Serosal and cutaneous recordings of gastric myoelectrical activity in patients with gastroparesis

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Chen, Jian de Z., Bruce D. Schirmer, and Richard 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.—The aims of this study were to *1*) investigate gastric myoelectrical activity in patients with gastroparesis, *2*) validate the cutaneous electrogastrogram (EGG) in tracking the frequency change of the gastric slow wave, and *3*) investigate the effect of electrical stimulation on gastric myoelectrical activity. Gastric myoelectrical activity was recorded in 12 patients with documented gastroparesis using serosal electrodes for > 200 min in each subject. All recordings were made at least 4 days after surgery. Each session consisted of a 30-min recording in the fasting state and a 30-min recording after a test meal. The test meal (liquid or mixed) was selected according to patient's tolerance. Electrical stimulation was performed in three subjects via the serosal electrodes at a frequency of 3 cycles/min. Gastric myoelectrical activity was recorded using serosal electrodes in each session. The serosal recording showed slow waves of 2.5 to 4.0 cycles/min in all 12 subjects. Absence of spikes was noted in 11 of the 12 subjects. The simultaneous serosal and cutaneous recording of gastric myoelectrical activity showed that the frequency of the EGG was exactly the same as that of the serosal recording. Liquid meals resulted in a significant decrease in slow-wave frequency (Student's t test, $P = 0.006$), and the EGG accurately reflected this change. Electrical stimulation had no effect on the frequency of the gastric slow wave and did not induce spikes. It was concluded that *1*) the absence of spike activity was the main abnormality observed in these gastroenteric patients, *2*) the EGG accurately reflected the frequency of the gastric slow wave and was able to detect changes induced by the test meal, and *3*) electrical stimulation in patients with gastroparesis at the physiological frequency of 3 cycles/min may not have any effect on gastric myoelectrical activity.

electrogastrogram; electrogastrography; stomach; electromyogram; gastric emptying; gastrointestinal motility; electrical stimulation

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GASTRIC MOTILITY DISORDERS have been frequently observed in patients with gastroparesis. Because gastric motility is controlled by myoelectrical activity of the stomach, it is of great interest to study gastric myoelectrical activity in gastroparetic patients, and it is also of interest to investigate the effect of electrical stimulation on gastric myoelectrical activity.

Gastric myoelectrical activity consists of slow waves and spikes. The gastric slow wave is omnipresent, and its frequency in humans is ~3 cycles/min. Spikes are superimposed on the slow wave and are directly associated with gastric contractions. Gastric myoelectrical activity can be measured intraluminally by intubating the stomach with a catheter containing electrodes (2, 6, 16) or serosally by implanting electrodes on the serosal surface of the stomach (13, 22, 25, 28) or by a cutaneous method of placing electrodes on the abdominal skin (4, 8, 29, 30). The cutaneous recording of gastric myoelectrical activity is usually termed the electrogastrogram (EGG).

Gastric myoelectrical rhythmic abnormalities in patients with gastroparesis have been reported in the literature (1, 10, 15, 20, 34, 35). In a recent study Bortolotti et al. (6), using intraluminal electrodes, observed a large variety of myoelectrical rhythmic abnormalities associated with motor disorders in six patients with chronic idiopathic gastroparesis. Similar results were reported by Abell et al. (1) in patients with diabetic gastroparesis.

The cutaneous EGG has been shown to be a reliable method for the measurement of gastric myoelectrical activity. A previous study in dogs using both cutaneous and serosal electrodes showed that the frequency of the gastric slow wave could be detected in the EGG, and the spike activity was reflected in the EGG as an increase in amplitude (28). A similar study in humans has recently been reported: both normal and abnormal gastric myoelectrical activities could be recognized from the EGG, except abnormalities involving a loss of coupling (13).

Electrical stimulation has been an exciting area since ancient times. It has been very successfully applied in the field of cardiology. However, the role for electrical stimulation in the gastrointestinal tract has been very rarely discussed (17, 19, 26, 27). In a study performed in our laboratory (5) the effect of electrical stimulation of the stomach on gastric myoelectrical activity in 10 dogs was investigated. A model of gastroparesis was implemented on five dogs using truncal vagotomy and combining it with injections of glucagon, which induces gastric electrical dysrhythmias. It was shown that electrical stimulation had no effect on the frequency of the gastric slow wave and did not induce spike activities.

The aims of our study were to *1*) measure gastric myoelectrical activity in patients with gastroparesis using serosal electrodes, and investigate whether gastric myoelectrical rhythmic abnormalities frequently reported in the literature will be seen in the serosal recording; *2*) investigate whether a test meal will change the pattern of gastric myoelectrical activity, and whether the cutaneous EGG can detect such a change using the serosal recording as a "gold standard"; and *3*) electrically stimulate the stomach via the implanted serosal electrodes, and investigate the effect of electrical stimulation of the stomach on gastric myoelectrical activity in patients with gastroparesis documented by delayed gastric emptying of a solid meal.

Table 1. *Patient information*

Patient	Sex	Age, yr	Gastroparesis	GE, %	P-Obstruction
J1	F	20	Idiopathic	73	No
J2	F	39	Idiopathic	76	No
J3	F	24	Idiopathic	79	Yes
J4	F	30	Idiopathic	75	Yes
J5	M	46	Diabetic	93	No
J6	F	33	Diabetic	83	No
J7	F	39	Diabetic	100	No
J8	M	34	Diabetic	ND	No
J9	M	28	Diabetic	87	No
J10	F	28	Diabetic	ND	No
J11	F	32	Diabetic	80	No
J12	F	39	Idiopathic	ND	No

GE, percentage of gastric retention after 2 h; P-Obstruction, intestinal pseudoobstruction; ND, not done because patient could not tolerate gastric emptying study; F, female; M, male.

