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Analysis of the Electrogastrogram Using Discrete Wavelet Transform and Statistical Methods to Detect Gastric Dysrhythmia

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Abstract Electrogastrography (EGG) is a method of recording stomach electrical activity from cutaneous electrodes placed on the abdominal surface. Compared with other electrophysiological measurements, such as electrocardiography, the progress of the applicability of the EGG has been very slow. Unlike imaging or manometrical studies, stomach motility disorders are not diagnosed based only on abnormal EGG parameters. Limitations of EGG recording, processing, computation, acceptable normal parameters, technique and reading should be known to conduct subjective assessments when EGG is used to resolve stomach dysfunction. Therefore appropriate application of non-invasive EGG should go on providing more information and insight in understanding these limitations. And so the aim of this study were to contribute the evolution of the EGG to enter the clinical world as a routine check-up method and to develop new time-frequency analysis method for the detection of gastric dysrhythmia from the EGG.

Keywords Electrogastrography · Discrete wavelet transform · Statistical methods

Introduction

Stomach has a rhythmic electrical oscillation to accomplish the digestive process simultaneously. This spatiotemporal oscillation is called gastric myoelectrical activity (GMA). GMA is composed of gastric slow waves or electrical control activity and spike potentials or electrical response activity. The gastric slow wave is omnipresent, and its frequency in humans is 3-cycles/minute (cpm) or 0.05 Hz. It determines the propagation and the maximal frequency of the gastric contractions. The occurrence of antral contractions is directly associated with spike potentials that are superimposed on the slow waves [1]. The gastric slow wave is believed to be present even during quiescent periods when smooth muscle contractions are absent. When gastric smooth muscle contractions occur, spike potentials are phase locked to the gastric slow wave. The disruption of the normal gastric slow wave may not only abolish the gastric contraction, but it may also disrupt the temporal and spatial relationship between contractions required for trituration and propulsion [2]. Abnormality in the frequency is called gastric dysrhythmia, which includes tachygastria and bradygastria.

Tachygastria is defined an increase in the frequency of the gastric slow wave from 3 to 4–9 cpm. Tachygastria develops when an ectopic pacemaker, often in the antrum, generates an oscillatory pattern at an abnormally high frequency that overdrives the rest of the stomach. Thus, during tachygastria, the stomach is usually atonic. And same as the tachygastria, bradygastria is defined a decrease in the frequency of the gastric slow wave from 3 to 1–2 cpm. With bradygastria, the contractile efficiency of the stomach is reduced as a result of decrease in the number of antral contractions [3].

Dysrhythmic activities in GMA may lead to gastric motor dysfunctions resulting in a variety of gastrointestinal disorders, such as gastroparesis, functional dyspepsia and gastro-oesophageal reflux disease [4–6]. For this reason, a non-invasive and reliable test would be very beneficial for detecting gastric dysrhythmia, and the associated gastric motility abnormalities.

Electrogastrography (EGG) is a method of recording GMA from cutaneous electrodes placed on the abdominal

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surface. The EGG is attractive because it is noninvasive and does not disturb ongoing activity of the stomach. Numerous studies have shown that the EGG is an accurate measure of the gastric slow wave [7–9].

Although the first human EGG was recorded by Alvarez as early as 84 years ago [10], EGG still has several drawbacks. The lack of standardized methodology in terms of electrode positions, recording periods, test meals, analytic software and normal reference values makes the significance of EGG recording controversial in diagnosing stomach motor dysfunction. Unlike imaging or manometrical studies, stomach motility disorders are not diagnosed based only on abnormal EGG parameters [11]. Limitations of EGG recording, processing, computation, acceptable normal parameters, technique and reading should be known to conduct subjective assessments when EGG is used to resolve stomach dysfunction. Therefore appropriate application of non-invasive EGG should go on providing more information and insight in understanding these limitations.

Extracting morphological patterns and useful information from visual analysis of EGG waveforms has been unsuccessful mainly due to the nature of the gastric electrical field, the low amplitude of the EGG signal and the high level of noise.

Since the signal-to-noise ratio of EGG is low and visual analysis is useless, computer-aided analysis is essential [12]. The frequency is assumed to be a reliable character of EGG because the association of gastric contractions with frequency is reported to be 80–85%, while that with amplitude is 30–40%.

