24-Hour Ambulatory Electrogastrography in Healthy Volunteers

G. LINDBERG, M. IWARZON & B. HAMMARLUND
Karolinska Institutet, Section of Gastroenterology and Hepatology, Dept. of Medicine, Huddinge University Hospital, Huddinge, Sweden

Lindberg G, Iwarzon M, Hammarlund B. 24-Hour ambulatory electrogastrography in healthy volunteers. Scand J Gastroenterol 1996;31:658–664.

Background: Development of electrogastrography, the recording of gastric electric rhythm from cutaneous electrodes, for clinical purposes has been hampered by methodologic problems and the lack of an ambulatory technique. We have evaluated a newly developed system for ambulatory electrogastrography. *Methods:* 24-Hour recordings were obtained from 30 healthy volunteers. We used digital filtering, a Hamming window, and spectral analysis to determine the dominant frequency of successive 256-sec segments of data. *Results:* Low-frequency noise disturbed the primary signal. After secondary filtering a stable normogastric (2–4 cpm) rhythm was present during a median of 49% (range, 34–79%) of the recording time. The mean frequency of gastric electric activity varied from 2.92 ± 0.15 cpm (mean ± SD) at mid-day to 2.72 ± 0.13 cpm in the late night. *Conclusions:* Ambulatory recording of electrogastrography needs technical improvement. The electrogastrogram shows a circadian variation in frequency.

Key words: Electrodes; electrodiagnosis; gastrointestinal motility, computer-assisted signal processing; human; reference values; stomach

Greger Lindberg, M.D., Section of Gastroenterology and Hepatology, Dept. of Medicine, K63, Huddinge University Hospital, S-141 86 Huddinge, Sweden (fax: +46 8 6082241)

The recording of gastric electric activity from cutaneous electrodes, so-called electrogastrography (EGG) was first described by Alvarez in 1922 (1). The technique received renewed attention after the work by British and Dutch research groups. Brown et al. (2) and Smallwood (3) showed that a 3-cpm (cycles per minute) rhythm was present for most of the recording time irrespective of contractile activity in the stomach. Smout et al. (4) showed that the changes in the cutaneous potentials measured by EGG resulted from the co-ordinated propagation of rhythmic depolarizations and repolarizations of gastric smooth muscle, the slow-wave rhythm. They also found that electric response activity contributed to the electrogastrogram by increasing its amplitude.

EGG attempts to record a comparatively weak signal from a background of much electric noise. There is low-frequency noise, such as base-line changes from changes in posture and motion artefacts, and there is high-frequency noise from muscular and cardiac activity. It is therefore necessary to apply some kind of filtering before a reliable EGG signal can be recorded. Short-term registrations from supine subjects have utilized bandpass filters with the lower cut-off set at 0.6–1.4 cpm and the upper cut-off at 4.8–30 cpm (2, 5–8). In normal volunteers such recordings have yielded an interpretable EGG for 60–97% of the recording time (2, 5, 7, 10).

The use of computers for signal analysis was shown to greatly improve the ability to detect gastric electric rhythm in recordings of EGG (9). The most widely applied technique for computer analysis of the EGG has been to use Fourier transforms of successive, overlapping segments of data to arrive at a so-called running spectral analysis (10, 11). Thus, EGG has shown disturbances of the gastric electric rhythm in patients with unexplained nausea or vomiting (10), diabetic (12, 13) or idiopathic gastroparesis (14–16), and gastric ulcer (17). Both abnormally fast rhythms, tachygastria, and abnormally slow rhythms, bradygastria, have been reported to occur in such patients. The relation between changes in electric rhythm and the contractile activity of the stomach remains uncertain.

Although EGG has been around for more than 70 years, the measurement of gastric electric activity has not gained access to clinical practice. One of the reasons for this may be the lack of an ambulatory technique to record EGG over long periods of time. Portable recorders have long been in use for ambulatory monitoring of oesophageal pH (18), and more recently techniques for long-term monitoring of small-bowel motility have been developed (19, 20). In the present study we have evaluated a new method of 24-h ambulatory EGG monitoring using a portable digital recorder. The aims of our study were to determine the proportion of time during which the ambulatory EGG would yield a reliable measure of gastric electric rhythm, to compare the EGG signal from different electrode placements, to determine the normal variation of gastric electrical rhythm, and to ascertain whether there is a variation of the frequency of this rhythm over the 24 h.

MATERIALS AND METHODS

Subjects

Thirty healthy volunteers, 15 men and 15 women (mean age, 29 years; range, 19–39 years), served as subjects. They had no present or significant past history of gastrointestinal disease. None of the subjects had taken any drugs during the preceding week, and none required medication during the study period. The study was approved by the Ethics Committee of Huddinge University Hospital, and informed consent was obtained from each subject.