MATERIALS AND METHODS

Subject. Twelve patients (Table 1; mean age 32.7 yr) with gastroparesis participated in the study. All but one patient had a documented delayed gastric emptying of an isotope-labeled solid meal. One patient was not able to eat the test meal for the gastric emptying study. Five patients were diagnosed as having idiopathic gastroparesis, and seven patients had diabetic neuropathy. Two patients had evidence of intestinal pseudoobstruction. The common symptoms of these patients were severe nausea, vomiting, abdominal pain, weight loss, and anorexia. All patients had failed to adequately respond to prokinetic therapy for impaired gastric emptying. A feeding jejunotomy tube was surgically placed for nutritional support. No medications with known effect on gastrointestinal motility were given on days of the study. The protocol was approved by the Human Investigation Committee at University of Virginia Health Science Center, and written consent forms were signed by all subjects before the study.

Gastric emptying of solid meal. The standard test meal for determining gastric emptying of solids consisted of 7.5 oz commercial beef stew mixed with 30 g chicken livers. The chicken livers were microwaved to a firm consistency and cut into 1-cm cubes. The cubes were then evenly injected with 18.5 MBq (500 μCi) of technetium-99m sulfur colloid. The liver cubes were mixed into beef stew, which was heated in a microwave oven. After the intake of this isotope-labeled solid meal, the subject was asked to lie supine under the gamma camera for 2 h. The percentage of gastric retention after 2 h was calculated. Gastric emptying was performed before the study in nine patients, and all had gastric retention of $>70\%$ after 2 h (Table 1) and half time for gastric emptying in excess of 150 min. Three other patients had delayed gastric emptying performed by other hospitals before being admitted to the University of Virginia Hospital and could not tolerate the gastric emptying study at the University of Virginia Hospital because of severe nausea and vomiting.

Placement of serosal electrodes. Bipolar recording electrodes were implanted on the serosal surface of the stomach during the scheduled surgery for the placement of the feeding jejunostomy tube. Four pairs of electrodes (S_1–S_4) were arranged in an arching line along the greater curvature from the corpus to the pylorus at intervals of 4 cm (Fig. 1). The fourth pair (S_4) was 4 cm proximal to the pylorus. The distance between two electrodes in each pair was 4 mm. The electrodes were 28-gauge stainless steel cardiac pacing wires (A & E Medical, Farmingdale, NJ). The electrodes were affixed to the gastric surface by partially embedding the wire in the seromuscular layer of the stomach. Wires were brought out through the

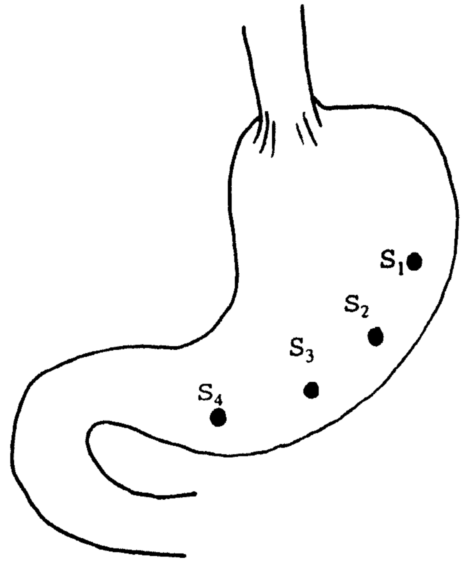

Fig. 1. Position of implanted serosal electrodes along greater curvature. Interval between adjacent electrodes was 4 cm, and fourth pair (S_4) was 4 cm proximal to pylorus.

abdominal wall percutaneously and placed under a sterile dressing until needed for recording studies.

Placement of cutaneous electrodes. The abdominal skin at the recording site was cleaned with sandy skin prepping paste (OMNI Prep, Weaver) to achieve better conduction and to reduce skin-electrode motion artifacts. Four electrodes (biopotential skin electrode, In Vivo, Metric, CA) filled with electrode jelly (Beckman, Fullerton, CA) were placed on the abdominal surface. Three "active" electrodes (*electrodes 1–3*) were placed over the stomach, and a common reference electrode (*electrode 0*) was placed 6–10 cm superior near the right breast (Fig. 2). Three cutaneous recordings were made by connecting each active electrode with the reference electrode.

Simultaneous serosal and cutaneous recordings. To avoid gastric myoelectrical abnormalities resulting from laparotomy and the immediate postoperative period, all recordings were made at least 4 days after surgery. Simultaneous serosal and cutaneous recordings were obtained in 15 sessions from the 12 subjects. The procedure in each recording session was as

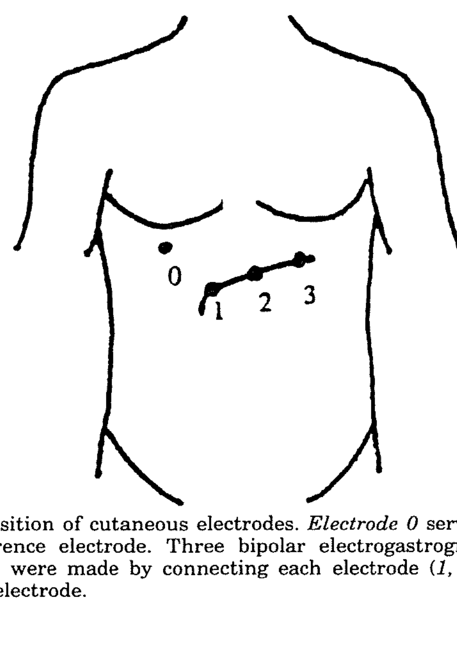

Fig. 2. Position of cutaneous electrodes. *Electrode 0* served as common reference electrode. Three bipolar electrogastrogram (EGG) recordings were made by connecting each electrode (*1, 2,* or *3*) to reference electrode.

