Relation between postprandial gastric emptying and cutaneous electrogastrogram in primates

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BRULEY DES VARANNES, S., M. MIZRAHI, AND A. DUBOIS. Relation between postprandial gastric emptying and cutaneous electrogastrogram in primates. Am. J. Physiol. 261 (Gastrointest. Liver Physiol. 24): G248-G255, 1991.-The relation between the cutaneous electrogastrogram (EGG) and gastric emptying was investigated in six rhesus monkeys. Gastric emptying was measured using scintigraphy after administration of two 80-ml mixed solid liquid meals (1.5 and 5.0 kcal/kg) tagged with ^{99m}Tc-sulfur colloid and ¹¹¹In-diethylenetriamine pentaacetic acid. Six epigastric bipolar recordings of the EGG were concurrently obtained, digitized, and band-pass filtered. Portions of the signal with motion artifacts were automatically detected and excluded using two microwave motion sensors. During the early postprandial period, gastric emptying was greater after the 1.5-kcal/kg meal than after the 5-kcal/kg meal, and EGG amplitude increased significantly compared with fasting only after the 1.5-kcal/kg meal. Both emptying and EGG amplitude subsequently decreased after the 1.5-kcal/ kg meal, whereas these two parameters increased after the 5kcal/kg meal. As a result, EGG amplitude was significantly correlated with gastric emptying of solids in all six animals. In contrast. EGG frequency was not significantly different between the two meals and was not correlated with emptying. These results indicate that both the EGG and gastric emptying are modified differently by meals with different caloric contents and that the EGG may represent a useful, although indirect, index of gastric emptying.

emptying of solids; emptying of liquids; caloric meals; gastric motility

ANTRAL MECHANICAL ACTIVITY is known to increase markedly after mixed meals, and this increase is directly correlated with gastric emptying of radiolabeled solids (2, 12). In addition, emptying of liquids is believed to be determined by the pressure gradient between stomach and duodenum as well as by coordinated motor events involving stomach, pylorus, and duodenum (4, 8, 20). Because various normal and abnormal patterns of gastric contractility may be responsible for different rates of emptying, it is important to further develop clinically applicable methods to measure gastric motility.

Intraluminal manometry permits the evaluation of fasting and postprandial distal antral motility (2), but this technique is invasive and difficult to use in unanesthetized animals. In addition, because the stomach is a cavity that may be filled with variable and possibly large volumes of fluids, solids, and air, the Pascal principle predicts that intraluminal manometry does not provide reliable recording of the contractile activity of the proximal stomach (35). The electrical activity recorded from the stomach is thought to reflect neuromuscular events that control gastric motility. In healthy primates, several types of electrical and mechanical activities can be recorded: the proximal stomach exhibits small electrical fluctuations at 1/min and concurrent tonic contractions. but propagated phasic contractions have not been detected (18). The mid- and distal stomach generate electrical potentials at $\sim 3/\min$ that are called slow waves or electrical control activity (ECA). In addition, fast electrical potentials called spikes or electrical response activity (ERA) may be superimposed onto the ECA. The ERA, but not the ECA, is accompanied by detectable phasic contractions that propagate in an aboral direction (29). However, serosal recording of gastric electrical activity requires surgical implantation of electrodes, which is feasible in animals but is rarely possible in humans. The use of suction electrodes and magnetic force maintaining intraluminal electrodes in contact with the gastric mucosa has been proposed (1), but these techniques are invasive and may modify gastric motility.

Cutaneous electrogastrography (EGG) has been shown to reflect accurately both the electrical and mechanical activity of the stomach (26) and therefore represents an attractive alternative to serosal or mucosal gastric electromyography. However, the exact nature of this type of recording remains controversial, and its precise quantitation has been difficult. Finally, the exact relation between the EGG and gastric emptying is unknown.

We therefore obtained multidirectional recordings of the cutaneous EGG and simultaneously measured gastric emptying of solids and liquids using scintigraphy. We determined 1) whether meals with different emptying rates induce different gastric electrical activities that could be detected using the cutaneous EGG and 2) whether the EGG is correlated with gastric emptying of solids and/or liquids. We observed that gastric emptying and the amplitude of the cutaneous EGG follow a similar time course after two meals with different caloric contents and that these parameters were significantly correlated in most animals.