Electrogastrography

We used three silver/silver chloride adhesive electrodes (Cleartrace, Medtronic Andover Medical Inc., Haverhill, Mass., USA) to obtain a single bipolar differential lead from the upper abdominal wall. Subjects were randomly assigned to one of three electrode placements. In group A one active electrode was placed at the midpoint between the xiphoid and the navel, and the other 5 cm to the left and 3 cm *below* this. The reference electrode was placed on the right leg. In group B the reference electrode was placed on the right flank just above the iliac crest, whereas the active electrodes were the same as in group A. In group C one active electrode was placed at the midpoint between the xiphoid and the navel, whereas the other was placed 5 cm to the left and 3 cm *above* this. The reference electrode was the same as in group B. The locations of the measurement electrodes were chosen to correspond with the two most frequently reported best configurations (5, 6, 9, 12, 14, 17), whereas the reference electrode was placed in locations with an assumed difference in exposure to motion artefacts. The skin was lightly abraded with sandpaper before attaching the electrodes.

The EGG signal was recorded using a specially designed digital recorder (Digitrapper-EGG, Synectics Medical, Stockholm, Sweden). The recording device included a one-channel EGG pre-amplifier, a bandpass analog filter, an analog-to-digital (8-bit precision) converter, and 96 kbyte of memory. The filter had a 1.8- to 16.0-cpm passband with a roll-off of 6 dB/octave. The EGG signal was sampled at a rate of 1 Hz. The device was equipped with four push buttons to record the time of meals, symptoms, and changes in body position (upright or supine). The weight of the recording device including a 9-V alkaline battery was approximately 300 g.

Procedure

Subjects were interviewed and examined to exclude those with significant medical findings. After a 4-h fast the subjects were randomized to one of the three electrode configurations, and the electrodes were placed on the abdominal skin. The electrodes were connected to the portable recorder, and the EGG recording started. The number of meals during the study period was limited to three, but no restriction was put on timing or on the type of food for the three meals. The subjects were instructed to use the push buttons on the recorder to mark the beginning and the end of each meal, any change from upright to supine or vice versa, and any occurrence of nausea or abdominal pain. Symptoms, meals, and activities were also manually recorded by the subjects on diary cards.

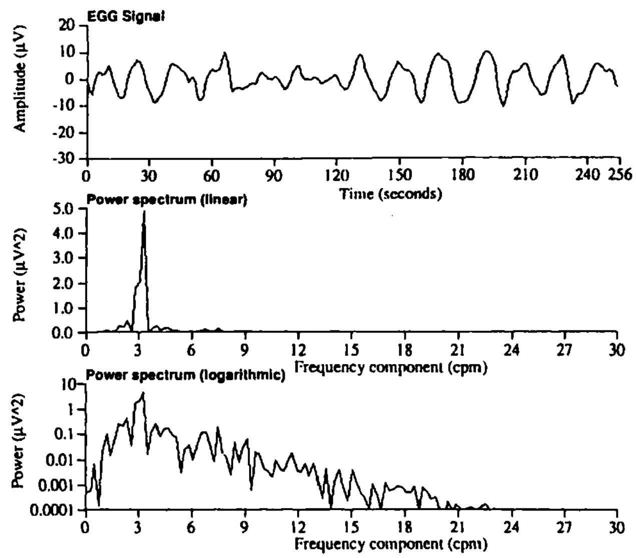

Fig. 1. Frequency estimation of gastric electric rhythm using fast Fourier transform of a 256-sec segment of data from a cutaneous recording of electrogastrography (EGG). Top: The original EGG curve. Middle: Power spectrum expressed on a linear scale. Bottom: Power spectrum expressed on a logarithmic scale.

All subjects resumed normal activities during the study, which continued for 24 h. The evening and the night were spent at home. Subjects returned to the laboratory at about the same time the following day, at which time recordings were terminated.

Analysis of EGG

Each recording resulted in approximately 86,400 measurement values, and on completion of the recording these were transferred to a MS-DOS microcomputer. The manufacturer of the Digitrapper-EGG also provided a computer program (Multigram) for the analysis of EGG. This program performed a so-called running spectral analysis in which fast Fourier transforms were calculated from segments of data 4 min and 16 sec long (256 measurement values). Each new segment overlapped the previous segment by 75% of its length. Hence, 1 min and 4 sec of new data were entered into each run.

