

Detection of gastric slow wave propagation from the cutaneous electrogastragram

J. D. Z. CHEN,¹ XIAOPING ZOU,¹ XUEMEI LIN,¹ SHOU OUYANG,² AND JIE LIANG¹

¹Lynn Institute for Healthcare Research, Oklahoma City, Oklahoma 73112;

and ²Xiamen Medical Research Institute, Xiamen 361003, China

Chen, J. D. Z., Xiaoping Zou, Xuemei Lin, Shou Ouyang, and Jie Liang. Detection of gastric slow wave propagation from the cutaneous electrogastragram. *Am. J. Physiol.* 277 (*Gastrointest. Liver Physiol.* 40): G424–G430, 1999.—The gastric slow wave is originated in the proximal stomach and propagates distally toward the pylorus. It determines the maximum frequency and propagation of gastric contractions. The aim of this study was to detect the propagation of the gastric slow wave from the surface electrogastragram (EGG). The study was performed in 11 healthy subjects of normal weight. Gastric myoelectrical activity was recorded for 1 h in the fasting state with the use of a specially designed multichannel recording device that was composed of four identical amplifiers with cutoff frequencies of 1.8 and 16.0 cycles/min. Four active electrodes were placed on the abdomen along the gastric axis and were connected to a common reference electrode placed near the xiphoid process, yielding four-channel bipolar EGG signals. Cross-covariance analysis was performed to compute the time lag among the four channels. There was a time lag in EGG waveform between channels 1 and 4 (9.6 ± 1.1 s); the average time during which the time lag was observed (≥ 3 s) was $89.9 \pm 9.0\%$. There was a significant difference in the time lag among different adjacent channels ($P < 0.04$); the time lag observed between channels 3 and 4 was significantly smaller than that between channels 1 and 2 ($P < 0.03$). No correlation was found between the body mass index and the time lag between channels 1 and 4 ($r = -0.31$, $P = 0.3$). It was concluded that, with a multichannel recording device with identical multiamplifiers and an appropriate arrangement of abdominal electrodes, the propagation of the gastric slow wave could be identified from the EGG in healthy subjects. This method may be used to detect the coupling of the gastric slow wave noninvasively.

electrogastrography; gastric motility; gastric emptying stomach

APPROPRIATE PROPAGATION of gastric contractions or antroduodenal coordination is of great importance to the emptying of the stomach. It is known that gastric motility is regulated by gastric myoelectrical activity that consists of gastric slow waves and spike or second potentials. Spike or second potentials are superimposed on gastric slow waves and are directly associated with gastric contractions. The gastric slow wave determines the propagation and maximum frequency of gastric contractions. It is originated in the proximal part of the stomach and propagates distally toward the pylorus with increasing velocity and amplitude. The

normal frequency of the gastric slow wave is 3 cycles/min (cpm) in healthy humans. Abnormalities in the frequency of the gastric slow wave have been reported in a number of clinical settings and have been associated with gastric motor disorders and gastrointestinal symptoms (1, 9, 10, 13, 14, 19, 20).

Electrogastrography is a noninvasive technique to record gastric myoelectrical activity with the use of abdominal surface electrodes (8). Previous studies have indicated that the electrogastragram (EGG) is a reliable measurement of the gastric myoelectrical activity. The dominant frequency of the EGG has been shown to be the same as the frequency of the gastric slow wave measured from internal electrodes (5, 12, 17). The relative increase of EGG amplitude at the gastric slow wave frequency is associated with gastric contractions (4, 17, 18). Spectral analysis methods have been introduced or developed to qualitatively and quantitatively analyze the EGG (2). The parameters extracted from the EGG are almost exclusively based on spectral analysis of one-channel EGG recording. The information on the coupling or propagation of the gastric slow wave is completely lost. Abnormalities associated with the propagation of the gastric slow wave cannot be detected from the EGG with the current methodology of spectral analysis.

One previous study reported the observation of slow wave propagation from the EGG using a multichannel recording device and ultrasound or X ray for the localization of the stomach (7). The study, however, has never been reconfirmed during the past 10 years. Meanwhile, a number of computer simulation studies have suggested that the detection of the propagation of the gastric slow wave from the EGG is possible (15, 16). The aim of this study was therefore to investigate the feasibility of the detection of the gastric slow wave from multichannel EGG recordings without the assistance of ultrasound or X ray.