In almost all studies of EGG signal detection to date, running spectrum analysis (RSA) has been used [13, 14]. Fourier analysis, which is the core of this technique, is suitable only for stationary signals but EGG is a non-stationary and non-deterministic signal thus questioning the traditional techniques utilizing Fourier analysis [15]. In addition, EGG applications need several minutes' data for each RSA to yield reasonable frequency resolution. However, dysrhythmic events (or nonstationarity) may occur within 1–2 min [16]. As a result, gastric dysrhythmia of brief duration may not be represented well using the RSA method.

In some respects, the short-time Fourier transform (STFT) is not ideally suited for analysis of EGG signals. The major drawback inherent in the STFT is that trade off is inevitable between temporal and spectral resolution [17]. If one uses a longer sliding time window to obtain higher spectral resolution, the underlying nonstationarity will be smeared out, resulting in lower temporal resolution. Conversely, using a shorter window to achieve better temporal resolution will give lower spectral resolution. In addition, in the STFT analysis, taking the Fourier transform (FT) of a short data frame of the EGG signals leads to a distortion of the spectral estimate and leakage of signal energy into spurious side lobes due to the sharp truncation of the signals. The spurious frequencies that are created by STFT sonograms can cause a wrong diagnosis especially for the bradygastric patients [18].

As mentioned above, EGG is a non-stationary signal. Its properties such as frequency, amplitude and phase in the slow waves change with time and subject. Therefore the method, which is used to extract diagnostic features from EGG signals, must be suitable for nonstationarity. Wavelet transform (WT) is designed to address the problem of non-stationary signals. It involves representing a time function in terms of simple, fixed building blocks, termed wavelets. These building blocks are actually a family of functions, which are derived from a single generating function called the mother wavelet by translation and scaling or dilation operations [19]. Scaling compresses the mother wavelet and translation shifts it along the time axis and so it has a varying window size, being broad at low frequencies and narrow at high frequencies, thus leading to an optimal time-frequency resolution in all frequency ranges. The WT can be categorized into continuous and discrete. Discrete wavelet transform (DWT) is often used because a considerable effort and a vast amount of data being necessary to calculate a continuous wavelet of a signal.

Our study is implemented a DWT-based analysis for detecting dysrhythmic activities from the EGG signals. After the EGG signal was decomposed using DWT, Power spectral density (PSD) value of wavelet-packet details and approximation coefficients was obtained. Decomposing the EGG signals means that dividing EGG signal into different frequency subbands. The computation of the signal energy in the subband is more accurate than the computation of signal energy based on the PSD. In clinical practice, to classificate the EGG using the PSD and features of the details and approximation coefficients as a normal or abnormal, reliability of these features must be proved. Therefore, a statistical method, Mann–Whitney *U* test was used and results are statistically compared with "paired-samples *T*-test" method as healthy and normal subjects.

And so the aim of this study was to contribute the evolution of the EGG, to enter the clinical world as a routine check-up method characterizing the abnormalities of the frequency effectively and to develop new time-frequency analysis method for the detection of gastric dysrhythmia from the EGG.

Materials and methods

Subjects

EGG signals were participated from 16 healthy volunteers (12 males and 4 females; mean age, 21 years; range 19–23 years) and 16 diabetic gastroparesis patients (10 males and 6 females; mean age, 19 years; range, 13–21 years) in this study. Diabetic gastroparesis is commonly present in long-standing insulin dependent diabetes mellitus. Symptoms include bloating, distension, nausea, and vomiting. When severe and chronic, gastroparesis can be associated with dehydration, poor nutritional status, and poor glycemic control in diabetics and it is defined as a chronic disorder of gastric motility as evidenced by delayed gastric emptying of a solid meal [20]. All of the diabetic gastroparesis patients had previously established diagnosis of the delayed gastric emptying via radioscintigraphy. Radioscintigraphy is currently the established gastric emptying test for diagnosis of delayed gastric emptying. The healthy volunteers were with no past history of gastric dysrhythmic diseases. None of the subjects were taking medications that may affect gastrointestinal motility.

