinical disorders can be related to EGG signals with any certainty (KINGMA, 1989; MINTCHEV *et al.*, 1993).

The objective of this work is to introduce quantitative methods for the evaluation of EGG and to test these methods on normal volunteers as a first step towards reliable clinical applications of EGG.

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2 Information extracted from gastric electrical activity

2.1 *Migrating myoelectrical complex and contractions*

Counting the occurrence of spike activity from short-distance bipolar (SDB) recordings obtained with wire electrodes implanted on the serosa is the most reliable method of assessing contractions from gastric electrical signals (CODE and MARLETT, 1975; SMOUT, 1980). As a direct consequence of that, a histogram of migrating myoelectrical complex (MMC) can be built.

Unfortunately, contractions cannot be reliably assessed from internal long-distance bipolar (LDB) or cutaneous EGG recordings (MINTCHEV *et al.*, 1993), and therefore obtaining MMC from these techniques could be a theoretical speculation, rather than a practical possibility.

2.2 *Electrical coupling between different parts of the stomach*

Electrical activity in a normal stomach has a rigid temporal organisation. Although the velocity of propagation from the distal corpus to the terminal antrum can differ individually, it has been shown that corresponding waves recorded from different areas of a normal stomach maintain a consistent time shift between them. This phenomenon has been called electrical coupling (FAMILONI *et al.*, 1987; 1991). Even in cases of significant frequency irregularities, the pattern of electrical coupling in the stomach may be preserved. Normal electrical coupling between different parts of the stomach corresponds to a distal direction of propagation of gastric electrical and contractile activity.

Electrical coupling can easily be studied invasively with a set of serosal SDB electrode pairs implanted in the areas of interest (FAMILONI *et al.*, 1987). Although LDB signals cover greater stomach areas, they can also be used to assess electrical coupling (MINTCHEV *et al.*, 1993).

A previous study (CHEN *et al.*, 1989) has reported that the direction of propagation can also be assessed from EGG recordings. In another study, analysis of the EGG waveform has been suggested as an indirect method for the non-invasive assessment of the direction of propagation of GEA (FAMILONI *et al.*, 1991). However, there has not been a comparative study of SDB and EGG signals to objectively prove these assumptions.

The possibilities of EGG signals registering gastric electrical coupling are examined in this study.

2.3 *Gastric electrical frequency*

The frequency of GEA can be assessed by all recording techniques, but with different degrees of reliability. It could be very informative in identifying gastric electrical irregularities, which are believed to be related to irregularities in contractile activity (ABELL and MALAGELADA, 1988; HAMILTON *et al.*, 1986; CHEN and MCCALLUM, 1991). Some investigators assume that tachygastria (gastric electrical signals with frequencies above 4 cycles $\min^{-1}$) and bradygastria (below 2.25 cycles $\min^{-1}$) could be related to certain gastric motility disorders (ABELL and MALAGELADA 1988). Biphasic serosal SDB signals have very well defined time characteristics and are very reliable in assessing frequency (SMOUT, 1980; SMOUT *et al.*, 1980; MINTCHEV *et al.*, 1993). It has also been shown that the frequency of EGG signals (if recorded properly) is reliably related to gastric electrical frequency, i.e. it can show gastric electrical irregularities (ABELL and MALAGELADA, 1988; CHEN and MCCALLUM 1991; MINTCHEV *et al.*, 1993).

3 Quantitative computer methods to extract information from digital EGG

3.1 *Quantitative assessment of EGG amplitudes*

Many authors believe that the appearance of spikes in internal recordings of GEA corresponds to an increased EGG amplitude, i.e. gastric contractions can be assessed by amplitude analysis of EGG (SMOUT *et al.*, 1980; ABELL and MALAGELADA 1988; CHEN and MCCALLUM, 1991; GELDOF *et al.*, 1986). The dynamics of the EGG amplitudes can be assessed (although not quantitatively) from the well known three-dimensional and grey-scale plots (KINGMA *et al.*, 1981; VAN DER SCHEE *et al.*, 1987) adopted from image-processing techniques and involving fast Fourier transforms (OPPENHEIM and SCHAFER, 1975). Increments in EGG amplitudes are also relatively easy to follow in the time domain, if the electrodes are positioned properly and the amplifier has an adequate bandwidth.