The fast, or discrete Fourier transform divides the original signal into a series of discrete frequency components, the power spectrum. In the present study the power spectrum comprised the powers of 129 frequency components into which the original curve was transformed (Fig. 1). The power is a measure of the amplitude of frequency components. Since the recording frequency was 60 min^{-1} (1 Hz) and the number of data points was 256, each step along the frequency scale—that is, the resolution in the frequency domain—became 60/256 ~ 0.23 cpm.

The analysis software was set to distinguish four frequency strata: bradygastria (<2 cpm), normogastria (2–4 cpm),

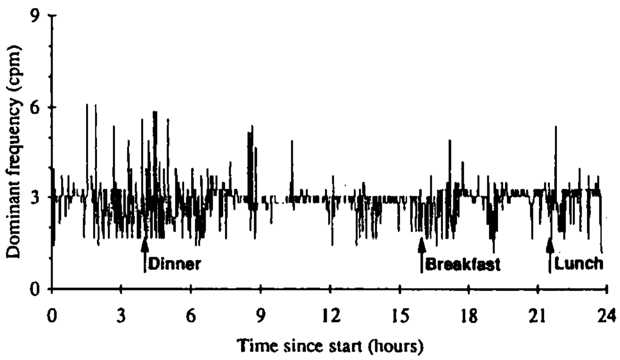

Fig. 2. Representation of a 24-h electrogastrographic recording. The graph shows the dominant frequency from fast Fourier transforms of successive 256-sec data segments with 75% overlap from one segment to the next. The recording started at 1500 h. Arrows indicate the meals taken by the subject during the recording.

tachygastria (4–10 cpm), and duodenal/respiratory rhythms (>10 cpm). The Multigram program enabled us to calculate two measures: the amount of power attributed to each frequency stratum and the percentage of time during which the dominant frequency—that is, the frequency component with the largest power—fell within each frequency stratum. The interpretation of the amount of power attributed to a frequency stratum is unclear, particularly in the ambulatory setting, in which artefacts often have a much larger amplitude than the signal. Our analysis was therefore mainly directed towards the dominant frequency, which was interpreted as a mode measure of frequency in the amplitude domain.

In addition to the analyses available in Multigram, we used the modular analysis program LabView 2 (National Instruments, Austin, Tex., USA) to perform secondary filtering and analysis of the EGG data. The LabView 2 program was run on an Apple Macintosh IIvx series of computers. We used a Hamming window to reduce leakage in accordance with Geldof et al. (17) and a digital Butterworth bandpass filter with the passband set to 1.8–12.0 cpm (roll-off, 24 dB/octave) before subjecting the EGG data to Fourier analysis. We determined the dominant frequency and its power for each period of 256 sec with the same overlap as in the Multigram analysis. Fig. 2 shows the dominant frequency over 24 h in one of the subjects. The results of the LabView 2 analysis were used to calculate the absolute and relative times during which the EGG showed a dominant frequency with normal 3-cpm (2- to 4-cpm) rhythm, bradygastria, and tachygastria.

Stability of the dominant frequency

An inherent problem with the Fourier transform is that any set of data with the pre-determined number of data points will yield a power spectrum, and there are no rules to tell an artefactual frequency component from one that is true. We assumed that the normal gastric electric rhythm would be roughly stable over time and that this would be reflected by the dominant frequency of the power spectrum. Pilot studies showed that artefacts often caused high-amplitude, transient deviations of the electrogastrogram. Such artefacts would normally be filtered off because of their higher frequency, but it was noted that the analog filter of the recording device took some 15–60 sec to stabilize and during the process of stabilization the EGG signal became distorted by the dampened oscillations of the filter. In the running spectral analysis such artefacts tended to cause temporary deviations of the dominant frequency. We therefore studied the occurrence of stable rhythms in the EGG and we hypothesized that the longer the dominant frequency stayed the same, the likelier it was that it would reflect the true frequency of the gastric electric rhythm. We calculated the proportion of time with normogastric or tachygastric rhythms that stayed at roughly the same frequency (±0.23 cpm) over two, three, and four successive segments, and we used these measures to assess the reliability of the ambulatory recording.

Statistical analysis

Mean frequencies showed a normal distribution, and groups were compared using one-way ANOVA with Scheffé's F-test (21) for inter-group comparisons. Data on proportions of different electric rhythms did not always fit the normal distribution. Groups were therefore compared using the Kruskal–Wallis test (22), and we used Ryan's procedure (23) for multiple comparisons. However, data on the quality of the EGG signal during different time periods were analysed using ANOVA for repeated measures.