MATERIALS AND METHODS

Animals. Six male 3- to 5-yr-old purpose-bred domestic rhesus monkeys, Macaca mulatta (wt 3-5 kg), were transferred to our facility. Upon arrival, they were housed in individual stainless steel cages in conventional holding rooms of an American Association for Accreditation of Laboratory of Animal Care (AAALAC)-accredited animal facility, where they were guarantined for 45 days. Monkeys were provided with tap water ad libitum, commercial primate chow, and fruits. After they had three negative tuberculosis tests performed 2 wk apart, two 4h habituation sessions were held. During those sessions. as well as during subsequent studies, animals were seated in a primate restraining chair placed inside a ventilated. lighted, and sound-absorbing booth that had the rear side cut to position a gamma camera close to the monkey. Studies were performed between 8:00 A.M. and 12:00 P.M. after an 18-h fast and at intervals of at least 4 days.

Cutaneous electrogastrogram. Six adhesive cutaneous electrodes (Ag-AgCl, Red Dot, 3M, St Paul, MN) were placed on the epigastric area that had been previously shaved and cleaned with alcohol. A drop of electrode paste (EKGsol, Beck-Lee, Bendix Scientific, Rochester, NY) was poured onto the electrodes that were positioned 2.5 cm apart in a hexagonal configuration. A seventh electrode was placed in the center of the hexagon and used as the reference (Fig. 1). The electrodes were held in place using a large adhesive tape wrapped around the abdomen. In addition, a grounding electrode was placed on the left leg. The electrodes were attached to a lead selector box interfaced with a multichannel R711 recorder amplifier (Sensormedics, Anaheim, CA), providing bipolar recordings between each of the six peripheral electrodes and the central one (channels I-VI). In addition, the movements of the monkey were detected using two microwave motion sensors (model D7, Microwave Sensors, Ann Arbor, MI), rewired as previously described (24) and placed on either side of the monkey inside the booth (Fig. 2).



FIG. 1. Positions of cutaneous electrodes used to record electrogastrogram from epigastric area. Central electrode was used as a reference to obtain 6 bipolar recordings.

The two motion signals and the six EGG channels were low-pass filtered at 30 Hz but not high-pass filtered (DC-30 Hz), amplified, displayed on paper, and taped using a multichannel analog recorder (model PR2230, Ampex, Redwood City, CA) for subsequent digitization and computer analysis. Before and after each session, a 1-mV sinusoidal signal (frequency 3 cycles/min) produced by a sine-wave generator (model 5100, Wavetek, San Diego, CA) was recorded for subsequent calibration of the six EGG channels.

Experimental procedure. A 10-Fr double-lumen nasogastric Ventrol Levine tube (National Catheter, Mallinckrodt, Argyle, NY) was introduced into the stomach. Proper positioning was verified by aspirating 3 ml of the gastric contents; if <3 ml of fluid were obtained, a water recovery test was performed with 5 ml, and the position of the tube was adjusted accordingly. The seated monkey was then placed in the booth described above. The chair could be rotated on its vertical axis, permitting the positioning of the monkey with either its front or its back facing a gamma camera. Two video cameras allowed continuous observation of the monkey on a video monitor without opening the booth. After a 1-h basal recording of the EGG was obtained, the door of the booth was opened and one of two 80-ml mixed solid-liquid meals at 20°C was administered intragastrically in 2 min through the nasogastric tube. The tube was then removed and the door was closed.

Test meals. The meals were either 1) a low-caloric meal (LCM) (1.5 kcal/kg), prepared by adding 40 ml of tap water to 40 ml of radiolabeled chicken liver ground to 1- to 2-mm-diam particles and suspended in tap water (5) (caloric composition: proteins 64%, 3.6 kcal; lipids 27%, 1.5 kcal; carbohydrates 9%, 0.5 kcal); or 2) a high-caloric meal (HCM) (5 kcal/kg) made of two bouillon cubes (Wyler) diluted in 40 ml of water added to the 40 ml isotopic meal (caloric composition: proteins 31%, 5.9 kcal; lipids 25%, 4.8 kcal; carbohydrates 44%, 8.5 kcal).

Measurement of gastric emptying. The solid phase of the meal was tagged according to the method of Wirth et al. (34) and was composed of 1.2 g chicken liver and 0.5 mCi of ^{99m}Tc-sulfur colloid bound to 0.5 g for analyticgrade cation exchange resin with a diameter from 0.3 to 0.85 mm (Chelex-100, Bio-Rad Laboratories, Richmond, CA). The average labeling efficiency was 98.5%, and the in vitro stability was >99%, with an average loss of 0.7% of the total activity in simulated gastric fluid. Animal studies have also demonstrated the in vivo stability of the binding, with an average of 0.045% of the administered ^{99m}Tc appearing in the blood at 1 h and 0.41% appearing in the 24-h urine collection (34). Initial validation studies using ¹¹¹In-sulfur colloid-tagged chicken liver concurrently with the ^{99m}Tc-sulfur colloid-tagged resin showed identical emptying curves of the two markers. The liquid phase (40 ml of water) was tagged with 0.1 mCi of ¹¹¹In-diethylenetriamine pentaacetic acid (5).