Measurement of EGG and hardware

All subjects fasted for 6 h or more before the study. The EGG recording was performed in a quiet room with the subject in the supine position. They were asked not to talk and to keep relatively still during the recording time in order to avoid motion artifacts. Three electrodes filled with electrodes jelly were placed over on the abdominal skin. Two active electrodes were positioned below the left costal margin and between the xyphoid process and umbilicus. The electrode positioned in the right upper quadrant is a reference or common electrode (Fig. 1). The cutaneously recorded electrogastrogram (EGG) shows a 3-cpm wave pattern. The fundus has no rhythmical electrical activity [4].

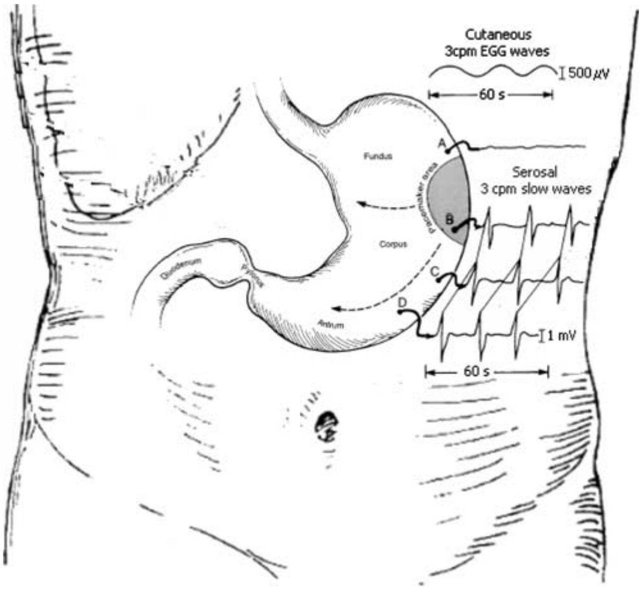

Fig. 1 Representation of used electrode placement for EGG recordings. The cutaneously recorded electrogastrogram (EGG) shows a 3-cpm wave pattern. The fundus has no rhythmical electrical activity

EGG signal acquisition was conducted by Biopac Sys MP100WSW unit in the Nuclear Medicine Department of Erciyes University Hospital. The system hardware was composed of a Biopac MP100WSW EGG recorder, an input–output card and a personal computer. The signals were amplified with a gain of 2000 (EGG100C amplifier). The serial output of EGG recorder device unit was sampled at 200 samples/s and then sent to a PC via an input–output card. A personal computer (PC) was used for storage, displaying and spectral analysis of the acquired EGG data.

Although, direct visual analysis of the EGG is impossible, the visual inspection of the waveform can be used to detect any obvious major movement artifacts. These major movement artifacts were defined as abnormally large positive or negative peaks in the tracing and when we identified high amplitude movement artifact by visual analysis, we removed using the locally developed program.

Discrete wavelet analysis of EGG signals

All WTs can be specifed in terms of a low-pass filter h, which satisfies the standard quadrature mirror filter condition:

$$H(z)H\left(z^{-1}\right) + H(-z)H\left(-z^{-1}\right) = 1 \tag{1}$$

where $H(z)$ denotes the z-transform of the filter h. Its complementary high-pass filter can be defined as

$$G(z) = zH\left(-z^{-1}\right). \tag{2}$$

A sequence of filters with increasing length (indexed by i) can be obtained.

$$H_{i+1}(z) = H\left(z^{2^i}\right)H_i(z) \tag{3}$$

$$G_{i+1}(z) = G\left(z^{2^i}\right)H_i(z), \quad i = 0, \ldots, I-1 \tag{4}$$

with the initial condition $H_0(z)=1$. It is expressed as a two-scale relation in time domain

$$\begin{aligned} h_{i+1}(k) &= [h]_{\uparrow 2^i} * h_i(k), \\ g_{i+1}(k) &= [g]_{\uparrow 2^i} * h_i(k), \end{aligned} \tag{5}$$

where the subscript $[\cdot]_{\uparrow m}$ indicates the up-sampling by a factor of m and k is the equally sampled discrete time.