Table 2. *Frequency of slow wave measured from cutaneous and serosal electrodes and effect of test meals*

Session No. (Patient)	Before Meal		After Meal		Spikes After Meal, %	Test Meal
	Serosal	Cutaneous	Serosal	Cutaneous		
1 (J1)	3.29	3.29	3.05	3.05	0	Milk, 120 ml
2 (J1)	3.10	3.10	2.90	2.90	0	Osmolite, 240 ml
3 (J2)	3.76	3.76	3.05	3.05	0	Osmolite, 240 ml
4 (J2)	3.45	3.45	2.75	2.75	0	Water, 200 ml
5 (J3)	4.10	4.10	4.10	4.10	0	Orange juice, 120 ml
6 (J3)	3.05	3.05	3.28	3.28	0	Mixed meal, 250 kcal
7 (J4)	3.05	3.05	3.05	3.05	0	Mixed meal, 250 kcal
8 (J5)	2.90	2.90	2.85	2.85	0	Osmolite, 240 ml
9 (J6)	2.92	2.92	2.80	2.80	0	Water, 120 ml
10 (J7)	2.90	2.90	2.70	2.70	0	Osmolite, 240 ml
11 (J8)	2.95	2.95	2.95	2.95		Turkey sandwich, 200 kcal
12 (J9)	2.65	2.65	Not able to eat			
13 (J10)	3.15	3.15	2.80	2.80	0	Milk, 120 ml
14 (J11)	3.15	3.15	2.85	2.85	0	Milk, 120 ml
15 (J12)	2.95	2.95	2.95	2.95	50*	Water, 120 ml
Mean	3.09	3.09	3.00	3.00	0	Liquids, 171 ml/patient†

In each patient 30-min preprandial and 30-min postprandial recordings were made. Frequency presented is peak frequency of each 30-min recording calculated by power spectral analysis method. Osmolite (240 ml) contained 240 kcal, or 14% protein, 31% fat and 55% carbohydrate. Liquid meals had significant effect on slow-wave frequency. Mean frequency (excluding *sessions 6, 7,* and *11* in which mixed or solid meals were used) was 3.24 ± 0.39 (SD) cycles/min in fasting state and 2.98 ± 0.39 (SD) cycles/min in fed state. In *patient J8* intravenous infusion of erythromycin (6 mg/kg) was given 10 min after eating. Total postprandial recording time was 60 min in patient. No spikes were noted in postprandial period before infusion. Spikes were observed in 80% of slow waves during 50 min after infusion of erythromycin. * Same amount of spikes was observed in 30-min preprandial EGG. Frequency difference was significant ($P = 0.006$, Student's t test). †n = 11 patients receiving liquids.

follows. On the day of the study the patient was fasted for >6 h and given no medications with known effects on gastrointestinal motility. The patient was lying in a supine position during the study and was asked not to talk or move to minimize motion artifacts. Respiration was monitored using a Pneumotrace belt. All signals derived from serosal and cutaneous electrodes were displayed on recording charts by a dynograph chart recorder (Beckman) and simultaneously recorded on a tape recorder (Thorn EMI). The low and high cutoff frequencies were 0.02–30 Hz for the serosal recordings to record spike activities. The cutoffs for the cutaneous recordings were 0.02–0.3 Hz. After 30 min of baseline recording, a meal was consumed according to the patient's tolerance or preference (Table 2). After the meal the recording continued for another 30 min. Because the aim of this part of the study was to investigate whether the cutaneous electrodes can track any change of gastric myoelectrical activity, the meal was only used to make such a change and thus was not uniform.

Data analysis for simultaneous serosal and cutaneous recordings. To investigate whether the cutaneous EGG could track the frequency of the gastric slow wave, all simultaneously recorded serosal and cutaneous signals were subjected to computerized spectral analysis. All signals were played back from the tape recorder, digitized by a 12-bit analog-digital converter (Metrabyte), scaled, and stored in real units (microvolts) in ASCII files on an IBM-AT computer. The sampling frequency was 2 Hz for the cutaneous recording and 60 Hz for the serosal recording. The digitized serosal recording was filtered by a digital low-pass filter with a cutoff frequency of 0.5 Hz and sampled again at 2 Hz to reduce the volume of data.

A smoothed power spectral analysis method, periodogram method (23), was applied to compute the power spectrum of the recording. Decibel (dB) unit was used to represent the power of the signal. Assuming a sinusoidal signal with an amplitude of A, its power P in dB is expressed as $P = 20 \times \log(A)$. Power spectra of 30-min preprandial and 30-min postprandial recordings in each subject were computed using the periodogram method. The frequency of the gastric slow wave recorded by the serosal and cutaneous electrodes was obtained from the power spectra. Figure 3, *top,* presents a 30-min EGG recording and Fig. 3, *bottom,* shows the power spectrum of this recording. The first peak frequency from the left is the frequency of the slow wave, whereas the second peak from the left represents the harmonic of the primary frequency.

Additional serosal recordings. Besides one or two sessions using both the serosal and cutaneous electrodes, one or more additional serosal recordings were made in each subject. Serosal recordings for >200 min were obtained from each subject (4,230 min in 12 subjects; Table 3). The serosal recording was visually analyzed. The percentage of rhythmic abnormalities and the percentage of spike activities superimposed on slow waves were computed. A gastric slow wave range of 2–4 cycles/min was considered to be normal, and all other activities were considered to be abnormal. More specifically, gastric rhythmic abnormalities include dysrhythmias, tachygastrias (regular frequency of >5 cycles/min), bradygastrias (regular frequency of <2 cycles/min), and arrhythmias (no rhythmic activity or mixed activity with different frequencies).