Images were acquired using a gamma camera (Pho/Gamma HP, Nuclear-Chicago, Searle, Chicago, IL) and a medium energy collimator with a 20% window around the 140-keV peak for the ^{99m}Tc activity and a 20% window around the 247-keV peak for the ¹¹¹In activity.



One-minute anterior and posterior images were obtained at 2, 5, 10, 13, 16, and 20 min after the administration of the meal and at 10-min intervals during the subsequent 160 min. Data were stored on-line on a computer (Medical Data System A³, Ann Arbor, MI) for subsequent analysis.

Gastric emptying was analyzed using a previously described method (5). Briefly, gastric and intestinal outlines were defined as the regions of interest in sequential scans, and the activity of each isotope was determined within these areas. Corrections were made for ^{99m}Tc decay and for Compton scatter from ¹¹¹In into the ^{99m}Tc window. The geometric mean over anterior and posterior activities was calculated, and the percentage of each phase of the meal remaining in the stomach was expressed as the ratio of the stomach activity divided by the sum of the gastric and intestinal activities (Fig. 3, A and B). Gastric emptying of solids and liquids was then expressed in three different manners.

FIG. 2. Example of recordings obtained during present experiments. Top: EGG recorded before (left) and 5 min after (right) a mixed liquid-solid meal. Middle: same signals after digital filtering (0.02-0.11 Hz); +, peak of each wave as detected using software. Bottom: concurrent recording of movements (including respiration) of animal. Thick black lines define windows during which no motion artifacts are present. Note that motion artifacts occasionally appear to increase the amplitude of the EGG or to modify the shape of the wave.

WINDOW

First, curve fitting of the entire emptying of liquids and solids was performed using the Weibull function (32), also described as the power exponential model (6). and using the equation

$$x_t = 2^{-(t/t_{1/2})^{\mu}}$$

where x_t is the amount of marker present in the stomach at time t, $t_{1/2}$ is the half-emptying time, and β reflects the shape of the curve. We then calculated the fractional emptying rate (FER) using the equation

$$FER = t_{1/2}/\ln (0.5)$$

Second, because we were interested in evaluating the relation between the EGG and gastric emptying in a minute-by-minute fashion, we calculated the FER for each 3- to 10-min time interval using the following linear function

$$\text{FER} = \left[(x_{t_i} - x_{t_{i+1}}) / x_{t_i} \times 100 \right] / (t_{i+1} - t_i)$$



FIG. 3. Percentage of marker remaining in stomach (A and B) and fractional emptying rate (C and D) for liquids and solids in 6 rhesus monkeys after administration of LCM (1.5-kcal/kg meal; ▲) and HCM (5.0-kcal/kg meal; \triangle). Values are means \pm SE. LCM compared with HCM: * P < 0.01; † P < 0.05.

FER =
$$[\ln(x_{t_{i+1}}/x_{t_i}) \times 100]/(t_{i+1} - t_i)$$

In addition, when the complete curve is considered, a series of straight lines satisfactorily approximate an exponential curve (discrete calculation method). The average FER was then calculated for each 30-min-period (Fig. 3, C and D).

Analysis of EGG. The taped signals were digitized at 2 Hz with a 1-Hz low-pass analog filter (model 3342, Krohn-Hite, Avon, MA) for the six EGG channels and at 20 Hz with a 10-Hz low-pass analog filter for the sum of the two motion signals. Each digitized EGG channel was then band-pass filtered with an optimal finite impulse response filter (0.02–0.11 Hz, i.e., 1.20–6.60 cycles/ min), designed using the Remez exchange algorithm (22) and converted to millivolts using the previously recorded calibration signals. EGG peaks were detected in the filtered signal using a Compaq 386/20 computer (Houston, TX), with the Xenix operating system (Santa Cruz Operations, Santa Cruz, CA) and locally developed software (Fig. 2) (9). The software locates peaks by detecting increasing and decreasing trends in a signal. The points at which these trends change are the peak begin point, end point, and crest. A trend is defined as a user-specified minimum number of consecutive local changes. A local change is considered to occur when a point is less than the local minimum or greater than the local maximum plus a user-specified minimum increase.