The normalized wavelet and scale basis functions $\varphi_{i,l}(k)$, $\psi_{i,l}(k)$ can be defined as

$$\begin{aligned} \varphi_{i,l}(k) &= 2^{i/2}h_i\left(k - 2^i l\right), \\ \psi_{i,l}(k) &= 2^{i/2}g_i\left(k - 2^i l\right), \end{aligned} \tag{6}$$

where the factor $2^{i/2}$ is an inner product normalization, i and l are the scale parameter and the translation parameter, respectively. The DWT decomposition can be described as

$$\begin{aligned} s_{(i)}(l) &= x(k) * \varphi_{i,l}(k), \\ d_{(i)}(l) &= x(k) * \psi_{i,l}(k), \end{aligned} \tag{7}$$

where $s_{(i)}(l)$ and $d_i(l)$ are the approximation coefficients and the detail coefficients at resolution i, respectively [21, 22].

In the present study, EGGs were decomposed with 'db3' Daubechies Wavelets to the third level. Third detail signals and third approximation signal at the third level were reconstructed from the coefficient matrices. PSD calculations for each of these signals were made using the Welch method. A Hanning window of 100 samples with an overlap of 50 samples was used in the Welch method. All calculations were computed using Matlab software package (The MathWorks co. MATLAB® version 7.1).

Welch method for spectral analysis of EGG signals

We made the spectral estimate with Welch's method [23], which can be expressed as follows [24]:

$$\widetilde{P}_{per}(\omega) = \frac{1}{MUL} \sum_{i=1}^{L} \left| \sum_{n=0}^{M-1} x_N^i(n) W(n) e^{-j\omega n} \right|^2, \tag{8}$$

where

$$\begin{aligned} & x_N^i(n) = x_N[n + (i-1)M], \\ & \quad 0 \leqslant n \leqslant M-1,\ 1 \leqslant i \leqslant L, \end{aligned} \tag{9}$$

$$U = \frac{1}{M} \sum_{n=0}^{M-1} W^2(n), \tag{10}$$

Where $x_N(n)$ is the signal of length N and is divided into L sections with length M overlapping each other, $x_N^i(n)$ is the number i section of $x_N(n)$; $W(n)$ is the window function of length M [25].

The value of each parameter was normalized to the range of zero to one that is observed to be the maximum PSD.

Results and discussion

EGG has been proposed as a diagnostic test for the clinical evaluation of patients with unexplained nausea, vomiting, abdominal pain and diabetic gastroparesis. One of the main problems with the assessment of EGG is the poor quality of the recording, i.e., the weakness of the real gastric signal and the strong interference such as respiratory, motion artifacts and electrocardiography. As a result, direct visual evaluation of EGG is impossible and computer-aided analysis is essential. The EGG signal is by nature a nonstationary signal in terms of its frequency, amplitude and wave shape. Therefore, this study implemented a DWT analysis for examination EGG signals.

The DWT analyzes the signal at different frequency bands by decomposing the signal into a coarse approximation and detail coefficients. These coefficients represent different sub-frequency bands. DWT is used for the extraction of frequency and amplitude features from the EGG by decomposing the signal into multiple sub-frequency bands.

In this study, first, the EGG signal was decomposed into details and approximation coefficients using DWT. Second, we obtained PSD of wavelet-packet details and approximation coefficients. Both normal coefficients and PSD parameters of DWT obtained from healthy and diabetic persons were used as the input data to statistical processes. Third, the five parameters of DWT data obtained three period–*4 min* of EGG records from 16 healthy subjects and 16 diabetic patients are calculated from listed parameters as follows:

(a) Maximum value of each DWT coefficients
(b) Minimum value of each DWT coefficients
(c) Mean value of each DWT coefficients
(d) Maximum PSD value of each DWT coefficients
(e) Mean PSD value of each DWT coefficients

EGGs were decomposed with 'db3' Daubechies Wavelets to the third level. DWT coefficients are composed of three detail wavelet coefficients (D1, D2, D3) and three approximation signal levels (A1, A2, A3). Since the detail wavelet coefficients are corresponded to noise levels of EGG signal, the study has been focused in approximation signal levels in all analysis results. Therefore, the detail wavelet coefficients are not considered during analysis results in this study.