RESULTS

Ten subjects were randomized to each group. The three groups A, B, and C included five, six, and four women, respectively. The mean ages in the three groups were 30, 26,

Table I. Analysis of 24-h ambulatory electrogastrography, using Multigram. Percentage of time with a dominant frequency of less than 2 cpm (bradygastria), between 2 and 4 cpm (normogastria), and more than 4 cpm (tachygastria) in 30 healthy volunteers divided into 3 groups with different electrode placements (A–C). Values are given as median and range

Electrode placement (no. of subjects)	Bradygastria	Normogastria	Tachygastria
A (10)	74.8% (53.2–85.8%)	25.1% (13.9–46.8%)	0.2% (0.0–0.8%)
B (10)	68.1% (38.2–82.5%)	31.7% (17.5–61.3%)	0.2% (0.1–0.6%)
C (10)	68.8% (38.8–77.8%)	30.1% (18.2–60.4%)	0.7% (0.1–5.8%)
Total (30)	69.5% (38.2–85.8%)	28.9% (13.9–61.3%)	0.3% (0.0–5.8%)

Table II. Analysis of electrogastrography after secondary filtering using a Butterworth digital bandpass filter with the passband set to 1.8–12.0 cpm. Percentage of time with a dominant frequency of less than 2 cpm (bradygastria), 2–4 cpm (normogastria), and more than 4 cpm (tachygastria) in 30 healthy volunteers divided into 3 groups with different electrode placement (A–C). Values are given as median and range

Electrode placement (no. of subjects)	Bradygastria	Normogastria	Tachygastria
A (10)	27.0% (17.5–37.3%)	71.1% (59.9–81.7%)	2.5% (0.7–2.8%)
B (10)	23.1% (9.3–30.9%)	75.5% (67.5–89.1%)	1.7% (1.0–2.7%)
C (10)	19.6% (9.6–27.1%)	76.5% (69.7–88.1%)	2.6% (1.7–10.8%)
Total (30)	22.7% (9.3–37.3%)	74.8% (59.9–89.1%)	2.4% (0.7–10.8%)

B versus C $p < 0.05$

and 28 years. None of the subjects reported any symptoms during the study. The results of the EGG analysis using the Multigram program are shown in Table I. The dominant frequency fell in the normogastric (2–4 cpm) region for a median 28.9% (range, 13.9%–61.3%) of the recording time, whereas bradygastric (<2 cpm) rhythms dominated in 69.5% (38.2%–85.8%) of the recordings. Tachygastric frequencies (4–10 cpm) were found in 0.3% (0%–5.8%). There was no difference between the groups with different electrode placements.

Further analysis using the LabView 2 program enabled us to filter off much of the low-frequency noise that disturbed the initial analysis. Table II shows the results after secondary filtering of data. In contrast to the results in Table I, this analysis showed that normogastric rhythms were present during 74.8% (59.9%–89.1%) of the recording time. Group C had a higher prevalence of tachygastric rhythms than group B ($p < 0.05$). One subject in group C had three nocturnal episodes of tachygastria at frequencies between 6.3 and 7.0 cpm, which lasted 26, 13, and 24 min, respectively. Short tachygastrias lasting 6 min or less were noted in four other subjects, two in group A and two in group C.

Reliability of the dominant frequency

The reliability of the recorded signal was determined from the stability of the dominant frequency. As can be seen in Fig. 3, the percentage of time with a reliable signal decreased as the requirement for stability increased from one to four successive segments. Bradygastric rhythms were not included in this part of the analysis because stable bradygastric rhythms only occurred at frequencies near the lower border of the bandpass filter, which indicated that they were caused by artefacts. When the dominant frequency was required to be stable for three successive segments, the median percentage of stable normogastric rhythms was 49.4% (34.1%–79.0%), whereas the percentage of tachygastria was 0.2% (0%–4.9%). At this level the 95th percentile for tachygastria was less than 1% of the recording time, and we accepted this as an ad hoc criterion for reliability. There was no difference between the three subject groups with regard to the percentage of time with stable normogastric or tachygastric rhythms. To ascertain whether the quality of the EGG signal was better at any particular time of the day or the night, we calculated the percentage of time with a reliable normogastric rhythm during the four 6-h periods 0000–0600, 0600–1200, 1200–1800, and 1800–2400 h. We found no difference between these time periods, nor was there a difference between groups with different electrode placements.

The effect of meals on gastric electric rhythm

The intake of a meal led to a decrease in frequency for about 15 min, after which the frequency increased to a somewhat higher level than before the meal. These changes were seen in all meals, but they were more pronounced with the breakfast meal (Fig. 4). In seven patients with stable rhythms for more than 50% of the time 30 min before breakfast and 60 min after breakfast the mean frequency before breakfast was 2.92 cpm. During the first 15 min after the beginning of the meal the frequency decreased to 2.75 cpm ($p < 0.05$), but at 15 to 60 min after the meal the mean frequency increased to 3.01–3.07 cpm. The power of the dominant frequency increased from 5.35 (arbitrary units) before breakfast to 15.60 at 15–60 min after the meal ($p < 0.05$).