The sum of the two motion signals was used to select the periods of the EGG signals that lasted at least 1 min, did not contain motion artifacts, and could be reliably analyzed (Fig. 2). After the detection of the end of a motion artifact, the next period started 5 s later so as to discard any residual abnormality in the EGG signal because of this last motion. An interval of 5 s was chosen after carefully examining initial recordings and demonstrating to our satisfaction that all tracings had returned to baseline within that time interval. Automatic analysis of the peaks detected in each artifact-free period was performed in each of the six EGG channels, providing the mean instantaneous frequency (reciprocal of the distance between two peaks) and the amplitude of each peak. The weighted mean of each of these parameters was then calculated for each 10- and 30-min interval (Figs. 4-6). All recordings were visually inspected to verify that no artifact remained in any selected period. Because the absolute value of EGG amplitude is influenced by exogenous factors such as electrode-skin resistance, tissue conductivity, and electrode distance to the stomach (7, 10), basal values (Table 1) were subtracted from postprandial values to obtain the change (Δ) in frequency and amplitude for each time interval (Figs. 4-6).

Statistical analysis. Results were expressed as means \pm SE. An analysis of variance with repeated measures (33) was used to determine the effects due to meal, time,

FIG. 4. Mean EGG Δ amplitude in 6 rhesus monkeys after administration of LCM (1.5-kcal/kg meal; Δ) and HCM (5.0-kcal/kg meal; Δ). Fasting values were subtracted from postprandial values and these calculated Δ amplitudes are represented as means \pm SE. ^a P < 0.05 for LCM compared with fasting; ^b P < 0.05 for HCM compared with fasting. LCM compared with HCM: *P < 0.01; †P < 0.05.

or channel on the time courses of emptying and EGG parameters. This statistical method takes into account the fact that measurements are repeated in the same animals over time by establishing a distinction between a factor that classifies the subjects into groups (grouping factor) and a factor for which each subject is measured at all levels (within-subject factor). Computer implementation of this statistical method was performed using locally developed programs. For the EGG, analysis of variance was performed first on the average of the six channels determined in each animal (1 value/animal, 6 values/meal) and second on all six channels considered simultaneously in each monkey (6 values/animal, 36 values/meal). This latter approach permitted subsequent testing of the effect of meal and time for each channel individually. A priori analysis (i.e., a test that is planned before collection of data) was conducted to examine the statistical significance of the effect of the meal at time t_i (simple effect of meals at each time). The significance of the difference of an EGG parameter after a meal compared with fasting was assessed using Dunnett's method for a posteriori multiple comparisons of individual mean values with a control (33).

In each monkey, a joint multivariate normal distribution of the variables was assumed to calculate an unbiased minimum variance estimate of the multiple correlation coefficient between FER and all six EGG channels taken concurrently (33). This coefficient is an estimate of the maximum correlation that can be attained between one variable (i.e., FER for each interval) and a linear combination of other variables (i.e., EGG amplitude in channels I–VI for the corresponding intervals). No weighting factors were applied among channels.

RESULTS

Effect of meals on gastric emptying. Emptying of liquids tended to be exponential after LCM and was approxi-





FIG. 5. Mean EGG Δ amplitude in channels I-VI as recorded in 6 rhesus monkeys after administration of a 1.5- (\blacktriangle) and a 5.0-kcal/kg meal (\triangle). Fasting values were subtracted from postprandial values, and these calculated Δ amplitudes were averaged in each monkey. Mean EGG Δ amplitude values were then calculated for group of 6 monkeys and are represented as means \pm SE. ^a P < 0.05 for LCM compared with fasting; ^b P < 0.05 for HCM compared with fasting. LCM compared with HCM: ^{*} P < 0.01; [†] P < 0.05.

mately linear after HCM. The mean percentage of liquids remaining in the stomach after HCM was significantly higher compared with LCM from 16 to 180 min (P < 0.05; Fig. 3A). FER, when calculated for the entire curve using the power exponential model, was significantly less after HCM than after LCM (0.36 ± 0.08 vs. $2.99 \pm 1.18\%$ / min; P < 0.05). In addition, the coefficient β (representing the shape of the curve, especially during initial emptying) tended to be greater after HCM than after LCM, but the difference was not statistically significant (1.35 \pm 0.22 vs. 0.84 \pm 0.09; NS). Finally, the time course of emptying after the two meals was different: FER was significantly less after HCM than after LCM only from 0 to 60 min (P < 0.05; Fig. 3C), whereas it was similar after the two meals from 90 to 180 min.