The approximation coefficients of EGG signals obtained from healthy subjects and gastric dysrhythmic subjects are given in Fig. 2a and b, respectively. The horizontal axis is the number of samples, whereas the vertical axis is the normalized amplitude. PSD graphics with Welch method for healthy and gastric dysrhythmic subjects can be seen in Fig. 3a and b, respectively. The horizontal axis is the frequency, whereas the vertical axis is the amplitude of the PSD. The amplitude of PSD is distinctive differences between normal and diabetic gastroparetic subjects, as seen Fig. 3a,b.

Finally, these results are statistically compared with "paired-samples *T*-test" method as healthy and gastroparetic subjects by using SPSS software. Used statistical analyses

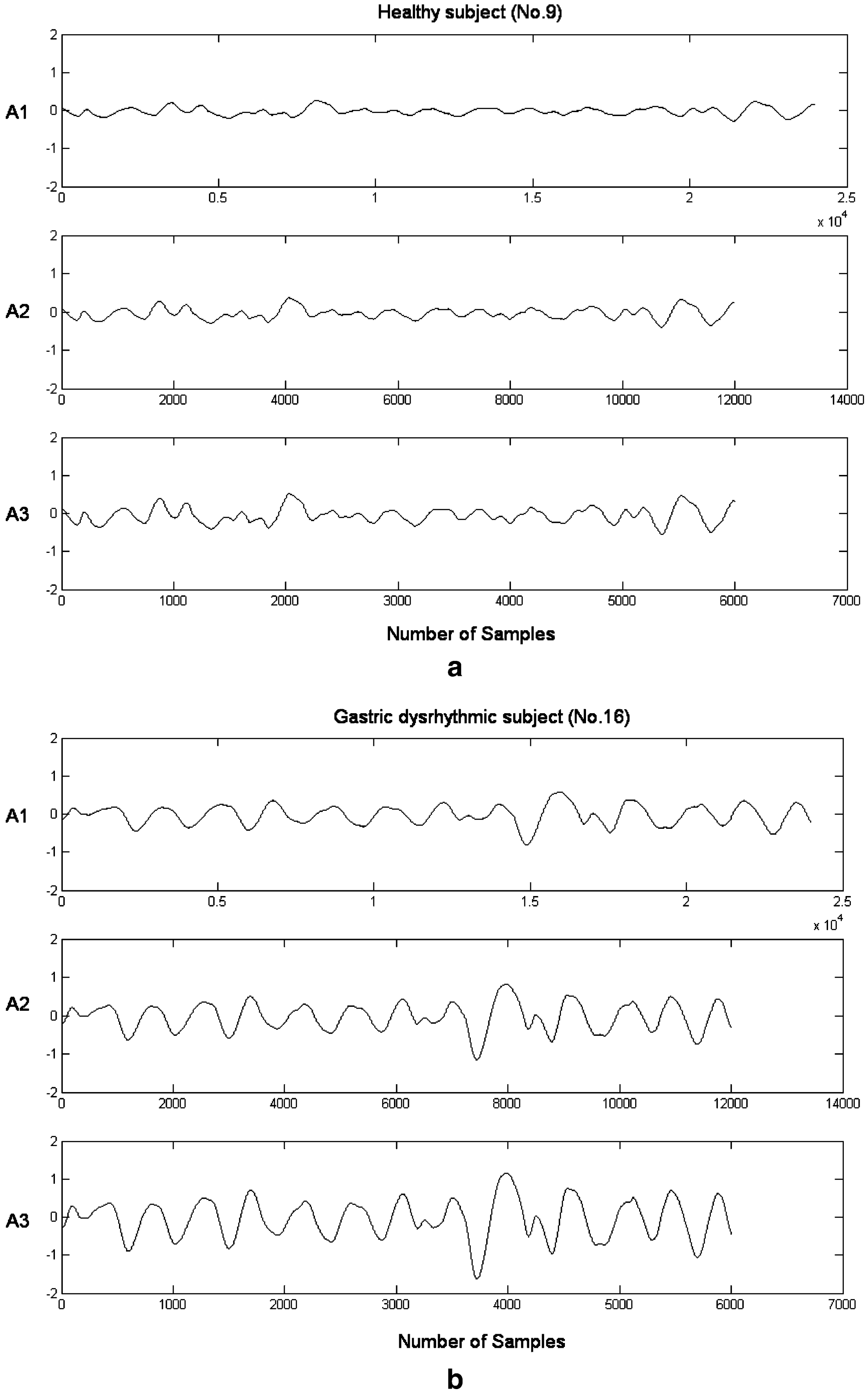

Fig. 2 Decomposition of EGG for **a** normal subject with 'db3' wavelet, **b** gastroparetic subject with 'db3' wavelet