Protocol of electrical stimulation. Electrical stimulation of the stomach was performed in three subjects (*J1, J3,* and *J5*) ≥1 mo after surgery. The study was accomplished on 2 consecutive days. On *day 1* myoelectrical activity of the stomach was recorded using the serosal electrodes. An electrical stimulator was connected to the serosal electrodes S_1, but no electrical current was sent to the electrodes. The subject received "sham stimulation." The recording lasted 0.5 h before a test meal and 2 h after the test meal. The test meal was 240 ml osmolite (240 kcal, of 14% protein, 31% fat, and 55% carbohydrate). The liquid meal was chosen because the patients could not tolerate a solid meal. On *day 2* the same procedure was followed except that the patient's stomach was stimulated via electrodes S_1. The stimulator used was a commercially available unit from World Precision Instruments (WPI, New Haven, CT), model A310, isolated by a WPI isolator, model A350D. To mimic the gastric slow wave, the frequency of the stimulating pulse was selected to be 3 cycles/min. The width of the pulse was 300 ms. It was asynchronously delivered to the proximal electrodes.

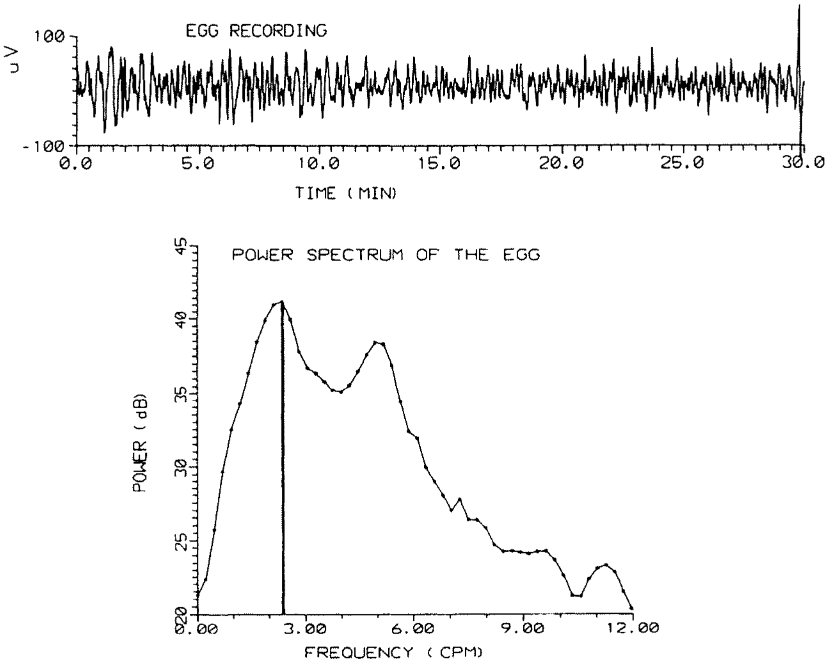

Fig. 3. Example showing frequency estimation of gastric slow wave from cutaneous EGG. *Top:* 30-min cutaneous EGG recording. *Bottom:* power spectrum of 30-min EGG. First peak from left in power spectrum shows frequency of gastric slow wave. Second peak from left represents harmonic of primary frequency. CPM, cycles/min.

The stimulator was used in a constant-current mode, and the amplitude was set at 4 mA. Electrical stimulation was applied after 30 min of baseline recording and continued until 2 h after the same test meal, which was given 30 min after the stimulation.

Statistical analysis. Student's *t* test was used to investigate the effect of the testing liquid meal on the frequency of the gastric slow wave. No specific statistical analysis methods were required to investigate the correlation between the frequency of the EGG and that of the serosal recording and to investigate the effect of electrical stimulation on gastric myoelectrical activity because (as shown in RESULTS) *1*) the frequency of the EGG was exactly the same as that of the serosal recording and *2*) electrical stimulation has no effects at all on gastric myoelectrical activity.

RESULTS

Gastric myoelectrical activity by serosal electrodes. About 70 h of recordings of gastric myoelectrical activity were obtained in the 12 patients via the implanted serosal electrodes. Table 3 presents the duration of recording in each subject and the percentages of electrical rhythmic abnormalities and spikes. It can be seen that regular slow waves (2–4 cycles/min) were observed in all 12 patients (Figs. 4 and 5). The percentage of gastric myoelectrical rhythmic abnormalities was <5% with a mean value of 1.1%. This small amount of gastric rhythmic abnormalities was mostly observed after the intake of the test meal (Fig. 6). Nine of the 12 patients showed the absence of spike activities (0–2.7%) either in the fasting or postprandial periods (Figs. 4 and 5). Two patients (J6 and J8) showed 8.6 and 6.2% of spike activities (Fig. 7), respectively. One patient showed a significant amount of spike activities (32.5%).

Table 3. *Myoelectrical activity measured by serosal electrodes*

Patient	Total Recording, min	Rhythmic Abnormalities, %	Spikes, %	No. Sessions
J1	1,030	1.5	0.5	5
J2	260	0.0	0.0	3
J3	260	0.0*	0.0	3
J4	260	0.0	0.0	3
J5	440	0.5	0.5	3
J6	210	0.0	8.6	2
J7	400	0.0	0.0	4
J8	360	2.6	6.2	3
J9	200	5.1	0.5	2
J10	320	3.1	1.8	2
J11	280	0.0	2.7	2
J12	210	0.0	32.5	3

*Frequency of slow wave in 1 recording session (34.6% of total recording) was 4.1 cycles/min.