Gastric emptying of solids was nonlinear after both meals. The percentage of solid markers remaining in the



FIG. 6. Mean EGG Δ frequency in 6 rhesus monkeys after administration of a 1.5- (\blacktriangle) and a 5.0-kcal/kg meal (\triangle). Fasting values were subtracted from postprandial values, and these calculated Δ frequencies were averaged in each monkey. Mean EGG Δ frequencies were then calculated for group of 6 monkeys and are represented as means \pm SE.

stomach was significantly greater after HCM than after LCM from 30 to 100 min (Fig. 3B). However, parameters for emptying were not significantly different between the two meals when FER calculated for the entire emptying curve (0.42 ± 0.22 vs. 0.26 ± 0.09 ; NS) and coefficient β (1.69 ± 0.74 vs. 2.73 ± 0.86 ; NS) were used. In contrast, FER was significantly (P < 0.05) greater after LCM than after HCM from 0 to 30 min (Fig. 3D), and FER decreased with time after LCM and increased with time after HCM.

Fasting cutaneous EGG. As shown in Table 1, values for EGG parameters during fasting did not vary significantly among channels, although EGG amplitude was greatest in channel II and smallest in channel IV.

Effects of LCM on cutaneous EGG. Both average $\Delta amplitude$ (i.e., the average of the means of the 6 channels in each animal) and $\Delta amplitude$ in channel III increased significantly (P < 0.05) during the first 30 min after LCM compared with fasting and returned toward 0 from 30 to 180 min (Figs. 4 and 5, denoted by a). There was no statistically significant variation of either average or channel Δ frequency after LCM (Fig. 6).

 TABLE 1. Fasting EGG parameters

Channel	Frequency,	Amplitude,		
	cpm	μν		
Ι	3.79 ± 0.14	143 ± 33		
II	3.80 ± 0.18	156 ± 37		
III	3.79 ± 0.15	124 ± 20		
IV	3.83 ± 0.13	83 ± 28		
V	4.09 ± 0.19	139 ± 33		
VI	4.13 ± 0.24	131 ± 29		
Avg	3.90 ± 0.08	131 ± 29		

Values are means \pm SE of values obtained in 6 monkeys on 6 cutaneous bipolar derivations (channels I–VI; see Fig. 1 for disposition). Averages were obtained by calculating means of 6 channels in each animal and then average (\pm SE) of these means.

Effects of HCM on cutaneous EGG. Average and channel I and II Δ amplitude increased significantly (P < 0.05) compared with fasting from 120 to 180 min after HCM (Figs. 4 and 5, denoted by b). In addition, a significant increase compared with that after fasting was observed in channel III from 150 to 180 min and in channel VI from 120 to 150 min (Fig. 5, denoted by b). There was no statistically significant variation of either average or individual channel Δ frequency after HCM (Fig. 6).

Difference between EGGs after two meals. Average and channel V and VI Δ amplitude was significantly greater after HCM than after LCM from 90 to 180 min (Figs. 4 and 5). In addition, a significant difference was observed between the two meals from 120 to 180 min in channels I-IV (Fig. 5). Neither average nor channel Δ frequency was significantly different between the two meals (Fig. 6).

Correlations between FER and EGG parameters. EGG Δ amplitude was significantly correlated with FER in all six monkeys for solids and in three of six monkeys for liquids (Table 2). EGG Δ frequency was significantly correlated with FER in two of the six monkeys for both solids and liquids.

DISCUSSION

Increasing the caloric contents of a meal has been shown to slow gastric emptying of both solids and liquids (13, 19). However, the exact role of gastric motility in the regulation of gastric emptying after mixed meals with various caloric loads remains unclear. After solid meals containing a fixed amount of calories, the average antral motility index was found to be directly correlated with emptying of solids and inversely correlated with the duration of the lag phase for emptying of solids (2). In addition, the rate of coordinated antral contractions was inversely correlated with the half time for emptying of solids (excluding the lag phase) (12). To further study the relation between emptying and gastric motility, we determined concurrently the time courses of emptying and EGG amplitude.

The EGG is believed to represent gastric motility, because experiments in which serosal or mucosal electrodes were used concurrently with cutaneous electrodes demonstrated the gastric origin of the 3/min component of the EGG (10, 16, 26, 27). Furthermore, both EGG amplitude and gastric motor activity increase at the time of appearance of ERA, which reflects mechanical activity

TABLE 2. Correlation coefficients between fractionalemptying rate and EGG amplitude

	Monkey No.					
	1	2	3	1	5	6
Solids	0.48*	0.73*	0.48*	0.47*	0.51*	0.68*
Liquids	0.21	< 0.10	< 0.10	0.56^{*}	0.73^{*}	0.49*
df	31	25	26	32	26	32

Note that degrees of freedom (df) vary among animals because some intervals have no artifact-free windows for EGG in some monkeys. * P < 0.01.