METHODS

Subject

The study was performed in 11 healthy subjects (5 females, 6 males, 32–45 yr old) with no history of gastrointestinal diseases and free of gastrointestinal symptoms. The body mass index of the subjects ranged from 18 to 26 kg/m² (22.4 ± 2.9). None of the subjects took medication in the weeks before and during the study. The research protocol was approved by the institutional review board at the Integris Baptist Medical Center of Oklahoma, and the written consent form was signed by all subjects before the study.

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Recording Device

A multichannel recording device was specially designed and developed for this study (Medtronic-Synectics, Shoreview, MN). The device consisted of four identical amplifiers with cutoff frequencies of 1.8 and 16.0 cpm (50% attenuation at these frequencies). A 12-bit analog-to-digital converter was installed in the recording device for the online digitization of the EGG. The multichannel recordings were online displayed on a computer monitor, and the digitized samples were stored on an IBM-compatible 386 PC computer. The device was tested before the study using a signal generator, and it was confirmed that the amplifiers did not generate any phase shifts among different channels when an identical sinusoid of 3 cpm was sent to the input of each channel.

Electrogastrography

Gastric myoelectrical activity in each subject was measured using surface electrogastrography with the device described above. Before the attachment of electrodes, the abdominal surface where electrodes were to be positioned was shaved, if hairy, and was cleaned with sandy skin prep paste (Omni prep Weaver, Aurora, CO) to reduce impedance. Six silver/silver chloride ECG electrodes (DNM, Dayton, OH) were placed on the abdominal skin as shown in Fig. 1, including four active electrodes (*electrodes 1–4*), one reference electrode (*electrode 0*), and a ground electrode. *Electrode 3* was placed 2 cm above the middle point between the xiphoid process and the umbilicus; *electrode 4* was 4 cm on the right horizontal to *electrode 3*; and *electrodes 2 and 1* were placed 45° upper left to *electrode 3* with an interval of 4–6 cm, depending on the size of the subject. The common reference electrode (*electrode 0*) was placed at the cross point of two lines, one horizontal-connecting *electrode 1* and the other vertical-connecting *electrode 3*. The ground electrode was placed on the left costal margin, horizontal to *electrode 3*. Connecting each of the four active electrodes to the common reference electrode derived four-channel EGG signals. The sampling frequency was 4 Hz.

The study was performed for 1 h in a supine position after a fast of 6 h or more. The subjects were allowed to watch

regular TV and were asked to stay awake, not to talk, and to remain as still as possible during the whole recording period to avoid motion artifacts.

Waveform Analysis

Waveform analysis was performed on the four-channel EGGs for the detection of time lags in waveform among different channels. Digital lowpass filtering was performed to increase the signal-to-noise ratio. The filter was a finite impulse response filter with a linear phase that does not disturb the phase characteristic of the signal to be processed. Normalized cross-covariance analysis was performed to compute the time lag between any two-channel EGG signals. The calculation was performed on a minute-by-minute basis. In this method, the first sum of the multiplication of the corresponding samples in two EGG signals was calculated. The second sum was computed by shifting the second EGG signal one sample forward or backward, and the n th sum was obtained by shifting the second EGG signal by n samples forward or backward. The time lag between the two time series was determined by the number of samples shifted backward or forward, which resulted in the maximum sum. The time lag was calculated every 1 min using this method. The average value for the whole 1-h recording period was obtained from these 60 values of the time lag.

The values of the time lag calculated included those between *channels 1 and 4*, *channels 1 and 2*, *channels 2 and 3*, and *channels 3 and 4*. The total time lag among the four channels was calculated using two methods: 1) the time lag between *channel 1 and channel 4*; and 2) the sum of the time lags between *channels 1 and 2*, *channels 2 and 3*, and *channels 3 and 4*.

A parameter called percentage of detectability was defined as the percentage of time during which a time lag of ≥ 3 s was found between *channels 1 and 4* or a time lag of ≥ 1 s between any two adjacent channels.

Spectral Analysis

Spectral analysis of the EGG was performed to derive the following EGG parameters in each channel.

EGG dominant frequency/power. The frequency at which the EGG power spectrum had a peak power in the range of 0.5–9.0 cpm was defined as the EGG dominant frequency. The power at the dominant frequency in the power spectrum was defined as the EGG dominant power. These two parameters were calculated using the smooth-power spectral analysis method (2). These values represent the average dominant frequency and power of the EGG during the entire recording period.

Percentage of normal gastric slow waves. The percentage of normal gastric slow waves was defined as the percentage of time during which regular 2–4 cpm slow waves were present over the entire recording period. It was computed with the use of the adaptive spectral analysis method (6). In this method, each EGG recording was divided into blocks of 2 min without overlapping. The power spectrum of each 2-min EGG was calculated and examined to see if the peak power was within the range of 2–4 cpm. The 2-min EGG was called normal if the peak power was within the 2–4 cpm range. Otherwise it was defined as dysrhythmia.