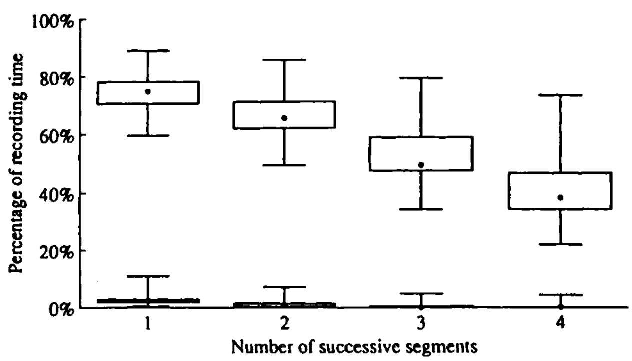

Fig. 3. Percentage of time with stable normogastric (2–4 cpm) or tachygastric (4–10 cpm) dominant frequency rhythms in 24-h recordings of electrogastrography from 30 healthy volunteers. Values are given as median, interquartile range, and full percentages as the criterion for stability increased from one to four successive segments. Dominant frequency was determined by fast Fourier analysis of successive 256-sec segments of data with an overlap of 75% from one segment to the next. The upper portion of the graph shows the normogastric rhythms, and the lower portion represents the tachygastric rhythms.

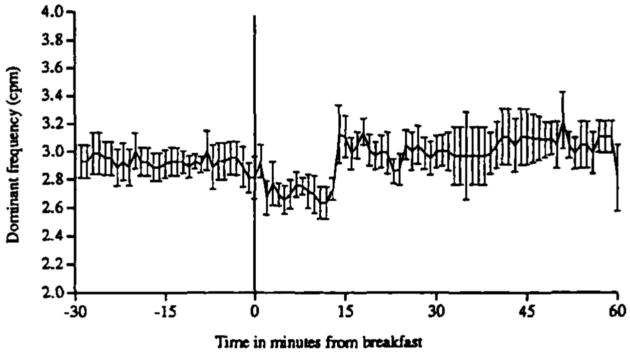

Fig. 4. Dominant frequency of electrogastrograms before and after breakfast in seven healthy volunteers. Bars indicate SEM. Time 0 indicates the beginning of the meal.

Variation of gastric electric rhythm over 24 h

The LabView 2 analysis enabled us to calculate the dominant frequency of each segment and this enabled us to study changes in the dominant frequency over time. The average dominant frequency during different time periods of the day and the night were calculated, to study the variability of the dominant frequency over 24 h. To avoid bias from artefacts all segments with a dominant frequency <2.34 cpm or >3.75 cpm were excluded from this part of the analysis. We found that the dominant frequency was lower during the night than it was during the day (Fig. 5). The minimum frequency (2.72 ± 0.13 cpm) was found between 0300 and 0600 h, and this was significantly lower ($p < 0.001$) than the mean dominant frequency (2.92 ± 0.15 cpm) during the period 0900–1200 h, when gastric electric rhythm reached its maximum frequency. The mean frequency during the late night was also significantly lower than the frequency (2.85 ± 0.15 cpm) during 0600–0900 h ($p < 0.01$), 1200–1500 h (2.89 ± 0.20 cpm; $p < 0.001$), 1500–1800 h (2.84 ± 0.15 cpm; $p < 0.05$), and 1800–2100 h (2.88 ± 0.16 cpm; $p < 0.001$). The frequency (2.75 ± 0.15 cpm) during the early night (0000–0300 h) was also significantly lower than the frequency during the periods 0900–1200 h ($p < 0.001$), 1200–1500 h ($p < 0.01$), and 1800–2100 h ($p < 0.05$).

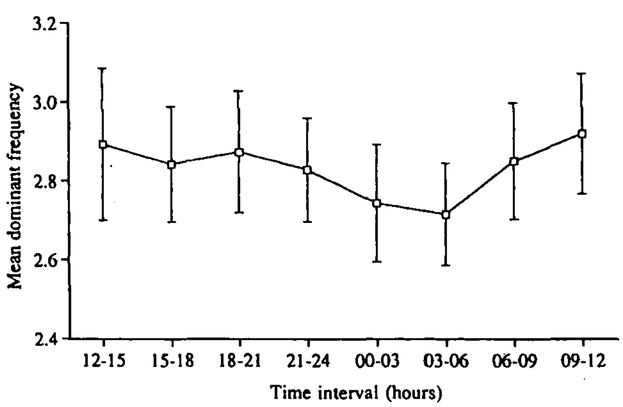

Fig. 5. Variation of gastric electric rhythm over 24 h. Mean (±SD) values for normogastric dominant frequencies during different intervals of 24-h recordings of electrogastrograms in 30 healthy volunteers.