To introduce some quantification when measuring the amplitude (or power) dynamics in a given recording, the overall spectral maximum of its three-dimensional spectral plot is found. A dominant spectral component from a given spectrum is considered to have increased in power (and is therefore worth attention) if it exceeds 25% of the overall spectral maximum. This allows us to replace three-dimensional (or grey-scale) plots with black and white 'contrast plots', where black represents dominant spectral components that exceed the cut-off level of 25% (MINTCHEV and BOWES, 1994). If changes in EGG power actually represented the contractile dynamics, this plot would be an image of the MMC, obtained non-invasively. Unfortunately, this has been proven not to be the case (MINTCHEV *et al.*, 1993).

3.2 *Methods to assess EGG frequency*

Visually counting the number of waves in a certain time interval is fairly reliable when dealing with SDB signals, but some lower amplitude or irregular LDB and EGG waves can easily be missed. This reduces the objectivity and the reliability of the method in comparative studies, and therefore a quantitative evaluation would be appropriate.

Although counting SDB waves in the time domain can easily be implemented by computer, a rather more sophisticated mathematics involving Fourier transforms is required for the analysis of LDB and EGG signals in the frequency domain (OPPENHEIM and SCHAFER, 1975). First, it has become almost a standard requirement to build the three-dimensional plot of the signal, especially when dealing with EGG (KINGMA *et al.*, 1981). When studying frequency, we normalise the dominant peak in each spectrum to 100%. Furthermore, the maxima of the dominant peaks from each spectrum are arranged in a plot versus time and connected with lines, (i.e. the amplitude information was completely eliminated) to obtain a two-dimensional time–frequency plot. It is quite obvious that

(*a*) each time–frequency plot is built by points, each of which represents the frequency of the dominant peak in the corresponding spectrum.
(*b*) as the spectra in the three-dimensional plot represent successive time intervals, the points that build up the time–frequency plot are shifted with this interval along the time axis.

(*c*) when overlap is introduced, the time interval T_I between any two successive points in the time-frequency plot is given by

$$T_I = [N/F_s].[100 - OVL)/100] \qquad (1)$$

where *OVL* is the percentage of overlap used, *N* is the number of points of the Fourier transform, and F_s is the sampling frequency used.

In our studies, frequency analysis is done using a 512-point fast Hartley transform (FHT) (BRACEWELL 1986; MINTCHEV *et al.*, 1991), which was found to be more convenient than the FFT, because of its speed and the real nature of its coefficients.

To evaluate quantitatively the time–frequency plot obtained from a given gastric electrical channel, we calculate the mean value, variance and SD of the points that build up that plot (time-frequency points).

3.3 *Methods to assess gastric electrical coupling*

Gastric electrical coupling can be assessed directly from different SDB channels simply by connecting the corresponding waves with lines. As long as these lines remain parallel, the coupling is intact.

It has been pointed out already that LDB and EGG signals are close to sine waves. This makes the application of cross-correlation analysis particularly suitable when assessing time shifts from these signals. The abscisse value of the maximum of the cross-correlation function calculated from corresponding intervals of two EGG or LDB channels represents the average time shift between the two signals. Time shifts extracted from the cross-correlation functions calculated from successive time intervals of the two studied signals can be presented as a function of the recording time in a time-shift plot. Similarly to the time-frequency points from the time-frequency plots, the points from a given time-shift plot (time-shift points) can also be evaluated statistically.

Familoni *et al.* suggested that EGG waveform analysis could be used for the indirect assessment of direction of propagation (Familoni *et al.*, 1991). They pointed out that, in normal subjects, the descending portion of EGG waves usually dominates, which probably indicates the distal direction of propagation. During periods of uncoupling, the direction of propagation is disturbed. Therefore, uncoupling could be reflected by a change in EGG waveform. However, no quantitative evaluation of this suggestion has been made.

The simplest method of studying the character of the slope of the EGG waveforms in a certain time interval is to divide the total number of points with smaller amplitudes than their predecessor by the total number of points with larger amplitudes than their predecessor in the whole interval. A ratio greater than unity would indicate that the descending arms of the waves dominate in this interval. To study quantitatively the dynamics of the EGG waveforms in the whole recording, these ratios can be obtained for successive time intervals and arranged versus time in a gradient plot. Symmetry in these plots is defined as fluctuations in the range of 5% around unity.