Statistical Analysis

All data were expressed as means \pm SD. ANOVA and paired Student's t -test were applied to investigate the difference observed in the time lag among different channels. Correlation analysis was performed to investigate the correla-

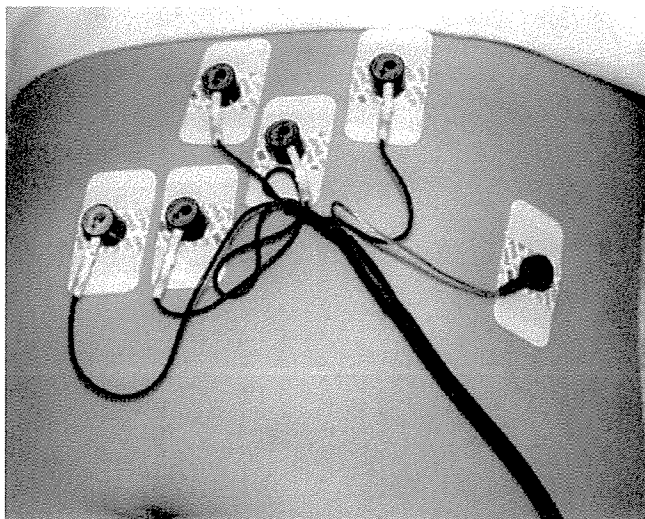


Fig. 1. Position of multiple electrodes on abdomen. Electrode closest to xiphoid process is connected to each of the 4 electrodes placed along gastric axis, yielding 4 bipolar electrogastrogram (EGG) signals. Electrode on left costal margin is a ground.

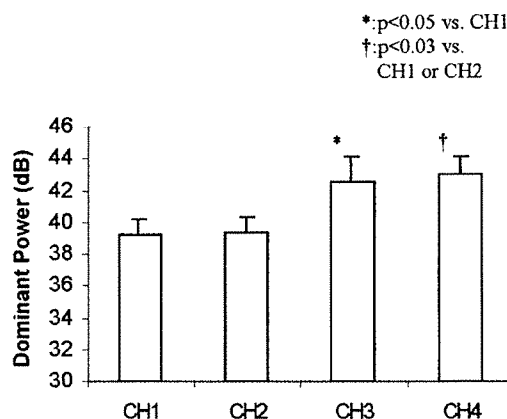


Fig. 2. Dominant power of EGG in 4 different channels. Most distal channel (*channel 4*, CH4) had highest dominant power. Dominant power in *channel 3* (CH3) was statistically significantly higher than that in *channel 1* (CH1), and dominant power in *channel 4* was statistically significantly higher than that in *channel 1* and *channel 2* (CH2).

tion between the detection of slow wave propagation and the body mass index. A *P* value of >0.05 was considered significant.

RESULTS

Normal gastric slow waves were observed in all subjects. The mean percentages of the normal 2–4 cpm slow wave were $96.2 \pm 1.5\%$, $96.0 \pm 1.8\%$, $94.9 \pm 1.8\%$, and $95.1 \pm 1.5\%$ in the four EGG signals from the proximal to distal channels, respectively. No difference was observed among the four channels in either the

percentage of normal 2–4 cpm slow waves or the dominant frequency. The dominant frequency in the eleven subjects ranged from 2.70 to 3.54 cpm. A significant difference was found, however, in the dominant power of the EGG among the four channel EGG recordings (see Fig. 2). The EGG in the more distal channels showed higher dominant power, and the most distal channel had the highest power. *Channel 3* had a higher power than *channel 1*, and *channel 4* had a higher power than both *channels 1* and *2*.

The propagation of the gastric slow wave was observed in all subjects in the four-channel recordings (see Fig. 3). The most obvious phase shift was noted between *channel 1* and *channel 4*. Visually, these two channels showed opposite phases in the waveform. Figure 4 presents minute-by-minute analysis of the time lag between two adjacent channels in one subject. The average time lag calculated based on the cross-covariance analysis of *channels 1* and *4* was 9.6 ± 1.1 s, with a range from 7.6 s to 11.1 s (see Table 1). The average percentage of detectability calculated based on *channels 1* and *4* was $89.9 \pm 9.0\%$, with a range of 78% to 100%. No correlation was found between the observed time lag between *channels 1* and *4* and the body mass index ($r = -0.31$, $P = 0.3$) or between the percentage of detectability and the body mass index ($r = -0.28$, $P = 0.4$). However, a significant correlation was established between the observed average phase shift between *channels 1* and *4* and the percentage of time during which the phase shift was observed ($r = 0.62$, $P < 0.03$).

