Accuracy of Cutaneous Recordings of Gastric Electrical Activity

MARTIN P. MINTCHEV,*p* Y. JACK KINGMA*uestra, and KENNETH L. BOWES*

*Departments of Surgery and Electrical Engineering, University of Alberta, Edmonton, Alberta, Canada

Background: This study was undertaken to determine the accuracy of cutaneous electrogastrography (EGG).

Methods: The ability of EGG to assess gastric contractions and electrical frequency, phase lag, and waveform was studied in 4 healthy volunteers with cutaneous electrodes before and after eating, 4 healthy fasting volunteers with intraluminal pressure recording tubes and cutaneous electrodes, 1 patient with surgically implanted gastric serosal electrodes, and 4 anesthetized dogs with serosal force transducers and implanted and cutaneous electrodes. In 2 of the dogs, an intragastric distending balloon was introduced.

Results: The use of long-distance serosal electrodes allowed direct comparison of internal and cutaneous signals. Cutaneous electrodes recognized 80%-85% of changes in frequency with spectral analysis. Only 30%-40% of increases in EGG amplitudes were associated with gastric contractions. Gradual distention of the canine stomach after blocking contractions with atropine and glucagon increased the EGG amplitudes. No appreciable phase lag could be discerned with EGG. The descending portion of the EGG waveform was predominant.

Conclusions: Frequency dynamics is currently the only reliable cutaneous EGG parameter.

In the last 10 years there have been several publications describing abnormalities in the cutaneous electrogastrogram in a variety of clinical conditions.1-4 Unfortunately, the diagnostic value of electrogastrography (EGG) remains in question, because although reportedly reliable in recognition of normal frequency and tachygastria, cutaneous recordings have not been shown to be accurate in assessing uncoupling and contractions.5

Ideally, abnormalities in gastric electrical activity would first be recognized with implanted electrodes, and the diagnostic value of cutaneous EGG would then be confirmed by simultaneous recording with both techniques. Unfortunately, this is rarely possible. In the current study, we compared invasively obtained gastric electrical and mechanical activity with cutaneous EGG and evaluated the reliability and usefulness of the four major properties of the cutaneous signal, i.e., frequency, amplitude, phase lag, and waveform.

Frequency

Gastric slow-wave frequency can occasionally be recognized visually in cutaneous recordings but is most reliably assessed using computer-aided running spectrum analysis. Such analysis depends upon wave-shape. Invasive recordings obtained with short-distance (2–8 mm) bipolar (SDB) electrodes produce signals with wave-shape that preclude recognition of the fundamental frequency with running spectrum analysis. Spectral comparison of records obtained cutaneously with those obtained from implanted electrodes is therefore difficult, if not impossible. A technique has been developed that allows internal recordings to be analyzed with the fast Hartley transform and compared directly with cutaneous EGG signals. A quantitative comparison of frequency changes in internal and cutaneous gastric electrical activity was also performed.

Amplitude

Increased signal amplitude is often attributed to the appearance of electrical response activity4 and is therefore assumed to indicate the presence of contractile activity. Significant increase in the amplitude of cutaneous gastric signals has been observed postprandially.5-8 In this study we determined the reliability of the relationship between amplitude changes in cutaneous EGG and the occurrence of gastric contractions.

Phase Lag

The direction of spread of gastric electrical activity over the stomach determines the direction of propagation of contractions. Chen et al.9 described phase lag (time shift) between different cutaneous EGG channels recorded from fasting and postprandial patients. In this study, the ability of cutaneous electrodes to recognize phase lag is re-examined.

Abbreviations used in this paper: EGG, electrogastrography; FHT, fast Hartley transform; FT, force transducers; ILP, intraluminal pressure; LDB, long-distance bipolar; SDB, short-distance bipolar.
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Waveform

Familoni et al.\textsuperscript{10} suggested that the propagation direction could be determined from the waveform of the cutaneous EGG. If the ascending portion (arm) of each wave was shorter than the descending arm, propagation of the EGG wave was considered aboral. This concept has been re-examined.