(7, 10, 14, 26, 27). These observations were recently confirmed clinically by showing that the 3/min activity disappeared after gastrectomy but not after colectomy (21).

The major technical difficulty that precluded extensive utilization of the cutaneous EGG in animals and in humans is its sensitivity to motion artifacts. Because this problem is most prominent with monopolar recordings, we obtained bipolar recordings as suggested by Van der Schee et al. (31). In addition, we used high-quality digital filtering to eliminate low- and high-frequency noise (10). Even so, we found that motion artifacts occasionally altered the EGG, and we excluded from analysis the periods during which the animal was not still. Another difficulty encountered by previous investigators was to determine the best number and the relative position of the cutaneous electrodes. In some studies, recordings were obtained from the epigastric sites that were producing the highest signal amplitude during a basal period (7). The disadvantages of this procedure are that it may enlarge interstudy variability and that the "basal" site may not remain important and relevant during the entire session. Therefore we placed seven electrodes in a hexagonal (also called "rosette") configuration (11, 17). This approach permitted a multidirectional mapping of the entire gastric area and allowed better interstudy reproducibility. Furthermore, the sensitivity to interindividual anatomic variations was reduced because the positioning of the electrodes was not based on the quality of the signal recorded during fasting.

In the past, the EGG has been analyzed using the fast Fourier transform technique, thus providing graphic illustration of the predominant frequencies by gray scale or pseudo-three-dimensional running spectrum (28, 30). However, these techniques seldom provided quantitative information regarding the amplitude of the EGG (7). In the present studies, we therefore used a different approach and developed a peak detection program to determine the amplitude and frequency of the EGG during 4h studies. Using this time-domain method, we found that mean fasting amplitudes (Table 1) tended to be greater for the channels that corresponded approximately to the longitudinal axis of the corpus (channels I and II) and of the antrum (channels V and VI), although the difference was not statistically significant. After the meals, EGG amplitude varied significantly only in certain channels and only at specific times during the postprandial period (Fig. 5). These observations confirm that the EGG reflects vectorial projections of gastric activity onto different axes (17), similar to the way the ECG reflects projections of the electrical activity of the heart.

To our knowledge, minute-by-minute correlation between EGG amplitude and gastric emptying has not been previously investigated. By determining the FER for short intervals, we demonstrated that both gastric emptying and the EGG followed a time course that depended on the type of meal. As illustrated by the solid and dotted lines in Figs. 3, C and D, 4, and 5, peak values for both FER and EGG amplitude were reached during the immediate postprandial period after the 1.5-kcal/kg meal (LCM) and between 90 and 180 min after the 5-kcal/kg

meal (HCM). Previous studies using either power spectrum or qualitative analysis of recordings obtained in humans have also demonstrated significant increases in EGG amplitude during the early emptying period of barium or milk meals (7, 10, 15). Similar to our observation, one of these studies showed that the increase in EGG amplitude was followed by a return to fasting levels in about 30 min (10). Other studies in humans showed increases in EGG amplitude during the first 35 min (7) or 55 min after a 239-kcal meal (i.e., 3.4 kcal/kg) (31). In addition, the different postprandial responses of the EGG amplitude that we observed after different meals are analogous to the variations of the gastric motor activity described after different nutrient meals (8). Thus the early increase of EGG amplitude after LCM and the late increase of amplitude after HCM probably reflect increased gastric mechanical contractions that in turn may be responsible for the concurrent stimulation of gastric emptying.

Our demonstration of significant correlations between FER and EGG amplitude in a majority of animals agrees with the observation of postprandial increases in mechanical responses measured using intraluminal antral manometry (2) or implanted force transducers (8). Similarly, our finding that the frequency of the EGG was not significantly modified postprandially confirms observations in humans immediately after a barium or a nutritive meal using fast Fourier transform and visual analysis (14, 15). However, others observed a short-lasting postcibal decrease in frequency when using running spectrum analysis of EGGs obtained in humans (7, 31). This discrepancy could be due to differences in methodology or to the fact that we analyzed our results in 30-min intervals, which may average out an early and shortlasting change in frequency. The observation that amplitude was increased and frequency tended to be decreased 90 min after HCM (Figs. 4-6) may be related to the progressive occurrence of stronger antral contractions, because a similar association was seen in dogs both during fasting (25, 27, 30) and after solid nutrient meals (8, 27).