DISCUSSION

To our knowledge this is the first study of ambulatory long-term monitoring of EGG. Despite the ambulatory setting and a large number of artefacts a stable normogastric signal was present for a median of 49% of the recording time. This is clearly a lower figure than the 60–97% time with an interpretable EGG signal that has been reported from stationary recordings (2, 5, 7, 10), but it still indicates that ambulatory monitoring of EGG is within reach. The filter of the recording device was insufficient for achieving an interpretable signal. After applying a digital filter with a much steeper roll-off, a large proportion of the low-frequency noise that disturbed the initial Fourier analysis could be filtered off. This indicates the need for a better filter in the recording device. However, it was not the artefacts themselves that caused problems in the analysis, but rather what seemed to be oscillations in the filter on stabilization after a transient artefact. There is a risk that a more complex filter might also lengthen the time taken to stabilize after an artefact.

We used the discrete Fourier analysis to determine the dominant frequency of successive overlapping segments of data. Several other methods have been used to analyse the EGG signal, including phase lock filtering (24), autoregressive modelling (25), autocorrelation (2), and adaptive filtering (26, 27). Most researchers agree that visual analysis is insufficient, not least because of the poor signal-to-noise ratio of EGG. The discrete Fourier analysis is preferred for computational reasons. It is much faster than the ordinary integral Fourier analysis. However, it is important to remember that there is a trade-off between precision and sensitivity when using this kind of analysis. To improve precision with regard to the estimate of frequency, long segments of data are needed, but the longer the segment is, the less sensitive the analysis becomes for periods of abnormal rhythms. In the present study we used 256-sec segments with an overlap of 75%. This size of the segment together with a Hamming window has been shown to enable the detection of tachygastrias with a duration of 1 min or more (11). With the additional criterion of a stable dominant frequency for at least 3 successive segments, the minimum detectable duration of tachygastria becomes 3 min. Whether this level of precision is clinically useful remains to be shown.

Our study confirmed that gastric slow-wave rhythm is omnipresent. Like others (5, 12) we found short periods of tachygastria in some of our normal volunteers. Long periods of tachygastria were found in one subject during the night. None of the tachygastrias was associated with symptoms. We also found that EGG frequency and amplitude changed to a typical pattern after meals, which confirmed the findings of others (2, 10, 28).

There was a large variation from one subject to another in the percentage time with a stable rhythm. In one-quarter of the subjects the recordings yielded a stable dominant frequency for >60% of the time. It is yet unknown which factors may determine the quality of the signal. We investigated three different placements of the electrodes but the exact position of the electrodes seemed to matter little. It is generally agreed that the measurement electrodes should be placed along the longitudinal axis of the antrum (28). However, in the ambulatory setting the shape and the position of the stomach may change depending on posture, motion, and intake of food. We did not use ultrasonography, for example, to locate the antrum in one or the other body position (29, 30), but it is possible that this could have improved the signal yield.

Artefacts were common but, much to our surprise, there was no difference in signal yield between different times of the day or the night. If artefacts caused by motion were important, one would have expected a lower signal yield during the active times of the day than during the night, but this was not the case in our study. Other reasons for artefacts should therefore be looked for. Static electricity has been little mentioned in the literature about EGG, but to judge from the acute nature of many artefacts seen in our recordings, static electricity may be an additional source of error, particularly in the ambulatory setting.

Skin conductivity may vary to a great extent from person to person, and this may influence the quality of the signal. We used sandpaper to prepare the skin, and this procedure usually leads to a resistance between electrodes of less than 10 kΩ (unpublished data).

Gastric slow-wave rhythm showed a characteristic variation over the 24 h, with maximum frequency at mid-day and minimum frequency during the night. This finding has not been reported previously, but at least one other measure of gastrointestinal motility, the propagation velocity of the migrating motor complex, has been shown to have a circadian variation (31).

ACKNOWLEDGEMENTS

This study was supported by grants from the Karolinska Institute (KI Fonder) and from Janssen-Cilag AB, Sweden.