Cutaneous EEG and effect of test meal. Table 2 presents the frequency of the gastric slow wave measured from the cutaneous and serosal electrodes and the effect of test meals. As on the serosal recordings, regular gastric slow waves were present on all cutaneous EGG recordings (see EGG tracings in Figs. 4 and 5). No difference was found in the frequency of the EGG among different electrodes. The frequency of the EGG on each recording was identical to that of the corresponding serosal recording (Table 2). Figure 8 presents the power spectra of a serosal recording and a simultaneously recorded cutaneous EGG. The fundamental frequencies of the serosal and cutaneous recordings were identical. The power spectrum of the serosal recording showed high-order harmonics, whereas that of the cutaneous recording showed only second-order harmonics. This was because the cutaneous signal was more sinusoidal than the serosal recording (there would be no harmonics if the signal were a sinus wave, whereas there would be many harmonics with power equal to that of the fundamental frequency if the signal were a square wave).

The test meal did not induce any spike activities in these patients but changed the frequency of the gastric

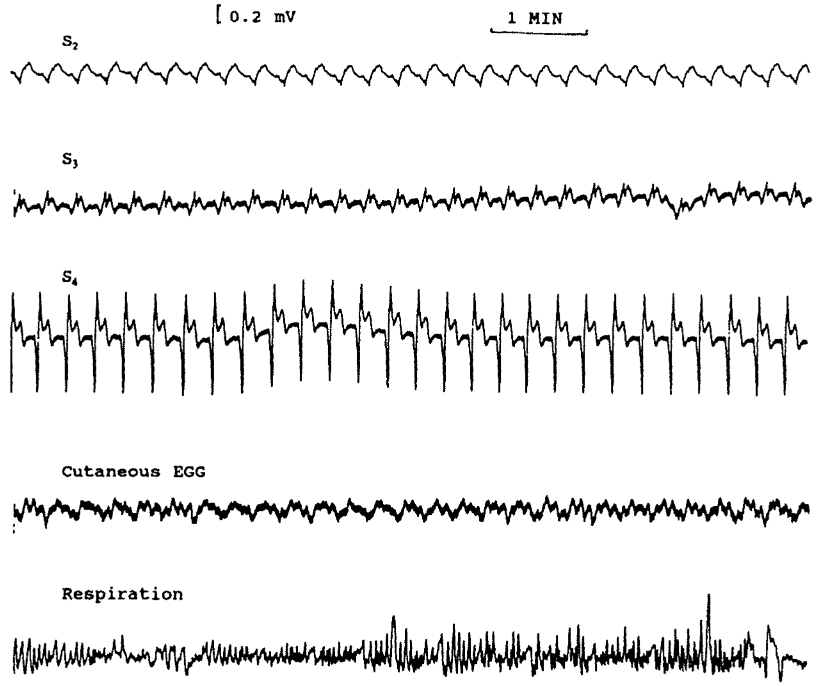

Fig. 4. Preprandial recordings obtained in *patient J1*. S_2–S_4: serosal recordings from stomach (distance to pylorus, 12, 8, 4 cm, respectively). Regular slow waves were present in both serosal and cutaneous recordings, but no spikes were noted in serosal recordings. Cutaneous EGG recording contained both gastric slow waves and myoelectrical activities from intestine.

slow wave as shown on Table 2. The cutaneous EGG was able to exactly track the frequency change of the slow wave as shown in Fig. 6. Excluding three sessions in which a mixed or solid meal was used, we investigated the effect of liquid meals on the frequency of the slow wave. The frequency of the slow wave after the intake of the liquid meals was significantly lower than that in the fasting state, 2.98 ± 0.39 (SD) cycles/min vs. 3.24 ± 0.39 (SD) cycles/min ($P = 0.006$, Student's t test).

A persistent rhythmic 10–12 cycles/min activity was superimposed on the normal 3 cycles/min slow wave on all cutaneous tracings. In the power spectra of all EGG recordings, a frequency peak at 10–12 cycles/min was present as shown in Fig. 8. This 10–12 cycles/min activity was not from the stomach because no similar rhythmic activity was present in the serosal recording of the stomach. It resembled respiratory artifact but in fact was not because the frequency of respiratory artifact was 2–5 cycles/min higher. In addition, it did not disappear when the patients were asked to hold their breath during the studies.

Effect of electrical stimulation. Six studies of electrical stimulation of the stomach were performed in three patients. No effects were found on gastric myoelectrical

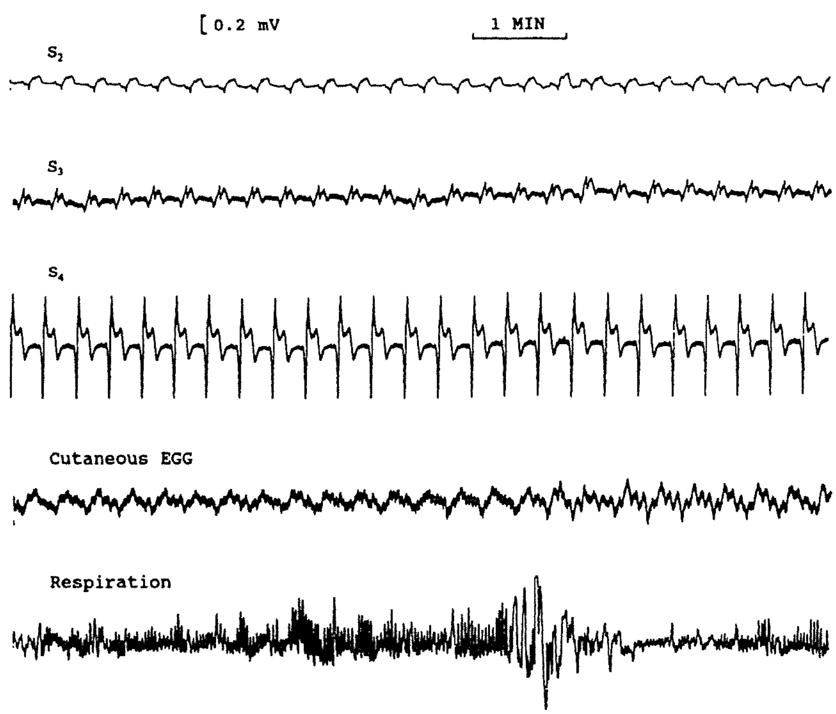

Fig. 5. Recordings obtained in *patient J1* after intake of 120 ml milk. S_2–S_4: serosal recordings from stomach (distance to pylorus, 12, 8, 4 cm). Regular slow waves were present but no spikes were noted. By comparing Figs. 4 and 5 one may notice decrease of slow-wave frequency after liquid meal.