Methods

Subjects

These studies were performed on one patient with surgically implanted and cutaneous electrodes, four volunteers with cutaneous electrodes, another four volunteers with an intraluminal pressure (ILP) recording tube and cutaneous electrodes, and four dogs with serosal electrodes, serosal force transducers (FT), and cutaneous electrodes. In two of the dogs, an intraluminal distending balloon was introduced also. The clinical study was approved by the Ethics Committee of the University of Alberta Hospitals, and informed written consent was obtained from each subject before the procedure. The animal study was approved by the University of Alberta Health Sciences Animal Welfare Committee.

The patient was a 42-year-old woman with a 10-year history of recurrent anorexia, nausea, vomiting, heartburn, and weight loss. Three years earlier, a vagotomy and pyloroplasty had been performed for duodenal ulcer without improvement in her symptoms. Investigation revealed slow gastric emptying with no organic obstruction and gastroesophageal reflux. She underwent fundoplication and insertion of three sets (3 cm apart) of stainless steel wire bipolar electrodes (0.5 cm apart) into the serosa of the antrum at operation. The technique has been previously described.\textsuperscript{10} The electrodes were removed 9 days after the operation. Four abdominal surface electrodes (Hewlett Packard 14445; Mississauga, Ontario, Canada) were attached to the abdominal surface overlying the serosal electrodes. Three 2-hour recordings of serosal and cutaneous electrical activity of the patient in fasting state were performed on subsequent days. Five additional recordings of 1-hour fasting and 1-hour postprandial activity were also performed on subsequent days. A standard 500-kcal meal containing 68 g of CHO (52%), 24 g of protein (19%), and 17 g of fat (29%) was ingested during a 20-minute break between the fasting and postprandial recordings.

Four volunteers underwent recording of cutaneous EGG from four electrodes placed 5 cm apart along the anterior projection of the stomach axis for 1 hour of fasting and 1 hour after the test meal.

In four other volunteers, a four-tube perfused intraluminal pressure monitoring assembly was introduced and positioned fluoroscopically in the gastric antrum. The recording assembly had four openings at 5-cm intervals from the distal tip. The tubes were perfused with water by an Arndorfer pump (Arndorfer, Greendale, WI). Simultaneous 2-hour recordings of ILP and cutaneous EGG in the fasting state were obtained from each subject.

Four fasting dogs underwent a laparotomy under Pentothal anesthesia (Abbott, Montreal, Quebec, Canada). Three sets of bipolar electrodes (0.5 cm apart) and force transducers were sutured to the antral serosa surface at 3-cm intervals. In two of the dogs, a fundal gastrotomy was made, and a 7-mm diameter tube with attached latex balloon for stomach distention was placed into the antrum. Four cutaneous electrodes (4 cm apart) were placed on the shaved anterior abdominal wall. The animals were killed at the completion of the measurements.

In the dogs and the patient with implanted electrodes, two types of recordings of serosal electrical activity were made. The usual SDB recordings from pairs of electrodes placed close together were obtained. In addition, by using electrodes from different SDB pairs, new pairs were obtained to give a long-distance bipolar (LDB) recording. The increment in distance between internal serosal bipolar electrodes produced signals with similar waveshape and spectral characteristics as those obtained cutaneously. Spike activity clearly recognized in SDB channels could not be seen in LDB recordings. Depending on the recording technique, the cutaneous electrode configuration formed two standard bipolar channels or 4 monopolar channels.\textsuperscript{9} A switching box was used for simultaneous recording of bipolar and monopolar channels. After amplification and filtering, the data were sampled at a rate of 10 Hz, and an analog-to-digital conversion was made.

Frequency

To study gastric frequency, we performed 2-hour experiments on the patient (2 LDB, 2 SDB, and 2 cutaneous bipolar channels; fasting and postprandial state), 4 healthy volunteers (2 cutaneous bipolar channels; fasting and postprandial state), and four unconscious fasting dogs (2 SDB, 2 LDB, and 2 cutaneous bipolar channels). The experiments on the patient were repeated on 5 consecutive days after the operation. For the LDB and cutaneous channels, time constant of 10 seconds with a cut-off frequency of the high pass filter of 0.017 Hz and cut-off frequency of 0.3 Hz of the low pass filter were used, whereas for the SDB channels, these parameters were 0.3 seconds and 22 Hz, respectively. To determine the reliability of registration of rhythm changes in LDB and cutaneous channels, we compared periods from the SDB with more than 25% change in duration than the precedent period to the same periods in LDB and cutaneous recordings. When representing the frequency dynamics, best results were achieved by normalizing each spectrum in the power three-dimensional plot, so that the fundamentals of all spectra had the same height. Power changes over time were therefore obscured, but the dynamics of the frequency peaks were clearly seen.
Amplitude

Three different experiments were performed to determine the relationship between antral contractions and cutaneous EGG amplitude changes.