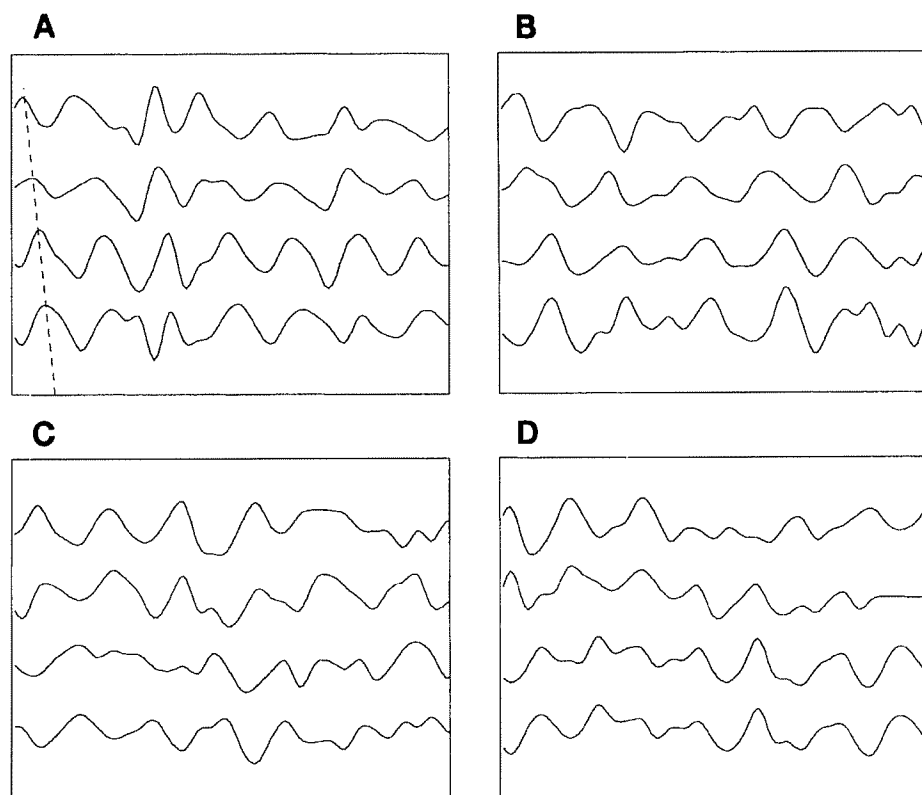


Fig. 3. A portion (2 min) of EGG recordings obtained from 4 different subjects (A–D). In each subject, propagation of gastric slow wave from proximal channel (top trace) to distal channel (bottom trace) can be visually appreciated.