Another indirect way of assessing gastric electrical coupling comes from the assumption that the uncoupling itself is nothing but asynchronous oscillations of different parts of the stomach. Consequently, gastric frequency measured most often from different EGG or LDB channels would not be one and the same. If the points that build up the time–frequency plot of an investigated channel are evaluated statistically, the probability density function (PDF) (Oppenheim and Schafer, 1975) can be built for this channel. In the case of normal electrical coupling, all maxima of the PDF functions obtained from all EGG channels should coincide on one position, which would be the gastric electrical frequency.

4 Recordings from healthy volunteers

Suggested quantitative techniques for evaluation were applied to 20 healthy volunteers with no history of gastrointestinal complaints. The volunteers underwent recording of the cutaneous EGG during 1 h of fasting and for 1 h after a 550 Kcal test meal. It was assumed that the lesser curvature begins at the xiphisternum and ends at the point where the mid-clavicular line meets the costal margin. The greater curvature is situated to the left and is inferior to the mid-clavicular line depending on gastric distention. The most proximal electrode* was placed 5 cm left of the xiphisternum on the costal margin, and four electrodes (3 cm apart) were placed linearly between the first electrode and the junction of the mid-clavicular line with the right costal margin. The bipolar combinations between the electrodes formed eight EGG channels. Body mass indexes (weight, kg/height, m) of the subjects were also calculated.

EGG signals were amplified in a bandwidth of 0·02–0·2 Hz (filter roll-off 6 dB oct^{-1}) and digitised with a sampling frequency of 10 Hz. After additional digital filtering with a bandpass Fourier filter (Oppenheim and Schafer 1975), a lower sampling frequency of 2 Hz was introduced.

* Neotrode, Medtronic, Haverhill, Massachusetts

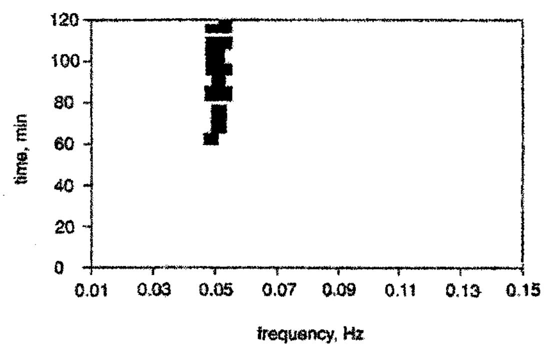

Fig. 1 *Contrast plot of a normal volunteer; a test meal was given after 1 h of recording; EGG amplitudes increased after feeding*

5 Results

5.1 *Contrast plots*

A variety of contrast plot patterns were obtained. The predominant pattern (seen in 12 out of 20 volunteers) showed an increased postprandial amplitude (Fig. 1). However, in five subjects the amplitudes in the postprandial and fasting states were comparable, and in three individuals the amplitudes in the fasting state were higher than the postprandial amplitudes (Fig. 2). These findings imply that, although many healthy subjects exhibit a substantial postprandial increment of EGG amplitude, this cannot be considered a typical pattern for diagnosis of eventual motility abnormalities, because there is a significant group of healthy people whose EGG amplitudes do not change much or can even decrease after feeding.

Our previous study (Mintchev *et al.*, 1993) showed that EGG amplitudes cannot be reliably related to gastric contractions.

The noise that accompanied EGG (predominantly from motion and respiration artefacts) introduced occasional false black bars in some contrast plots.

5.2 *Time-frequency plots*

The overall results from the volunteers showed that in at least three out of eight EGG channels the SD of the dominant frequency component, as assessed from the time–frequency plots, was less than 0.450 cycles min^{-1} (0·0075 Hz). These channels were qualified as stable. The frequency range, as assessed by the mean frequency in the stable channels, was in the range 2·5–3·75 cycles min^{-1} (0·0416–0·0625 Hz) Typical time–frequency plots obtained from a healthy volunteer and their statistical evaluation are shown in Fig. 3 and Table 1, respectively.

Maxima of the PDFs obtained from the time-frequency points in stable EGG channels coincided at the frequency of the dominant spectral component, indicating normal electrical coupling (Fig. 4).

Introducing a 75% overlap of the time-domain intervals when building time–frequency plots improved their stability, reduced the SD and narrowed the probability density functions in 12 cases. In five cases the overlap had a negative effect on the stability of the time–frequency plots, increased the SD and widened the probability density functions. In all these cases, however, at least three EGG channels exhibited SD less than 0·450 cycles min^{-1} and the maxima of their probability density functions coincided. Three recordings were not influenced by the overlap at all, i.e. the stability of the time–frequency plots obtained without any overlap remained the same after the overlap was introduced. EGG channels with SD of 0 cycles min^{-1} were seen in six volunteers, all of them with a BMI below 40 $kg\,m^{-1}$.