A comparison was made between contractions noted in ILP recordings and increments in amplitude seen with cutaneous electrodes in the 2-hour experiments with 4 healthy fasting volunteers (2 channels of cutaneous EGG, 3 channels of ILP). Recognizable contractions in an ILP channel were defined when the recorded pressure waves exceeded 25% of the maximal pressure recorded during the whole experiment in this channel. Similarly, recognizable increments in each separate cutaneous EGG channel were defined when the amplitude exceeded 25% of the maximal recorded EGG amplitude in this particular channel.

In two fasting dogs (2 channels of SDB, 2 channels of LDB, 2 channels of FT and 2 of channels cutaneous EGG), contractions as shown by serosal FT were compared with the changes in SDB, LDB, and cutaneous EGG. The periods of spike bursts in SDB were also compared with contractions and amplitude changes in LDB and cutaneous EGG. Antral contractile activity was stimulated with 0.25 mg/kg pentagastrin IV (Peptavlon; Ayerst Laboratories, Calgary, Alberta, Canada) on four separate occasions. Twenty minutes after each pentagastrin injection, mechanical activity was blocked with 0.25 mg glucagon. The antral balloon was then distended intermittently in stages after 200, 400, 600 mL air were introduced. Each air inflation was performed for approximately 20 seconds, and the new air volume was maintained constant for 5 minutes. Four distentions were performed in each dog. Changes in cutaneous EGG amplitude were noted. The examined amplitudes were considered to be increased when they reached or exceeded the level of 25% from the maximum both for the cutaneous EGG and the FT channels.

Phase Lag

In three 2-hour recordings from the patient in fasting state. LDB and SDB serosal signals obtained from different areas of the stomach were compared with four channels of cutaneous EGG recorded from the orthogonal projections of those areas on the abdominal wall. Separate 2-hour experiments were also performed on four fasting dogs using similar electrode configuration. In four volunteers, 4-channel cutaneous EGG was recorded for 2 hours (1 hour fasting and 1 subsequent hour postprandially) using the above cutaneous electrodes configuration. In all recordings from the patient, volunteers, and dogs, the signal from the proximal electrode was compared with the signal from the distal one. It was pointed out previously that with running cross-correlation analysis, mean time shifts could be obtained. We applied that approach for 4.27-minute intervals and arranged the obtained time shifts in a plot against time. When more than a half of the calculated time shifts in one experiment changed their polarity from their precedent, the results were termed "inconsistent". 1. recordings were filtered (bandpass digital filter, 0.02–0.1 Hz) so that only the fundamental gastric component remained. The processing was performed using the fast Hartley transform (FHT), and the cross-correlation functions were successively obtained from the transform. The possibility of direct calculation of the cross-correlation function from the Hartley coefficients was mentioned by Bracewell, and we found it more convenient in the time shift study than the method proposed by Chen et al.

Waveform

Waveform was studied in the same experiments that measured gastric frequency. In this investigation, we assumed that waveform of the cutaneous EGG was formed essentially by the first three harmonics of the signal. We therefore used a cut-off frequency of 0.3 Hz instead of 0.5 or 1 Hz, as recommended before and thus avoided most of the respiration artifacts. To assess the changes in the wave form, both ascending and descending arms of each wave were compared by a computer program. The waves were separated into three groups: waves in which ascending arm dominated, waves in which descending arm dominated, and symmetrical waves. The study was performed separately in fasting and postprandial states for the humans and before and after gastric distentions in dogs.

Results

Frequency

There was good correlation between the different recording methods. A comparison of visually evident frequency changes recorded with cutaneous and implanted electrodes is given in Table 1. Intermittent irregularities in gastric electrical activity were recorded from the patient during the first postoperative day (Figure 1).