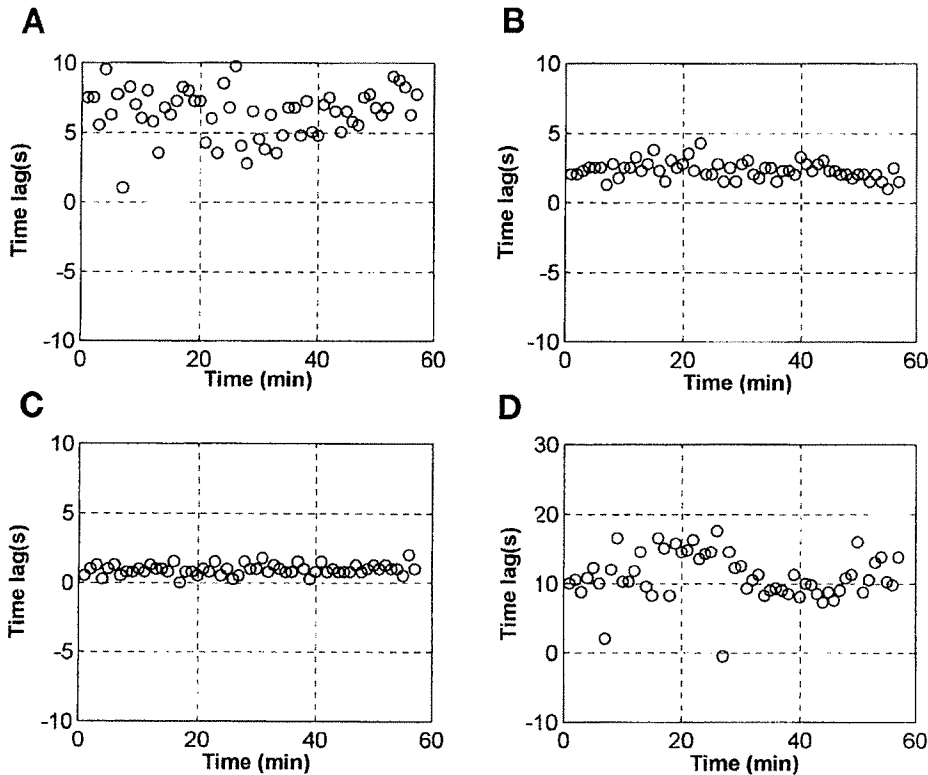


Fig. 4. Time lag between 2 channels of EGG in 1 subject. Time lag was calculated on a minute-by-minute basis with use of cross-covariance method. A: time lag between channels 1 and 2 during 1-h recording. B: time lag between channels 2 and 3. C: time lag between channels 3 and 4. D: time lag between channels 1 and 4.

There was a significant difference among the phase shifts observed between two adjacent channels ($P < 0.04$). The time lag observed between channels 3 and 4 (0.9 ± 0.6 s) was significantly smaller than those observed between channels 1 and 2 (2.5 ± 2.1 s, $P < 0.005$) and between channels 2 and 3 (2.2 ± 1.3 s, $P < 0.03$). The total time lag between channels 1 and 4 calculated by adding those between channels 1 and 2, channels 2 and 3, and channels 3 and 4 was 5.6 ± 3.1 s, which was substantially lower than the value calculated directly from channels 1 and 4 (see Table 1). The

total phase shift calculated this way was negatively correlated with the body mass index ($r = -0.77$, $P < 0.006$, see Fig. 5).

DISCUSSION

In this study we have found that the propagation of the gastric slow wave can be detected from multichannel recordings. The phase shift existed between the most proximal and distal EGG channels during about

Table 1. Time lag(s) between different channels and percentage of time during which propagation was observed

Subject	CH1-2	CH2-3	CH3-4	CH1-4	CH1-4*	Propagation
1	5.50	3.05	1.46	10.12	10.01	82.1
2	1.05	2.95	0.75	9.17	4.75	86.2
3	3.16	2.85	1.04	9.40	7.06	100.0
4	6.37	2.31	0.93	11.04	9.61	96.5
5	2.36	1.40	0.22	11.07	3.99	100.0
6	0.37	2.71	0.00	9.21	3.08	79.6
7	1.71	3.05	1.65	9.83	6.42	97.4
8	1.48	0.44	1.23	7.56	3.14	78.0
9	1.01	0.99	0.24	10.64	2.24	80.7
10	3.06	1.79	0.84	8.84	5.69	88.4
11	1.87	2.57	1.89	8.55	6.33	100.0
Mean	2.54	2.19	0.93	9.58	5.66	89.9

CH1-2, time lag between channels 1 and 2; CH2-3, time lag between channels 2 and 3; CH3-4, time lag between channels 3 and 4; CH1-4, time lag between channels 1 and 4; CH1-4*, time lag calculated by adding time lags CH1-2, CH2-3, and CH3-4. Propagation, % of time during which propagation was observed between channels 1 and 4.

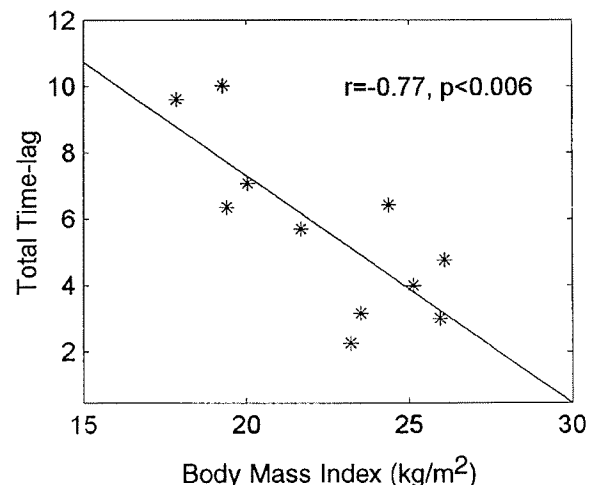


Fig. 5. Correlation between total time lag among the 4 channels and body mass index. Total time lag was calculated by adding time lags between channels 1 and 2, channels 2 and 3, and channels 3 and 4. A significant negative correlation was noted between total time lag and BMI.

