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Phase coupling analysis of gastric pressure activity via wavelet packet based diagonal slice spectra

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ABSTRACT

We propose a new analysis method to detect quadratic phase coupling (QPC) behavior of human gastric interdigestive pressure activity that has been acquired by a telemetric capsule-like mini-robot. The method is referred to as diagonal slice spectra. They are the Fourier transforms of the diagonal slices of the triple correlations, and can actually detect the phase coupling and coupled components respectively by expanding the real process into the complex counterpart through Hilbert transform. In order to learn more about the QPC structure in a certain frequency band that we are mostly interested in and obtain a higher frequency resolution, the method, named the wavelet packet based diagonal slice spectrum, is introduced. It shows that the nonlinear QPC behavior occurs during gastric contractions (phase II), whereas no distinct phase coupling occurs during gastric motor quiescence (phase I). It is the nonlinear cell-to-cell coupling mechanisms, existence of fast and slow waves and their interactions that nonlinear QPC structure of the gastric pressure activity occurs.

1. Introduction

The human gastric pressure activity, especially the gastric interdigestive pressure activity, is an important way to measure gastric motility, i.e., contractility of smooth muscles of the stomach, and coordinate gastric-duodenal motor activity. Proper evaluation of gastric motility includes evaluation on frequency and amplitude of the gastric pressure wave as well as their nonlinear interactions of the activity. It is reasonable to believe that the gastric pressure activity is nonlinear since there are already adequate evidences to convince us that the gastric myoelectric activity (GMA) at cell level is nonlinear chaotic, driven by the nonlinear coupling mechanisms of cell-to-cell [1–4].

In this study, we propose a telemetric capsule-like diagnosis system that can enter into human gastrointestinal (GI) tract and acquire the gastric pressure activity during its tour of the capsule mini-robot. Then, a method referred to as the wavelet packet based diagonal slice spectrum is proposed to detect the presence of quadratic phase coupling (QPC) that the human gastric pressure activity may hold.

2. Subjects and methods

2.1. Subjects

Ten healthy volunteers (5 men and 5 women aged 27–55 years) were recruited through a hospital advertisement before the experiment. All volunteers gave written informed consent. All were in good health, had no previous history of gastrointestinal symptoms or surgery, were not taking any medications, and had normal physical examinations. The experiment was conducted in the People's Hospital of Pudong New District of Shanghai, China.

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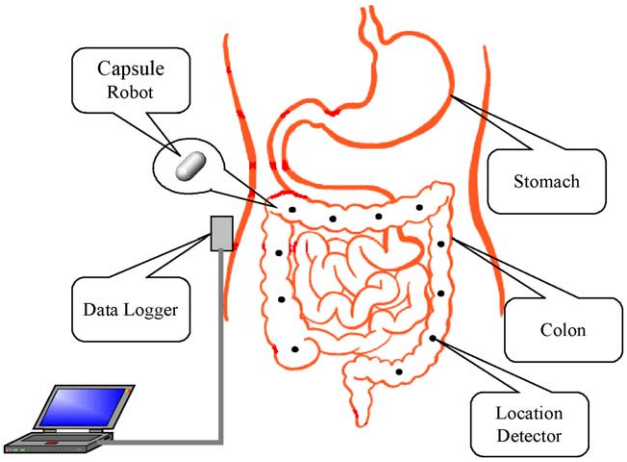

Fig. 1 – The diagnosis system for the GI tract.

2.2. *The overview of the diagnosis system*

The gastric interdigestive pressure activity was measured by using a telemetric capsule-like microsystem device developed for GI tract diagnosis in our institute in the past few years [5,6]. The four main components of the diagnosis system are: (1) an disposable and ingestible mini-telemetric capsule, which performs data acquisition of physiological parameters like gastric pressure activity within the GI tract under the normal physiological conditions; (2) an in vitro pocket data logger, which can be mounted around the waist of the subject and receives physiological data from the mini-telemetric capsule; (3) an ultrasonic locating unit, which performs detecting where the capsule is in the GI tract; (4) an in vitro data processing station, which is composed of a computer to download the acquired data from the pocket data logger via universal RS-232 interface and finally process them under the instruction and guidance of a doctor (see Fig. 1).