A well-defined peak of the fundamental gastric frequency in the spectral range of 2.54–3.67 cycles per minute was recognized after the application of the

<table>
<thead>
<tr>
<th>Dog</th>
<th>Patient</th>
<th>Dog 1</th>
<th>Dog 2</th>
<th>Dog 3</th>
<th>Dog 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDB/SDB (%)</td>
<td>EGG/SDB (%)</td>
<td>EGG/LDB (%)</td>
<td>EGG/LDB (%)</td>
<td>EGG/LDB (%)</td>
<td></td>
</tr>
<tr>
<td>Patient</td>
<td>93</td>
<td>87</td>
<td>83</td>
<td></td>
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</tr>
<tr>
<td>Dog 1</td>
<td>95</td>
<td>88</td>
<td>84.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog 2</td>
<td>89</td>
<td>83</td>
<td>79</td>
<td></td>
<td></td>
</tr>
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<td>Dog 3</td>
<td>93</td>
<td>82</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog 4</td>
<td>91</td>
<td>85</td>
<td>82.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Changes in frequency seen in denominator that were recognized in nominator.
FHT on successive 4.27-minute intervals of human cutaneous recordings. Use of the FHT significantly increased both the speed of spectral procedures and conversion speed.

Computer frequency analysis could not be applied to recordings obtained with electrodes implanted into the stomach in the usual manner, i.e., SDB recordings. The rapid bidirectional wave obtained in such studies yielded a broad frequency spectrum (Figure 2). The use of pairs of implanted electrodes separated by several centimeters (LDB) resulted in a signal that approximated a sine wave and resembled the cutaneous signal. This could be easily analyzed by the FHT. Comparison of frequency spectra obtained by implanted and cutaneous electrodes then became possible. Similar wave shapes and spectral characteristics were seen in LDB recordings and cutaneous EGG (Figure 2). Normalized three-dimensional plots were also very similar (Figure 3). The plots clearly showed postprandial frequency increments as reported previously.7

Amplitude

Amplitude of electrical signals from internal electrodes varied with distance from the pylorus in the
patient (0.6–2.2 mV) and dogs (0.4–2.0 mV). Cutaneous EGG were also of higher amplitude in electrodes near the pylorus in humans (0.05–0.52 mV) and dogs (0.01–0.45 mV). Force transducer amplitudes ranged from 0 to 0.54 N and intraluminal recordings ranged from 0 to 127 cm H₂O.

In dogs and humans, amplitude changes in cutaneous EGG did not reliably reflect gastric contractions. Only a minority of increased EGG signal amplitudes was associated with contractions, and the majority of contractions was not associated with increased EGG amplitude (Figures 4 and 5).

Distention of the atonic canine stomach with a balloon increased the amplitude of EGG signals even when gastric contractile activity was completely abolished by atropine and glucagon (Figure 6). Most of the cutaneous EGG amplitudes increased significantly after air infiltration, although force transducer channels and signals recorded with internal electrodes did not change (Figure 7).

**Phase Lag**

In the patient with implanted and cutaneous electrodes, time shift (phase lag) between the most distal and the most proximal implanted electrodes was consistently between 5 and 8 seconds. However, in cutaneous recordings no time shift was recorded in 2 of the 6 recording hours. In the remaining 4 hours, the time shift was very small, ranging from 0.5 to 1.8 seconds.

The time shift obtained from the four volunteers was inconsistent in the fasting state. After a test meal it became stable but remained close to zero in two of the cases. In the other two subjects, consistent phase shifts were not registered.

The time shift obtained from internal electrodes in dogs varied from 3 to 7 seconds. However, cutaneous recordings revealed a small but consistent time shift of 0.5 to 1.8 seconds for 64% of the 8-hour recording time.

**Waveform**

In the fasting state, waveforms displayed predominance of the descending arms or symmetry in all subjects. After feeding in humans, the descending arm in cutaneous waves dominated more evidently. Distention of the canine stomachs had little effect on the wave form of LDB signals but markedly increased the preponderance of the descending arms in cutaneous EGG waves (Table 2).

**Discussion**

Each single gastric antral muscle cell undergoes periodic depolarization, and the muscular array simu-
lates a series of relaxation oscillators, i.e., higher frequency oscillators drag up lower frequency oscillators to the higher frequency. The highest frequency oscillator in humans lies high in the greater curvature and periodically depolarizes at 3 per minute. Entraining all distal oscillators whose intrinsic frequency is lower to this frequency results in an aboral spreading wave of depolarization. Electrical response activity, which heralds contractions, is superimposed upon gastric electrical slow waves (or electrical control activity) so the frequency and direction of propagation of slow waves determines the frequency and direction of propagation of contractions.