are the Mann–Whitney *U* test and multiple logistic regression analysis. Statistical significance is taken as $p<0.05$. Table 1 summarizes all of the statistical results for five parameters obtained from healthy and diabetic gastroparetic (or gastric dysrhythmic) subjects by using WT method.

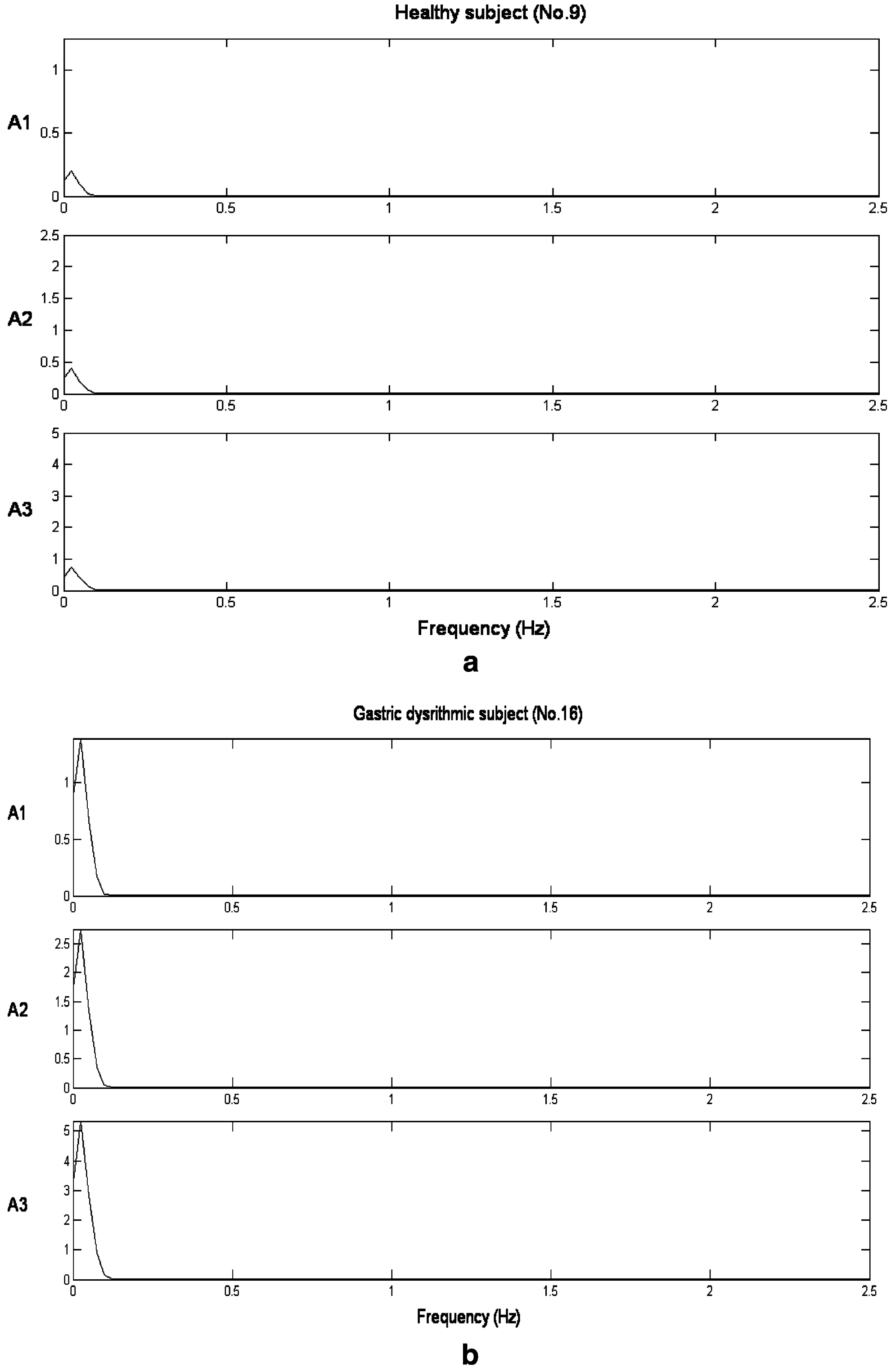

Fig. 3 PSD graphics of a decomposed **a** normal EGG, **b** gastroparetic EGG

Although the some analysis results are obtained as statistical significance, distinctive difference between normal and diabetic gastroparetic subjects are found in the results of 'minimum values of approximation coefficients (A1, A2, A3)', mean values of approximation coefficients (A1, A2, A3), 'maximum PSD values for first approximation coefficient (A1)', and 'mean PSD values for approximation coefficients (A1, A2, A3)' as shown in Table 1. This finding is a benefit tool to distinguish healthy and diabetic gastroparetic groups from each other.

Table 1 The statistical results of five parameters obtained from healthy and diabetic gastric dysrhythmic subjects by using DWT method

	Wavelet coefficients	Healthy subjects (mean±SD)		Gastric dysrhythmic subjects (mean±SD)		*p*
Maximum values	A1	0.8074	0.7976	1.2912	1.44071	.056
	A2	1.1413	1.12772	1.8112	2.00739	.059
	A3	1.6132	1.59451	2.5518	2.82311	.060
Minimum values	A1	−0.8371	0.92428	−1.8252	2.95799	**.035**
	A2	−1.177	1.31177	−2.5739	4.18131	**.035**
	A3	−1.6454	1.86819	−3.6362	5.90669	**.034**
Mean values	A1	−0.0066	0.08014	−0.0299	0.01831	**.038**
	A2	−0.0094	0.11338	−0.0423	0.02589	**.039**
	A3	−0.0133	0.1604	−0.0598	0.03654	**.039**
Maximum values of PSD	A1	1.0294	1.40131	1.9272	2.93023	**.049**
	A2	1.8923	2.67604	3.2589	5.01625	.081
	A3	3.3399	4.99564	5.2872	8.34125	.138
Mean values of PSD	A1	0.0187	0.02491	0.0365	0.05618	**.042**
	A2	0.0372	0.04956	0.0721	0.11129	**.043**
	A3	.0743	.09853	.1459	.22547	**.041**

The parameters with a significant difference are highlighted in bold