90% of the entire recording, and the average value was about 180° (or 10 s). The spectral analysis of the multichannel recordings showed similar EGG parameters among different channels, except the dominant power that was higher in the more distal channel.

Because of its noninvasive nature, electrogastrography has received more and more attention among researchers and clinicians. Although great progress has been made in the measurement and analysis of the EGG during the past 10 years, EGG studies have been performed almost exclusively based on one-channel recording and spectral analyses. A number of different abnormalities in the gastric slow wave have been observed in patients with gastric motility disorders. These include 1) abnormal frequency of the gastric slow wave. In this case the gastric slow wave may propagate distally, whereas its frequency is either too low or too high or arrhythmic; 2) ectopic pacemaker in the distal antrum firing at a higher frequency (tachygastria) and propagating retrogradely to the corpus; and 3) uncoupling of the gastric slow wave. In this case, the gastric slow wave does not propagate and its frequency is different at different regions of the stomach. The established method of the spectral analysis of one-channel EGG recording is able to detect the first category of the slow wave abnormalities but not able to detect the propagation and uncoupling of the gastric slow wave. The methodology presented in this paper would allow us to extract much more information on the gastric slow wave from the EGG, including the propagation and coupling or uncoupling. The experimental data obtained in this study demonstrated the feasibility of the detection of slow wave propagation and coupling or uncoupling.

The spectral analysis of the multichannel EGGs would provide relevant information regarding the coupling or uncoupling of the gastric slow wave. It is well known that smooth muscles in different regions of the stomach generate slow waves with different frequencies when measured from muscle strips. The smooth muscles in the proximal part of the stomach produce slow waves with higher frequencies, and those in the distal portion of the stomach produce slow waves with lower frequencies. When the smooth muscles are coupled in the whole stomach, the proximal part of the stomach that fires at the highest frequency drives the other parts of the stomach to the same high frequency (usually about 3 cpm). That is, when the gastric slow wave is coupled, it propagates distally. Accordingly, the multichannel EGG recordings should reveal an identical slow wave frequency at different locations as shown in this paper. When the gastric slow wave is uncoupled, however, the gastric slow waves at different regions may have different frequencies. Consequently, the multichannel EGG recordings would reveal different dominant frequencies at different locations, suggesting uncoupling of the slow wave. It is anticipated that the proposed multichannel recording method may become a useful tool to study the uncoupling of the gastric slow wave (or discoordination of gastric contractions) in patients with gastric motility disorders.

The observation of the slow wave propagation was reported in a previous study 10 years ago. With the similar arrangement of the abdominal electrodes and with the aid of ultrasound or X ray for the localization of the stomach, phase shifts were observed among different EGG channels in the fasting state in thin volunteers but not in obese volunteers. Forward propagation was observed in the majority of the thin subjects, and the total phase shift among the four channels was comparable with that reported in this study (7). In another study, retrograde propagation of tachygastria slow waves was observed in a few patients with gastroparesis (3). The position of the stomach was also localized with ultrasonography. In this current study, however, localization of the stomach was not performed and seemed unnecessary, which would make the methodology more practical and feasible in both clinical and research settings. Computer simulations performed by Kothapalli (15) with the use of a three-dimensional model, as well as those performed in our laboratory, also predicted that propagation of the gastric slow wave may be detected from the phase shift between different positional EGG channels (15, 16). The predicted total phase shift observable in the EGG was very close to the value reported in this study.

The detectibility of the slow wave propagation from the EGG seems to be associated with the thickness of the abdominal wall or body mass index. One of the previous studies failed to observe slow wave propagation from the EGG in obese volunteers (7). Our recent computer simulation results indicated that the detectibility of slow wave propagation decreases as the thickness of the abdominal wall increases (16). This current study showed that the detectibility is negatively correlated with the body mass index when the two channels are close but not correlated with the body mass index when the two channels are far apart. This is because the phase shift between two close channels is small and therefore sensitive to noise. It also indicates that the proposed method is less sensitive in detecting the phase shift between two close channels. It may be explained with the example of examining a continuous change of color from light to dark. When we look at the two extremes (lightest and darkest), we can accurately tell that they are very different. However, if we have to examine two very adjacent colors, we may say that there is no difference, and adding the differences (no difference) among the adjacent colors together we may get a false claim that there is no difference even between the lightest and the darkest. Although this is an exaggeration, the logic is similar. When the two-channel signals are obtained from the electrodes that are far away, the actual phase shift between the two channels is large and, therefore, is less sensitive to noise and more accurate.