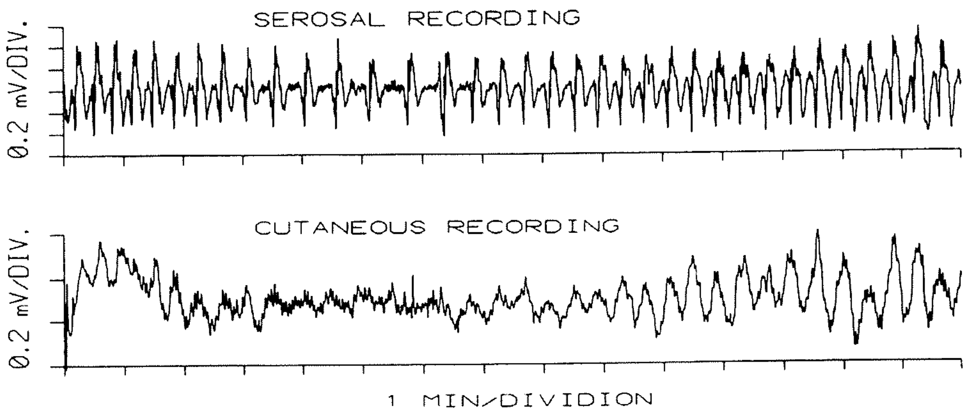

Fig. 6. Typical recording showing performance of cutaneous EGG in tracking frequency changes induced by test meal. Simultaneous serosal (S_4) and cutaneous recordings obtained in *patient J2* immediately after intake of 240 ml osmolite. Frequency of slow wave was decreased by liquid meal, and cutaneous EGG exactly followed same frequency change. Time is depicted on the horizontal axis in 1-min intervals, and on the vertical axis the scale is 0.2 mV per indicated interval.

activity. In the sham-stimulation sessions, regular 3 cycles/min slow waves were observed in the fasting state, an occasional occurrence of dysrhythmic activities was noted in postprandial period in some sessions, and no spikes were observed in the postprandial state. Gastric myoelectrical activity measured in six sessions

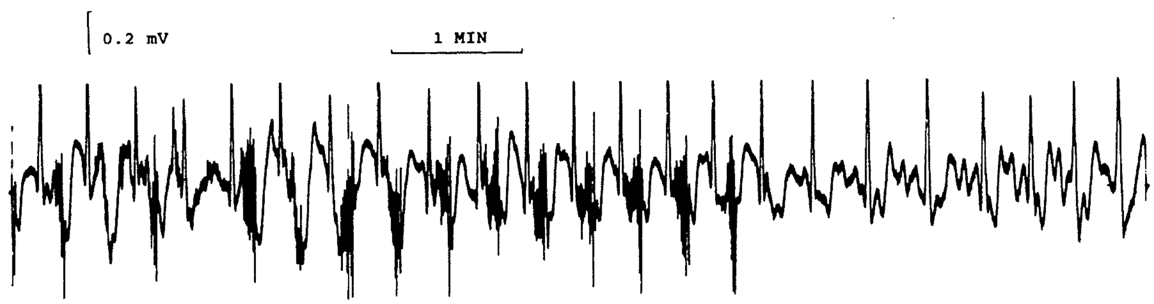

Fig. 7. Serosal (S_4) recording obtained in fasting state in *patient J6*. Spikes were appreciated only in this patient (8.6% of total recording).

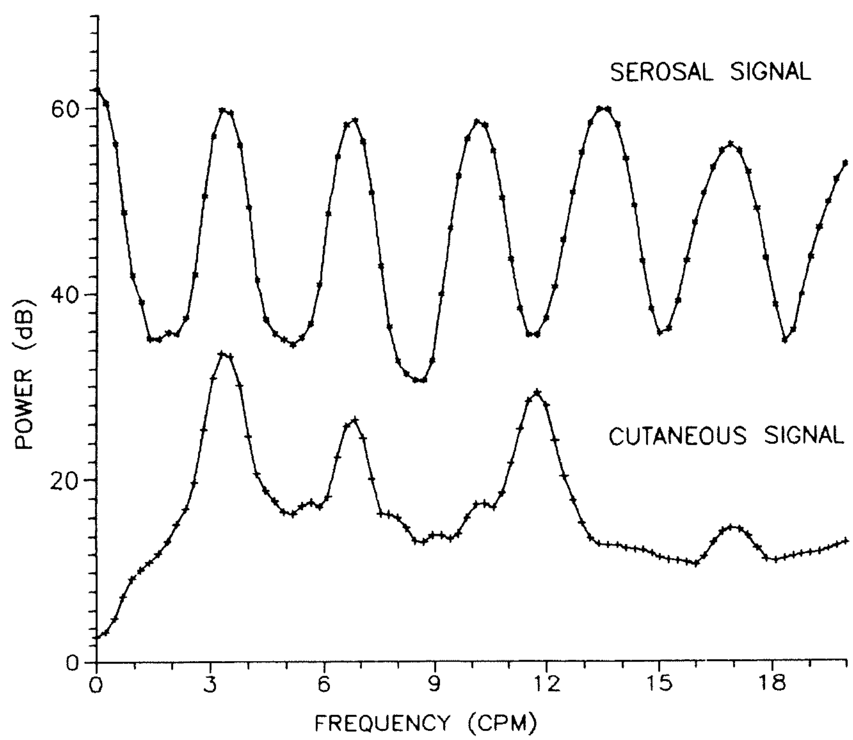

Fig. 8. Power spectra of gastric myoelectrical activity recorded by serosal and cutaneous electrodes (30 min, obtained in *patient J1*). Both spectra had primary frequency of 3 cycles/min. Power spectrum of cutaneous recording showed less harmonics than that of serosal recording. This is because cutaneous recording was more sinusoidal than serosal recording (see Figs. 4 and 5). Power spectrum of cutaneous recording also showed frequency peak of 12 cycles/min, indicating presence of electrical interference from small intestine.