SD = standard deviation

Conclusion

RSA based on FT has been widely used for frequency analysis of gastric electrical dysrhythmia [13, 14, 26]. One drawback of the FT with RSA is that EGG dysrhythmias need to be of certain duration to be detected by the calculation. Most EGG analysis programs use recording epochs of approximately 4 min duration for the RSA analysis. Most detectable rhythm disturbances must be 2 min or more in duration. Dysrhythmias of shorter duration may be missed by the RSA technique. In these methods several minutes of data are required to accurately compute a power spectrum of the EGG. Each power spectrum provides ensemble information of the signal. In our study we were demonstrated detecting dysrhythmia of brief duration with DWT analysis. In the RSA, any rhythmic variation within these several minutes cannot be detected and the exact time information of the rhythmic variations is not available. But DWT, which we used, is ability to compute the power spectrum not only at any particular time interval but at any particular time instant thereby resulting in the instantaneous determination of the rhythmic variation.

DWT analysis method enables us to define whether the EGG recording was normal or abnormal therefore the cutenous EGG can be used to asses whether the subject has normal or abnormal gastric electrical activity. We established that there were significant differences between the EGGs of diabetic gastroparetic and healthy subjects.

In conclusion, this paper has shown that the DWT analysis method very useful in analysis of cutaneous EGG recordings especially in detecting dysrhythmic events and rhythmic variations of the gastric slow wave in a cutaneously measured electrogastrographical signal. We believe that the successful application of the DWT shown in this paper will facilitate research on the EGG and its application to the diabetic gastroparetic patients.

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