It is well known that the slow wave propagates distally with increasing velocity and amplitude, i.e., a smaller phase shift between two more-distal channels and higher amplitude in a more-distal channel. This was also demonstrated in the data reported in this study. The average time lag observed between channels

3 and 4 was significantly smaller than that between channels 1 and 2 or between channels 2 and 3. Based on our experience from previous studies with the ultrasonographic localization of the stomach, we believe that electrodes 3 and 4 were above the antrum, whereas electrodes 1 and 2 were above the proximal stomach in most of the subjects. Our data also showed a significantly higher power in the more-distal EGGs.

We would like to point out that the following factors are important in the detection of slow wave propagation from the EGG.

1) All amplifiers in the multichannel recorder must be perfectly equal and do not bear any random phase shifts. This is, however, not easy, because the filters built into the amplifier are usually of nonlinear phase. We have previously tested two EGG multichannel recorders from two different companies and found that the amplifiers were not exactly equal. In this study, we tested the device using a sine wave and found it satisfactory.

2) The proper positioning of the electrodes is important. All EGG signals must be produced by connecting "active" electrodes to a common reference electrode, and the reference electrode should not be placed in a location where the gastric signal is strong. If the common reference electrode is located above the distal antrum, all EGG signals would be similar and no phase shifts would be observed. The active electrodes should be placed along the gastric axis.

3) Results may be influenced by the condition of the subjects. Assume that there are two internal signals, one in the corpus (*A*) and the other in the antrum (*B*). The surface EGG is then a weighted summation of these two signals expressed as $EGG = a \cdot A + b \cdot B$, where weight, *a* or *b*, is inversely correlated with the distance between signal *A* or *B* and the surface electrode. When the thickness of the abdominal wall is zero, $EGG1 = A$, for the electrode placed over the corpus, and $EGG2 = B$ for the electrode over the antrum. That is, EGG1 represents only signal *A*, whereas EGG2 represents only signal *B*. The phase shift between *A* and *B* is thus completely observed from EGG1 and EGG2. If the thickness of the abdominal wall is not zero, EGG1 represents mainly *A* and partially *B*, whereas EGG2 represents mainly *B* and partially *A*. The phase shift between *A* and *B* is still observable, but the observed phase shift may not be equal to the phase shift between *A* and *B*. If the thickness of the abdominal wall becomes infinite in comparison with the size of the stomach, the contributions of signals *A* and *B* to the EGG are always equal no matter where the surface electrode is located. That is, EGG1 is always equal to EGG2, and no phase shifts can be observed. In a real situation, the thickness of the abdominal wall is neither zero nor infinite, and therefore the phase shift may or may not be observed. To get the best results, the subject should be slim and not overweight.

4) The study should be performed in the fasting state. It becomes difficult in the fed state. The reason is that

there are second potentials or spike bursts superimposed on the slow wave in the fed state. These superimposed activities would smooth out the waveform differences among different positional EGGs. This was proven in computer simulations performed in our laboratory.

5) The filter should not be too narrow or sharp. A narrow and sharp filter will result in smoothed or sinusoid-like EGGs and make the observation more difficult.

6) An appropriate data analysis method should be used for detection of the phase shift. In this study, the phase shift was calculated based on the shift of energy centers of the waves between two channels.

In two separate previous studies, Smout et al. (17) and Familoni et al. (11) proposed dipole models of gastric slow waves. Based on the dipole model, the observation of this study may be interpreted as follows: channels 1 and 4 saw different sides of the same electrical dipole generated by depolarization of a ring of gastric smooth muscle. It should be noted that the methodology developed in this study is able to detect whether the gastric slow wave propagates and in which direction it propagates. It does not provide accurate information about the propagation velocity.

In conclusion, the propagation of the gastric slow wave is detectable from the multichannel EGG recordings with the use of an appropriate recording device and appropriate arrangement of the electrodes. The detectability of slow wave propagation is not correlated with the body mass index when the two channels are far apart in distance and is negatively correlated with the body mass index when the two channels are close in distance. The spectral analysis of the multichannels may provide useful information on the coupling or uncoupling of the gastric slow wave.

We are grateful to Loretta Dunnaway for assistance in the preparation of the manuscript and to Sigrid Elsenbruch for assistance in the statistical analysis of the data.

The generous donation of the recording equipment from Medtronic-Synectics is greatly appreciated.

Address for reprint requests and other correspondence: J. D. Z. Chen, GI Division, 4.106 McCullough Bldg., Dept. of Medicine, UTMB, 301 University Blvd., Galveston, TX 77555 (E-mail: jianchen@utmb.edu).