In summary, the present study documents the significant differences in the cutaneous EGG after two mixed solid-liquid caloric meals that empty at different rates, which indicate that the amplitude of postprandial EGG depends on the nutrient content of the meal. In addition, our observations that the amplitude of the EGG is significantly correlated with emptying indicates that further investigations are warranted to explore the possibility of using this noninvasive method for the study of gastric emptying.

The experiments reported herein were conducted according to the

principles set forth in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council, HHS/NIH Publ. No. 85-23.

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REFERENCES

- ABELL, T. L., AND J. R. MALAGELADA. Glucagon-evoked gastric dysrhythmias in humans shown by an improved electrogastrographic technique. *Gastroenterology* 88: 1932–1940, 1985.
- CAMILLERI, M., J.-R. MALAGELADA, M. L. BROWN, G. BECKER, AND A. R. ZINSMEISTER. Relation between antral motility and gastric emptying of solids and liquids in humans. *Am. J. Physiol.* 249 (*Gastrointest. Liver Physiol.* 12): G580–G585, 1985.
- CHEN, J., J. VANDEWALLE, W. SANSEN, E. VAN CUTSEM, G. VANTRAPPEN, AND J. JANSSENS. Observations of phase shift from cutaneous electrogastrography. *Proc. IEEE Eng. Med. Biol. Soc. 10th Int. Conf.* 10: 992–993, 1988.
- 4. DOOLEY, C. P., AND J. E. VALENZUELA. Antropyloroduodenal activity during gastric emptying of liquid meals in humans. Am. J. Physiol. 255 (Gastrointest. Liver Physiol. 18): G93-G98, 1988.
- DUBOIS, A., J. P. JACOBUS, M. P. GRISSOM, R. R. ENG, AND J. J. CONKLIN. Altered gastric emptying and prevention of radiationinduced vomiting in dogs. *Gastroenterology* 86: 444-448, 1984.
- ELASHOFF, J. D., T. J. REEDY, AND J. H. MEYER. Analysis of gastric emptying data. *Gastroenterology* 83: 1306–1312, 1982.
- GELDOF, H., E. J. VAN DER SCHEE, M. VAN BLANKENSTEIN, AND J. L. GRASHUIS. Electrogastrographic study of gastric myoelectrical activity in patients with unexplained nausea and vomiting. *Gut* 27: 799–808, 1986.
- GILL, R. C., M. A. PILOT, P. A. THOMAS, AND D. L. WINGATE. Effect of feeding on motor activity of canine stomach. *Dig. Dis. Sci.* 34: 865-872, 1989.
- 9. GUETTA, O., J. HAMILTON, J. J. CONKLIN, AND A. DUBOIS. Interfacing the stomach with a computer: an automated analysis of gastric electrical activity. *Proc. DECUS Soc. Dallas, TX* p. 73-77, 1986.
- HAMILTON, J. W., B. E. BELLAHSENE, M. REICHELDERFER, J. G. WEBSTER, AND P. BASS. Human electrogastrograms. Comparison of surface and mucosal recordings. *Dig. Dis. Sci.* 31: 33-39, 1986.
- HÖLZL, R. Surface gastrograms as measures of gastric motility. In: Psychophysiology of the Gastrointestinal Tract—Experimental and Clinical Applications, edited by R. Hölzl and W. E. Whitehead. New York: Plenum, 1983, p. 69–121.
- HOUGHTON, L. A., N. W. READ, R. HEDDLE, M. HOROWITZ, P. J. COLLINS, B. CHATTERTON, AND J. DENT. Relationship of the motor activity of the antrum, pylorus, and duodenum to gastric emptying of a solid-liquid mixed meal. *Gastroenterology* 94: 1285-1291, 1988.
- 13. HUNT, J. N. Regulation of gastric emptying by neurohumoral factors and by gastric and duodenal receptors. In: *Esophageal and Gastric Emptying*, edited by A. Dubois and D. O. Castell. Boca Raton: CRC, 1984, p. 65-71.
- KOCH, K. L., AND R. M. STERN. The relationship between the cutaneously recorded electrogastrogram and antral contractions in man. In: *Electrogastrography: Methodologies, Validation and Applications*, edited by R. M. Stern and K. L. Koch. New York: Praeger, 1985, p. 116-131.
- KOCH, K. L., W. R. STEWART, AND R. M. STERN. Effect of barium meals on gastric electromechanical activity in man. A fluoroscopicelectrogastrographic study. *Dig. Dis. Sci.* 32: 1217–1222, 1987.
- LAPORTE, J. L., L. O'CONNELL, A. DURAKOVIC, R. SJOGREN, J. J. CONKLIN, AND A. DUBOIS. Cross correlation analysis of gastric motility following exposure to ionizing radiation in primates (Abstract). *Dig. Dis. Sci.* 29: 565, 1984.
- MARTIN, A., AND J.-L. THILLIER. L'électrogastroentéro-graphie. Presse Med. 79: 1235–1237, 1971.
- MEYER, J. H. Motility of the stomach and gastroduodenal junction. In: *Physiology of the Gastrointestinal Tract* (2nd ed.), edited by L. R. Johnson. New York: Raven, 1987, p. 613-629.