Table 4. *Effect of electrical stimulation of stomach on gastric myoelectrical activity*

Session No.	Frequency			Dysrhythmias, %			Postprandial Spikes, %		
	Baseline	After pacing	After meal	Baseline	After pacing	After meal	Baseline	After pacing	After meal
1	2.90	3.02	3.00/3.20	0	0	1.7	18.0	0	0
2	2.90	3.00	2.80/3.10	0	0	4.2	2.5	0	0
3	3.00	3.00	2.80/3.10	0	0	0	0	0	0
4	2.95	2.95	2.80/3.20	0	0	7.5	0	0	0
5	3.24	3.40	3.30/3.40	0	0	0	0	0	0
6	3.20	3.25	3.00/3.10	0	0	1.7	0	0	0

Baseline, frequency of slow wave during 30-min baseline recording; after pacing, frequency of slow wave of 30-min preprandial recording after electrical stimulation; after meal, frequencies of slow wave of first 10-min/last 10-min postprandial recordings. Postprandial recording lasted for 120 min.

with electrical stimulation is summarized in Table 4. It was found that *1*) in the fasting state before stimulation, there were regular slow waves, no dysrhythmias, and a few episodes of spikes in two sessions; *2*) the parameters of gastric myoelectrical activity, i.e., frequency, percentage dysrhythmias and percentage spikes, in the fasting state with stimulation were not different from those without stimulation; and *3*) in postprandial period, the frequency of the gastric slow wave experienced a gradual shift from a lower frequency to a higher frequency, occasional occurrence of dysrhythmic activities were noted, and no spike activity was found. It was observed that electrical stimulation of the stomach did not entrain the frequency of the gastric slow wave and did not induce spikes. Gastric myoelectrical activity measured with electrical stimulation was of the same characteristic as that measured with sham stimulation.

DISCUSSION

Gastric myoelectrical abnormalities may be classified into rhythmic abnormalities, absence of spikes in the fasting state, absence of spikes after a solid or liquid meal, and uncoupling. Gastric myoelectrical rhythmic abnormalities have frequently been reported in patients with gastroparesis (1, 3, 6, 15, 20, 24). These include tachygastria (frequency >5 cycles/min), bradygastria (frequency <2 cycles/min), and arrhythmias (irregular frequency). Tachygastria was reported in patients with nausea and vomiting (34, 35). Bradygastria was recorded in patients with diabetic gastroparesis in a cutaneous EGG study (20). A large variety of gastric myoelectrical rhythmic abnormalities were recorded in patients with idiopathic gastroparesis (6) and diabetic gastroparesis (2) using intraluminal electrodes. Gastric myoelectrical abnormalities were found to be associated with motor disorders of the stomach (1, 6, 14, 31, 33).

Surprisingly, few gastric rhythmic abnormalities were observed in this study. The gastric slow wave observed in the 12 patients with gastroparesis participating in this study was normal. In 4,230 min of recordings made from implanted serosal electrodes only a small amount of time was accounted for by gastric rhythmic abnormalities. These rhythmic abnormalities mostly occurred after the intake of a meal. Our finding was in contrast to what has been reported in the literature, especially to a recent report by Familoni et al. (13). They investigated gastric myoelectrical activity in six patients undergoing laparotomy for fundoplication, cholecystectomy, or bowel resection using both serosal and cutaneous electrodes applying very similar methodology. A large variety of dysrhythmias was reported, such as tachygastria, electrical shutdown, and uncoupling. The discrepancy may be attributed to the fact that in the study reported by Familoni et al. (13) the recording was made in the immediate postoperative period, whereas in this study the recording was made at least 4 days (at most 1 mo) after laparotomy. Previous studies (25, 32) on postoperative gastric myoelectrical activity have shown that irregular gastric activities may occur in the initial postoperative period and return to normal 1 day after surgery. The dysrhythmias described by Familoni et al. (13) might be attributed to the effect of laparotomy.

Our study indicates that patients with gastroparesis may have normal gastric slow waves, although a number of previous studies using cutaneous or intraluminal mucosal electrodes have shown the high prevalence of gastric myoelectrical dysrhythmias in patients with gastroparesis. In a previous study (10) using cutaneous electrodes and advanced data analysis methods (8) we analyzed pre- and postprandial gastric myoelectrical activity in 27 gastroparetic patients who had not undergone surgery and jejunostomy placement. The following three EGG patterns were observed: *a*) 30% of patients showed normal EGGs, *b*) 40% of patients showed dysrhythmic EGGs, and *c*) 30% of patients showed decreased EGG amplitude in response to a solid meal. It seems that the patients in this study may fall into either *category a* or *category c* but not *category b*. It should be noted that these 12 patients reflect a subgroup of gastroparetic patients who were refractory to therapy with prokinetic agents, and jejunostomy was required to maintain nutrition. Hence gastric rhythmic abnormalities are not necessarily a marker for severity. Clearly our patients had a severe motility dysfunction.