Abnormalities in gastric electrical activity could have a profound effect on gastric motor function so that the recent quickening of interest in EGG is very understandable. Using cutaneous EGG, a large and growing number of clinical conditions have been associated with gastric electrical abnormalities. Before ac-
Table 2. Gastric Electrical Waveform

<table>
<thead>
<tr>
<th>Recording method</th>
<th>State</th>
<th>Waves with prolonged ascending arm (%)</th>
<th>Waves with prolonged descending arm (%)</th>
<th>Symmetrical waves (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient LDB</td>
<td>Fasting</td>
<td>24</td>
<td>64</td>
<td>12</td>
</tr>
<tr>
<td>Patient LDB</td>
<td>Fed</td>
<td>7</td>
<td>82</td>
<td>11</td>
</tr>
<tr>
<td>Patient EGG</td>
<td>Fasting</td>
<td>5</td>
<td>53</td>
<td>42</td>
</tr>
<tr>
<td>Patient EGG</td>
<td>Fed</td>
<td>2</td>
<td>62</td>
<td>36</td>
</tr>
<tr>
<td>Dogs LDB</td>
<td>Fasting</td>
<td>0</td>
<td>82</td>
<td>18</td>
</tr>
<tr>
<td>Dogs LDB</td>
<td>Distention</td>
<td>0</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Dogs EGG</td>
<td>Fasting</td>
<td>0</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>Dogs EGG</td>
<td>Distention</td>
<td>0</td>
<td>78</td>
<td>22</td>
</tr>
<tr>
<td>Volunteers EGG</td>
<td>Fasting</td>
<td>0</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>Volunteers EGG</td>
<td>Fed</td>
<td>0</td>
<td>59</td>
<td>41</td>
</tr>
</tbody>
</table>

Accepting these findings as "true bills", two vital questions demand answer. (1) Does cutaneous EGG accurately reflect gastric electrical activity? and (2) Does the reported electrical abnormality have an effect on gastric motor function?

We have some skepticism about the accuracy and relevance of some of the EGG properties. Therefore, we studied the ability of cutaneous recordings to detect each of these properties.

Most recorded EGG abnormalities have been changes in frequency, usually reported as bradygastria or tachygastria. Several investigators have suggested that increments in EGG amplitude are associated with antral contractions.6,7,8,12 The present study clearly shows that the amplitude of cutaneous EGG signals can increase significantly when there are neither antral contractions nor spikes in the SDB channels. A changed or changing position of the antrum with respect to the skin electrodes is sufficient to cause increased amplitude in cutaneous EGG. Such changes could for example be the result of feeding or any other mechanical displacement, which leads to a change in the distance between the source of the electrical field in the stomach and the cutaneous electrodes.

Running cross-correlation analysis based on direct application of the FHT facilitated the study of time shift dynamics. Chen et al.9 have reported occasional significant phase lags (or time shifts) between different sets of cutaneous electrodes. However, we could not confirm these results. No significant (above 2 seconds) time shift was noted in the different sets of cutaneous electrodes. It is possible that the cutaneous EGG signal is so integrated that the actual time shifts recorded internally cannot be registered on the abdominal wall.

Familoni et al.5 suggested that orad propagation of gastric electrical signals would result in prolongation of the ascending arm of the waves. In this study, the descending arm predominated in both internal LDB and cutaneous recordings in humans and dogs. After feeding or gastric distention, this preponderance became more marked in cutaneous recordings, probably because of an improved signal-to-noise ratio. Preponderance of the ascending arm of the waves was rarely observed. Unfortunately, oral propagation of gastric slow waves was not seen during this study, and the hypothesis suggested by Familoni et al.5 could not be directly tested.

EGG, although a very appealing noninvasive technique, is not currently of clinical diagnostic value. There is insufficient evidence that (1) abnormalities in EGG are commonly present in patients with gastric motor dysfunction and (2) cutaneous EGG can actually record gastric electrical abnormalities.

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Address requests for reprints to: Kenneth L. Bowes, M.D., Department of Surgery, MacKenzie Health Sciences Centre, University of Alberta, Edmonton, Alberta, Canada T6G 2B7.
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