In all healthy subjects the SD of the time–frequency points were lower than 0·450 cycles min^{-1} in at least out of eight standard EGG channels. The maxima of the probability density functions of the time-frequency points from these three stable

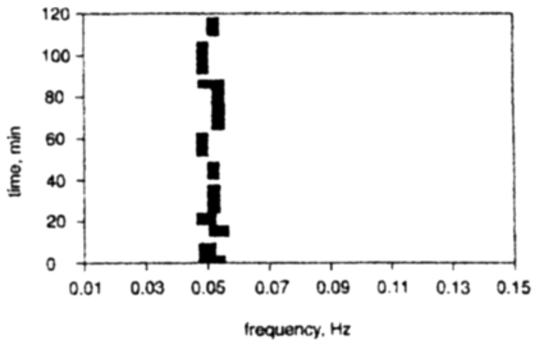

Fig. 2 *Contrast plot of another volunteer; postprandial EGG amplitudes did not increase significantly*

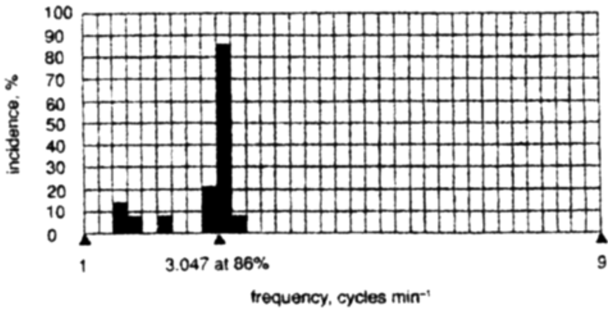

Fig. 4. *Probability density functions of points in time-frequency plots; maxima coincide at 3·047 cycles min^{-1}, but some other frequencies are also present, mainly from the unstable channel 5; frequency intervals = 0·23 cycles min^{-1}*

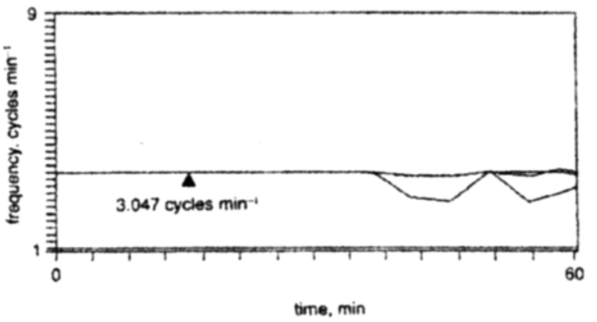

Fig. 3 *Typical time-frequency plots obtained for eight EGG channels recorded from a healthy volunteer; only one channel was partially unstable during the last 25 min of the test; frequency intervals = 0·23 cycles min^{-1}; time intervals = 4·27 min*

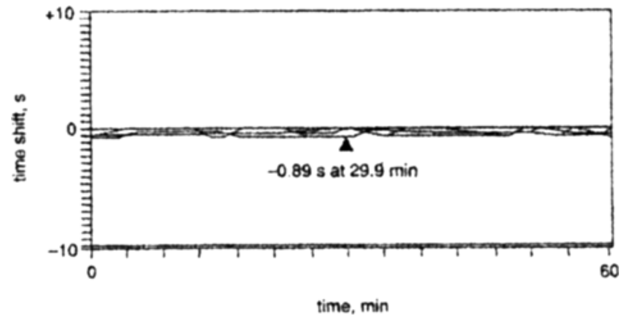

Fig. 5 *Time shift plots obtained for eight EGG channels of a normal volunteer; no time shifts greater than 1 s were detected; time-shift intervals = 0·59 s; time intervals = 4·27 min*

channels coincided at gastric electrical frequency, thus indicating normal electrical coupling.

5.3 *Time-shift plots*

Time-shift plots in six volunteers exhibited maximum time shifts of 1 s, even between the most distal electrode pairs (Fig. 5). As a rule, these volunteers had a BMI less than 40 kg m^{-1}. Only in three volunteers were the maximal time shifts in the range of 1·5–2 s. These volunteers were older females with a BMI less than 35 kg m^{-1} In the remaining 11 volunteers, the time-shift plots exhibited variations too large for any conclusions to be drawn.