REFERENCES

1. Alvarez WC. The electrogastrogram and what it shows. JAMA 1922;78:1116–9.
2. Brown BH, Smallwood RH, Duthie HL, Stoddard CJ. Intestinal smooth muscle electrical potentials recorded from surface electrodes. Med Biol Eng 1975;13:97–103.
3. Smallwood RH. Gastrointestinal electrical activity from surface electrodes [thesis]. Sheffield, UK, 1976.
4. Smout AJPM, Van der Schee EJ, Grashuis JL. What is measured in electrogastrography? Dig Dis Sci 1980;25:179–87.
5. Hamilton JW, Bellahsene BE, Reichelderfer M, Webster JG, Bass P. Human electrogastrograms. Comparison of surface and mucosal recordings. Dig Dis Sci 1986;31:33–9.
6. Riezzo G, Pezzolla F, Giorgio I. Effects of age and obesity on fasting gastric electrical activity in man: a cutaneous electrogastrographic study. Digestion 1991;50:176–81.
7. Mintchev MP, Kingma YJ, Bowes KL. Accuracy of cutaneous recordings of gastric electrical activity. Gastroenterology 1993; 104:1273–80.
8. Chen J, McCallum RW, Richards R. Frequency components of the electrogastrogram and their correlations with gastrointestinal contractions in humans. Med Biol Eng Comput 1993;31:60–7.
9. Familoni BO, Bowes KL, Kingma YJ, Cote KR. Can transcutaneous recordings detect gastric electrical abnormalities? Gut 1991;32:141–6.
10. Geldof H, Van der Schee EJ, Van Blankenstein M, Grashuis JL. Electrogastrographic study of gastric myoelectrical activity in patients with unexplained nausea and vomiting. Gut 1986;27: 799–808.
11. Van der Schee EJ, Grashuis JL. Running spectral analysis as an aid in the representation and interpretation of electrogastrographic signals. Med Biol Eng Comput 1987;25:57–62.
12. Pfister CJ, Hamilton JW, Nagel N, Bass P, Webster JG, Tompkins WJ. Use of spectral analysis in the detection of frequency differences in the electrogastrograms of normal and diabetic subjects. IEEE Trans Biomed Eng 1988;35:935–41.
13. Koch KL, Stern RM, Stewart WR, Vasey MW. Gastric emptying and gastric myoelectrical activity in patients with diabetic gastroparesis: effect of long-term domperidone treatment. Am J Gastroenterol 1989;84:1069–75.
14. Chen J, McCallum RW. Gastric slow wave abnormalities in patients with gastroparesis. Am J Gastroenterol 1992;87: 477–82.
15. Chen J, Schirmer BD, McCallum RW. Serosal and cutaneous recordings of gastric myoelectrical activity in patients with gastroparesis. Am J Physiol 1994;266:G90–8.
16. Rothstein RD, Alavi A, Reynolds JC. Electrogastrography in patients with gastroparesis and effect of long-term cisapride. Dig Dis Sci 1993;38:1518–24.
17. Geldof H, Van der Schee EJ, Smout AJPM, Van de Merwe JP, Van Blankenstein M, Grashuis JL. Myoelectrical activity of the stomach in gastric ulcer patients: an electrogastrographic study. J Gastrointest Motil 1989;1:122–30.
18. Vitale GC, Cheadle WG, Sadek S, Michel ME, Cuschieri A. Computerized 24-hour ambulatory esophageal pH monitoring and esophagogastroduodenoscopy in the reflux patient. A comparative study. Ann Surg 1984;200:724–8.
19. Gill RC, Kellow JE, Browning C, Wingate DL. The use of intraluminal strain gauges for recording of ambulant small bowel motility. Am J Physiol 1990;258:G610–5.
20. Lindberg G, Iwarzon M, Stål P, Seensalu R. Digital ambulatory monitoring of small bowel motility. Scand J Gastroenterol 1990;25:216–24.
21. Scheffé H. A method for judging all contrasts in the analysis of variance. Biometrika 1953;40:87–104.
22. Kruskal WH, Wallis WA. Use of ranks in one-criterion variance analysis. J Am Stat Assoc 1952;47:583–621.
23. Ryan TA. Significance tests for multiple comparison of proportions, variances, and other statistics. Psychol Bull 1960; 57:318–28.
24. Smallwood RH. Analysis of gastric electrical signals from surface electrodes using phaselock techniques. Med Biol Eng Comput 1978;16:507–18.
25. Linkens DA, Datardina SP. Estimation of frequencies of gastrointestinal electrical rhythms using autoregressive modelling. Med Biol Eng Comput 1978;16:262–8.
26. Van der Schee EJ, Kentie MA, Grashuis JL, Smout AJPM. Adaptive filtering of canine electrogastrographic signals. 2. Filter performance. Med Biol Eng Comput 1981;19:765–9.
27. Chen J, Vandewalle J, Sansen W, Vantrappen G, Janssens J. Multichannel adaptive enhancement of the electrogastrogram. IEEE Trans Biomed Eng 1990;37:285–94.
28. Mirizzi N, Scafoglieri U. Optimal direction of the electrogastrographic signal in man. Med Biol Eng Comput 1983;21:385–9.