Received 26 March 1998; accepted in final form 16 April 1999.

REFERENCES

1. Abell, T. L., and J.-R. Malagelada. Glucagon-evoked gastric dysrhythmias in humans shown by an improved electrogastrographic technique. *Gastroenterology* 88: 1932–1940, 1985.
2. Chen, J. A computerized data analysis system for electrogastrogram. *Comput. Biol. Med.* 22: 45–58, 1992.
3. Chen, J., and R. W. McCallum. Electrogastrogram: measurement, analysis and prospective applications. *Med. Biol. Eng. Comput.* 29: 339–350, 1991.
4. Chen, J., R. D. Richards, and R. W. McCallum. Identification of gastric contractions from the cutaneous electrogastrogram. *Am. J. Gastroenterol.* 89: 79–85, 1994.
5. Chen, J., B. D. Schirmer, and R. W. McCallum. Serosal and cutaneous recordings of gastric myoelectrical activity in patients with gastroparesis. *Am. J. Physiol.* 266 (Gastrointest. Liver Physiol. 29): G90–G98, 1994.
6. Chen, J., W. R. Stewart, and R. W. McCallum. Adaptive spectral analysis of episodic rhythmic variations in gastric myoelectric potentials. *IEEE Trans. Biomed. Eng.* 40: 128–135, 1993.

7. **Chen, J., J. Vandewalle, W. Sansen, E. van Cutsen, G. Vantrappen, and J. Janssens.** Observation of the propagation direction of human electrogastric activity from cutaneous recordings. *Med. Biol. Eng. Comput.* 27: 538–542, 1989.
8. **Chen, J. D. Z., and R. W. McCallum.** (Eds.) *Electrogastrography: Principles and Applications*, edited by J. D. Z. Chen and R. W. McCallum. New York: Raven, 1994.
9. **Cucchiara, S., G. Riezzo, R. Minella, G. Vallone, P. F. Vallone, I. Giorgio, and S. Auricchio.** Electrogastrography in nonulcer dyspepsia. *Arch. Dis. Child.* 67: 613–617, 1992.
10. **Dubois, A.** Gastric dysrhythmias: pathophysiological and etiologic factors. *Mayo Clin. Proc.* 64: 246–250, 1989.
11. **Familoni, B. O., T. L. Abell, and K. L. Bowes.** A model of gastric electrical activity in health and disease. *IEEE Trans. Biomed. Eng.* 42: 647–657, 1995.
12. **Familoni, B. O., K. L. Bowes, Y. J. Kingma, and K. R. Cote.** Can transcutaneous recordings detect gastric electrical abnormalities? *Gut* 32: 141–146, 1991.
13. **Hasler, W. L., H. C. Soudah, G. Dulai, and C. Owyang.** Mediation of hyperglycemia-evoked gastric slow wave dysrhythmias by endogenous prostaglandin. *Gastroenterology* 108: 727–736, 1995.
14. **Koch, K. L., R. M. Stern, M. Vasey, J. J. Botti, G. W. Creasy, and A. Dwyer.** Gastric dysrhythmias and nausea of pregnancy. *Dig. Dis. Sci.* 35: 961–968, 1990.
15. **Kothapalli, B.** Electrogastrogram simulation using a three-dimensional model. *Med. Biol. Eng. Comput.* 31: 482–486, 1993.
16. **Liang, J., and J. D. Z. Chen.** What can be measured from surface electrogastric activity: computer simulations. *Dig. Dis. Sci.* 42: 1331–1343, 1997.
17. **Smout, A. J. P. M., E. J. van der Schee, and J. L. Grashuis.** What is measured in electrogastric activity? *Dig. Dis. Sci.* 25: 179–187, 1980.
18. **Sun, W. M., A. Smout, C. Malbert, L. Edelbroek, K. Jones, J. Dent, and M. Horowitz.** Relationship between surface electrogastric activity and antropyloric pressure. *Am. J. Physiol.* 268 (Gastrointest. Liver Physiol. 31): G424–G430, 1995.
19. **Telander, R. L., K. G. Morgan, D. L. Kreulen, P. F. Schmalz, K. A. Kelly, and J. H. Szurszewski.** Human gastric atony with tachygastria and gastric retention. *Gastroenterology* 75: 495–501, 1978.
20. **You, C. H., K. Y. Lee, W. Y. Chey, and R. Menguy.** Electrogastrographic study of patients with unexplained nausea, bloating and vomiting. *Gastroenterology* 79: 311–314, 1980.