SD of the time-shift points decreased after feeding in 14 subjects.

In this study of healthy volunteers, we could not define a quantitative pattern of EGG time-shift dynamics typical for all subjects and independent of external factors such as BMI, noise etc.

5.4 *Gradient plots*

Three different patterns were observed in the gradient plots: predominance of the descending portion of the waves, symmetry (in the 5% band) and predominance of the ascending portion. In eight volunteers the number of waves with predominant descending portion was greater, whereas in three subjects the waves were symmetrical most of the time. In another four individuals the number of waves with predominant ascending portion was slightly higher. In the remaining five subjects the pattern was not found to be consistent, or feeding changed it (Fig. 6).

Similarly to the studies of amplitude and time-shift dynamics, the study of EGG waveform dynamics in healthy volunteers could not find a typical quantitative pattern.

6 Discussion

In this study we have used the power of computers to evaluate quantitatively the elusive EGG signals. Eight standard EGG channels were recorded from 20 healthy subjects, both in the fasting state and after feeding. The dynamics of their four parameters (amplitude, frequency, time shift between different channels and waveform) were assessed by computer using various digital signal-processing techniques. For the study of each EGG parameter, a separate two-dimensional computer plot was developed. The points that built up these plots were statistically evaluated.

Table 1 Basic averages obtained from the time-frequency plot on Fig.3.

	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7	Channel 8
mean cycle min^{-1}	3·030	3·013	3·013	3·013	2·645	3·013	3·013	3·013
variance cycle min^{-1}	0·190	0·007	0·007	0·016	0·460	0·007	0·007	0·007
SD, cycles min^{-1}	0·436	0·085	0·085	0·085	0·678	0·085	0·085	0·085

Channel 5 (the unstable channel in the time-frequency plot) shows SD greater than 0·450 cycles min^{-1}

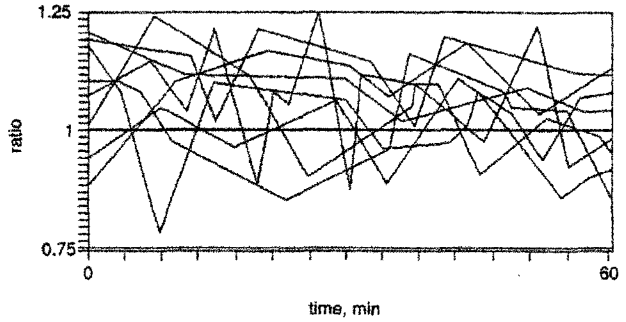

Fig. 6 *Gradient plot of a normal volunteer; ratios greater than 1 indicate predominance of the descending portion of the EGG waves; ratio intervals = 0·015; time intervals = 4·27 min*

An objective quantitative pattern of time-shift and waveform dynamics could not be extracted from this study. Therefore, we would hesitate to use these parameters clinically.

If the amplitude dynamics of EGG were representative for the dynamics of gastric contractions, some sort of presentation of MMC extracted from the EGG would be possible. A computer contrast plot was developed with the motive of representing MMC from EGG signals. False bars in these contrast plots can easily be determined when they co-exist with a bar in the EGG frequency area of a given contrast plot. If that is not the case, it is often difficult to distinguish between bars related to genuine EGG signals and false bars due to noise. One way of reducing the number of false bars is to increase the cut-off level of the contrast plot; another way is, of course, to reduce the external noise as much as possible.

However, we feel that many other factors whose influence cannot be controlled (such as body mass index, gastric distensions, displacements and some motion artefacts) contribute to the pattern of the amplitude dynamics of EGG, and the extent of this contribution can be neither quantitatively determined nor separated from the eventual contribution due to actual gastric spike activity. Therefore, in our opinion, EGG amplitude cannot be considered a reliable parameter for eventual clinical applications. This is also supported by the findings that many normal individuals do not exhibit substantial postprandial increment of the EGG amplitude.

Frequency dynamics was the only EGG parameter that could be quantitatively evaluated in this study. SD of the points that built up the time-frequency plots (the time–frequency points) were lower than 0·450 cycles $\min^{-1}$ (0·0075 Hz) in at least three out of eight EGG channels. The maxima of the probability density functions of the time–frequency points obtained from these stable channels coincided at gastric frequency. These two objective quantitative findings can be used for clinical applications of the EGG method in studies of regularity of gastric electrical frequency and electrical coupling between different parts of the stomach.

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