29. Chen J, McCallum RW. Effect of milk on myoelectrical activity of the stomach—an electrogastrographic study. Med Biol Eng Comput 1992;30:564–7.
30. Chen J, McCallum RW. Electrogastrography: measurement, analysis and prospective applications. Med Biol Eng Comput 1991;29:339–50.
31. Kumar D, Wingate DL, Ruckebusch Y. Circadian variation in the propagation velocity of the migrating motor complex. Gastroenterology 1986;91:926–30.

APPENDIX

The electrogastrographic (EGG) signal was recorded from three Ag/AgCl electrodes attached to the skin. Two of these were placed along the longitudinal axis of the antrum to maximize signal yield. The third was the common reference. The two electrodes along the antral axis connected to the recording device (Digitrapper-EGG, Synectics Medical, Stockholm, Sweden) as a bipolar differential lead.

The potential differences between the two measurement electrodes were amplified and ran through an analog bandpass filter before being digitized into 8-bit values, which were stored at a sampling rate of 1 Hz in the solid-state memory of the recording device. The passband of the filter was 1.8–16.0 cpm. The border values represent the frequencies with an attenuation of 3 dB. The roll-off—that is, the increase in attenuation of signal frequencies below and above these border values—was 6 dB/octave. A 24-h recording with this device yielded 86,400 measurement values, and a normal cycle of gastric electric rhythm was represented by about 20 data points.

The analysis of the EGG curve was based on Fourier transforms of successive segments of data. The Fourier transform establishes the relationship between a signal and its representation in the frequency domain, the power spectrum. The discrete Fourier transform divides the signal into a spectrum of 1 + (n/2) frequency components (where n, which has to be a valid power of 2, is the number of data points submitted for transformation). The relative contribution of each frequency component to the original curve is reflected by its power (Fig. 1).

The discrete Fourier transform is given by

$$X_k = \sum_{i=0}^{n-1} \chi i \cdot e^{-j2\pi ik/n} \quad \text{for } k = 0, 1, 2, ..., n-1$$

With Y representing the Fourier transform of the input sequence X with n data points it can be shown from the above formula that

$$|Y_{n-i}|^2 = |Y_{-i}|^2$$

which implies that the power in the $(n-i)^{\text{th}}$ element of Y can be interpreted as the power in the negative i^{th} component. Thus the total power for the i^{th} harmonic can be found using

Power in i^{th} harmonic

$$= 2 \cdot |Y_i|^2 = |Y_i|^2 + |Y_{n-i}|^2, \quad 0 < i < n/2.$$

The total power in the DC and Nyquist components are $|Y_0|^2$ and $|Y_{n/2}|^2$, respectively. The dominant frequency is the frequency component that has the largest magnitude.

When determining the number of data points that will be included in a discrete Fourier transform, a trade-off has to be made between, on the one hand, precision in the frequency estimate and, on the other hand, sensitivity to changes in the frequency of the underlying signal. In the present study we used segments with a length of 256 measurement values. This gives a reasonably good precision in the frequency estimate but only moderate sensitivity to changes in frequency. We therefore applied two more techniques to increase the sensitivity of our analysis. The first was to let successive segments overlap so that only 25% of a segment consisted of 'new' data.

The effect of this overlap is that any part of the recording except the first and the last minutes will be included in four successive segments. However, this may lead to so-called 'leakage' of frequency estimates from one spectrum to the next. For example, an artefact with a large amplitude may distort four successive Fourier transforms. Therefore, a Hamming window was applied to each segment before submitting it to the Fourier transform. The Hamming window attenuates the amplitude of the curve in the beginning and at the end of the segment in accordance with the following formula

$$y_i = x_i \cdot [0.54 - 0.46\cos(2\pi i/n)] \text{ where } i = 0, 1, 2, ..., n-1$$

The original data are the series $x_0, x_1, \ldots, x_{n-1}$, whereas the output series is composed of the series $y_0, y_1, \ldots, y_{n-1}$.

Since the original signal included many artefacts in both low- and high-frequency regions, a second filtering process utilizing a digital bandpass filter was included in the analysis. We used a Butterworth filter, which is an autoregressive moving-average filter. This filter utilizes polynomial coefficients derived from both a forward branch and a feedback branch, to modify the signal. The Butterworth filter has a smooth, monotonically decreasing frequency response outside the passband, and it is maximally flat within the passband. Several different settings of this filter were tried. In the end we decided to use a passband of 1.8–12.0 cpm, which affected as little as possible the frequency components between 3 and 10 cycles.

Received 16 September 1995
Accepted 28 December 1995