The outline of the mini-telemetric capsule robot, the core of diagnosis system looks like a little bigger pharmaceutical pill with 21.1 mm length, 10.0 mm diameter and 2.9 g weight. It is primarily composed of parameter sensitive sensors (e.g. pressure, temperature, etc.); a signal-processing unit (sampling & A/D); a signal-transmitting unit and a power supply (battery cells) [5,6].

The sampling rate of the system is about 0.5 Hz (that is, a sample every 2 s). The sampling is more than adequate to measure motility signals that, in humans, lie in the range from 1 cycle per minute (cpm) to 12 cpm (0.016–0.2 Hz).

2.3. *Data analysis*

2.3.1. *The diagonal slice spectra*

It is well known that when a harmonic process undergoes a nonlinear transformation or passes through a power-law device, for example, quadratic even cubic nonlinear phase coupling occurs. Our research will pay more attention on second order nonlinearities, i.e., quadratic phase coupling (QPC, coupling at sum and difference frequencies) since it is relatively meaningful and simple. Three harmonics with frequencies f_k and phases θ_k ($k = 1$–3) are said to be quadratically phase coupled if $f_3 = f_1 + f_2$ and $\theta_3 = \theta_1 + \theta_2$. Where, the triple (f_1, f_2, f_3) is also called a bifrequency [7].

The traditional power spectrum only concerning the magnitude square of the Fourier coefficients cannot provide information regarding such phase coupling [8–10]. The bispectrum or bicoherence based on higher order statistics, on the other hand, emphasizes the triple products of the Fourier coefficients and is really capable of providing such information. However, it costs much computer time, and the two-dimension graph is very complex as compared with that of one-dimension [11–13]. Diagonal slice spectra, which use the diagonal slices of the triple correlations, are just the new method which not only can provide phase coupling information but are much simpler and cost little computer time with a high-resolution ability in one-dimensional plot [14–17].

Slice spectra, which use the diagonal slices of the triple correlations, are also called $1\frac{1}{2}$D-dimension spectra since their dimension is between that of one-dimensional power spectrum and that of two-dimensional bispectrum or bicoherence.

The diagonal slice of the triple correlation of a real stochastic process is

$$c(\tau) = c(\tau, \tau) = E\{x(n)x(n+\tau)x(n+\tau)\}. \tag{1}$$

The diagonal slice spectrum is defined as the Fourier transform of the slice as follows:

$$S(\omega) = \sum_{\tau=-\infty}^{+\infty} c(\tau)\, e^{-j\omega\tau}\, d\tau. \tag{2}$$

It really contains the phase coupling and coupled components. However, it is confusing when multiple QPC relationships exist, and cannot tell which components involved in coupling and which ones are the coupled results. Thus, we need to expand the real sequences into their complex counterpart through Hilbert transform and do QPC analysis in the complex domain.

Consider the complex stochastic QPC harmonics:

$$x(n) = \sum_{i=1}^{3} A_i \exp(j(\omega_i n + \theta_i)), \tag{3}$$

where $A_i > 0$, $\omega_3 = \omega_1 + \omega_2$, θ_1, θ_2 are independent and uniformly distributed over $[0, 2\pi]$, $\theta_3 = \theta_1 + \theta_2$. As in Table 1, the third-order cumulants of a complex stochastic process have 2^3 different definitions depending on whether or not each entry in the cumulant is conjugated. Then, according to no. 2 and no. 6 in Table 1, the slice spectra, namely the FFT of the third-order cumulants, can be used to estimate the coupled ω_3 and the coupling components ω_1, ω_2, respectively. This is helpful for preventing confusion, especially when multiple QPC relationships present. Proving of no. 2 and no. 6 are given in Appendix A.

The diagonal slice spectra of the complex stochastic signals can give out the QPC structures and their estimations are taken over the whole frequency domain. However, in real application, we care more about the QPC structures in a certain frequency band, not the whole frequency domain. Take human gastric motility signals as an example. We care the fre-