Although the gastric slow wave was found to be normal, the absence of spikes observed in this study was unexpected and might be associated with motility disorders of the stomach. It is known that spike activities are directly related to the appearance of gastric contractions. In the fasting state the stomach contracts during *phases II* and *III* of the interdigestive migrating motor complex. In the postprandial state, the stomach contracts regularly and forcefully. Previous studies in dogs (18) and in humans (32) demonstrated the presence of spike activities either in the fasting or fed states. A previous study (32) performed by one of the authors may serve as the control study. In that previous study, serosal recording of gastric myoelectrical activity was made in 44 patients undergoing major abdominal surgery chosen at random, using exactly the same technique as in this study. The results revealed that 39.9% of slow waves were accompanied with spike activities in postoperative *days 1* and *2* and 47.2% 1 mo after surgery. The absence of spikes in this study indicated motor quiescence of the stomach in these patients. The possibility exists that the absence of spikes resulted from the abdominal surgery but is remote. Schirmer and co-workers (32) investigated gastric myoelectrical patterns of recovery after surgery and observed that gastric myoelectrical activity returned to normal 12–24 h after surgery. In the present study all recordings were performed > 4 days after surgery and most recordings were made 1 mo after surgery. Therefore, the absence of spikes was unlikely because of surgery and consistent with an underlying motor disorder.

Simultaneous serosal and cutaneous recordings in humans were first performed by Nelsen and Kohatsu (22). They claimed that the cutaneous EGG was a measurement of myoelectrical activity of the stomach instead of mechanical events of the stomach as had been theorized by investigators for many years. An excellent study of the correlation between the cutaneous EGG and serosal recordings in dogs was published by Smout et al. (28). Using Fourier transform, they reported that the frequency of EGG was the same as that of the serosal recording, and the EGG power increase was associated with spike activities presented in the serosal recording. A recent study in six patients by Familoni et al. (13) showed that the cutaneous EGG could recognize both normal and abnormal gastric myoelectrical activities except abnormalities involving a loss of coupling. Part of our study (simultaneous serosal and cutaneous recordings) was designed to demonstrate the ability of the EGG to detect the frequency change of the gastric slow wave. Test meals were used to alter the frequency of the gastric slow wave. The results showed that the EGG can precisely track the frequency change induced by the test meal.

The response of the significant decrease in gastric slow-wave frequency to the liquid meals observed in this study is consistent with previous studies (18, 28). Kelly et al. (18) reported a decrease of gastric slow-wave frequency after water in dogs. In a study investigating effects of different meals on the gastric slow wave in humans using cutaneous electrodes we found that a liquid meal (water) decreases the frequency of the gastric slow wave, whereas a solid meal increases the frequency of the gastric slow wave (9). Because the patients could not tolerate a solid meal, only liquid (or mixed) meals were used in this study. No spikes were observed after the liquid or mixed meals. This might be attributed to the gastric motility disorders in these patients or possibly to insufficient calories of the test meals or nature (liquid) of the test meals.

Besides the 3 cycles/min gastric slow wave a persistent 10–12 cycles/min electrical activity was observed on all cutaneous EGG tracings and in their power spectra. This 10–12 cycles/min electrical activity was superimposed on the regular 3 cycles/min slow wave. We believe it was of the jejunal origin because *1*) serosal recordings of myoelectrical activity in jejunum (32) showed that there exists persistent rhythmic myoelectrical activity and its frequency is the same as recorded in the EGG and *2*) during the surgery for the placement of the feeding jejunostomy tube the jejunum was pulled up and sewn against the abdominal wall, which brought the jejunum closer to the cutaneous electrodes. Persistent 10–12 cycles/min electrical activities were also observed in cutaneous EGGs in normal subjects (11). The possible contribution of myoelectrical activities from the small intestine superimposed on gastric slow wave in the EGG could confuse the interpretation of the EGG. Fortunately, the frequency of small intestinal myoelectrical activity is much higher than that of the gastric slow wave and even higher than that of tachygastria (usually defined as 4–9 cycles/min). Second, the intestinal myoelectrical activity, if present, is always superimposed on the gastric slow wave in an EGG recording. Using running spectral analysis method (12), one is able to determine whether a recorded high-frequency component stands for a tachygastrial event or simply an interference from other tissues by inspecting the presence (or absence) of frequency peaks at 2–4 cycles/min (normal frequency range of the gastric slow wave) in running spectra.

The effect of electrical stimulation on gastric myoelectrical activity in patients with gastroparesis has not been previously investigated. Our data showed that electrical stimulation of the stomach at 3 cycles/min did not have any effect on gastric myoelectrical activity. It could not entrain the frequency of the gastric slow wave and did not induce spike activities. Similar findings were reported in a recent study (5) in which the effect of electrical stimulation of the stomach in a canine model of gastroparesis was investigated.

In summary, the main abnormality of gastric myoelectrical activity observed in the 12 patients with gastroparesis was the absence of spikes. The lack of spikes may be associated with motility disorders in patients with gastroparesis. Although previous studies have reported the high prevalence of gastric myoelectrical rhythmic abnormalities, this study with serosal electrodes shows that some gastroparetic patients can have absolutely normal slow waves. In fact, these patients can also be the most refractory to medical therapy as demonstrated by the need for a jejunal feeding approach. Using the serosal recording as a gold standard, we have confirmed that the cutaneous EGG can accurately reflect the frequency of the gastric slow wave and have demonstrated that the cutaneous EGG is able to track the frequency change of the gastric slow wave induced by a test meal. We believe that the cutaneous EGG is also able to track any frequency change of the gastric slow wave on other stimuli and therefore is an attractive and reliable noninvasive method to investigate the effect of any pharmacological or prokinetic agents on gastric slow wave frequency. According to the findings in this study, we postulate that electrical stimulation of the stomach at 3 cycles/min may not have any effect on gastric myoelectrical activity.

We thank Dr. Barbara Burkett for a careful review of the manuscript.

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Received 22 April 1991; accepted in final form 25 August 1993.

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