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- MOORE, J. G., P. E. CHRISTIAN, J. A. BROWN, C. BROPHY, F. DATZ, A. TAYLOR, AND N. ALAZRAKI. Influence of meal weight and caloric contents on gastric emptying of meals in man. *Dig. Dis.* Sci. 29: 513-519, 1984
- PARASKEVOPOULOS, J. A., L. A. HOUGHTON, I. EYRE-BROOK, A. G. JOHNSON, AND N. W. READ. Effect of composition of gastric contents on resistance to emptying of liquids from stomach in humans. *Dig. Dis. Sci.* 33: 914–918, 1988.
- 21. PEZZOLLA, F., G. RIEZZO, M. A. MASELLI, AND I. GIORGO. Electrical activity recorded from abdominal surface after gastrectomy or colectomy in humans. *Gastroenterology* 97: 313–320, 1989.
- 22. RABINER, L. R., AND B. GOULD. Theory and Application of Digital Processing. Englewood Cliffs, NJ: Prentice-Hall, 1975, p. 136–140.
- READ, N. W., AND L. A. HOUGHTON. Physiology of gastric emptying and pathophysiology of gastroparesis. *Gastroenterol. Clin. N.* Am. 18: 359–373, 1989.
- SHIRES, J., N. FIALA, AND A. DUBOIS. Automatic motion detection in rhesus monkeys. Proc. IEEE Eng. Med. Biol. Soc. 10th Int. Conf. 10: 1862–1863, 1988.
- SMOUT, A. J. P. M., AND E. J. VAN DER SCHEE. Gastric pacemaker rhythm in conscious dogs. Am. J. Physiol. 237 (Endocrinol. Metab. Gastrointest. Physiol. 6): E279-E282, 1979.
- SMOUT, A. J. P. M., E. J. VAN DER SCHEE, AND J. L. GRASHUIS. What is measured in electrogastrography? *Dig. Dis. Sci.* 25: 179– 187, 1980.
- 27. SMOUT, A. J. P. M., E. J. VAN DER SCHEE, AND J. L. GRASHUIS. Postprandial and interdigestive gastric electrical activity in the dog recorded by means of cutaneous electrodes. In: *Gastrointestinal*

Motility, edited by J. Christensen. New York: Raven, 1980, p. 187–194.

- STERN, R. M., K. L. KOCH, H. W. LEIBOWITZ, AND I. M. LIND-BLAD. Spectral analysis of tachygastria recorded during motion sickness. *Gastroenterology* 92: 92–97, 1987.
- SZURSZEWSKI, J. H. Electrical basis for gastrointestinal motility. In: *Physiology of the Gastrointestinal Tract* (2nd ed.), edited by L. R. Johnson. New York: Raven, 1987, p. 383-422.
- VAN DER SCHEE, E. J., AND J. L. GRASHUIS. Contraction-related, low-frequency components in canine electrogastrographic signals. Am. J. Physiol. 245 (Gastrointest. Liver Physiol. 8): G470-G475, 1983.
- 31. VAN DER SCHEE, E. J., A. J. P. M. SMOUT, AND J. L. GRASHUIS. Application of running spectrum analysis to electrogastrographic signals recorded from dog and man. In: *Motility of the Digestive Tract*, edited by M. Wienbeck. New York: Raven, 1982, p. 241– 250.
- WEIBULL, W. A statistical distribution function of wide applicability. J. Appl. Mech. 49: 293–297, 1951.
- WINER, B. J. Statistical Principles in Experimental Design (2nd ed.). New York: McGraw-Hill, 1971.
- WIRTH, N., D. SWANSON, B. SHAPIRO, M. NAKAJO, J. L. COFFEY, F. ECKHAUSER, AND C. OWYANG. A conveniently prepared Tc-99m resin for semisolid gastric emptying studies. J. Nucl. Med. 24: 511– 514, 1983.
- 35. YOU, C. H., AND W. Y. CHEY. Study of electromechanical activity of the stomach in humans and in dogs with particular attention to tachygastria. *Gastroenterology* 86: 1460–1468, 1984.

