The Human Vector Magnetogastrogram and Magnetoenterogram

L. Alan Bradshaw,* J. K. Ladipo, Daniel J. Staton, John P. Wikswo, Jr., *Member, IEEE*, and William O. Richards

***Abstract*—Electrical activity in the gastrointestinal system produces magnetic fields that may be measured with superconducting quantum interference device magnetometers. Although typical magnetometers have detection coils that measure a single component of the magnetic field, gastric and intestinal magnetic fields are vector quantities. We recorded gastric and intestinal magnetic fields from nine abdominal sections in nine normal human volunteers using a vector magnetometer that measures all three Cartesian components of the magnetic field vector. A vector projection technique was utilized to separate the magnetic field vectors corresponding to gastric and intestinal activity. The gastric magnetic field vector was oriented in a cephalad direction, consistent with previously observed data, and displayed oscillatory characteristics of gastric electrical activity ($f = 3.03 \pm 0.18$ cycles/min). Although the small bowel magnetic field vector showed no consistent orientation, the characteristic frequency gradient of the small bowel electrical activity was observed. Gastric and intestinal magnetic field vectors were oriented in different directions and were thus distinguished by the vector projection technique. The observed difference in direction of gastric and intestinal magnetic field vectors indicates that vector recordings dramatically increase the ability to separate physiological signal components from nonphysiological components and to distinguish between different physiological components.**

***Index Terms*—Biomagnetism, electrogastrogram, gastric electrical activity, magnetogastrogram, superconducting quantum interference device (SQUID) magnetometer.**

I. Introduction

THE noninvasive measurement of both gastric and intestinal electrical activity could provide clinicians with a powerful diagnostic tool. To date, efforts to obtain such data have focused on the measurement of cutaneous potentials. The flow of ionic current in gastric and intestinal smooth muscle is associated with extracellular potentials that may be measured by serosal electrodes. The low-conductivity layers present in the abdominal wall smooth and attenuate the potentials as they propagate outward complicating cutaneous detection [1]. However, the magnetic fields created by smooth muscle electrical activity may be measured externally [2].

In humans, the gastric basic electrical rhythm (BER) oscillates with a frequency of about 3 cycles/min (cpm), and the small intestinal BER frequency ranges from about 12 cpm in the duodenum to about 8 cpm in the terminal ileum, decreasing in a stepwise fashion [3]–[5]. The BER produces magnetic fields that may be recorded by placing a superconducting quantum interference device (SQUID) magnetometer outside the subject's abdomen [6]. A SQUID is an extremely sensitive device that converts magnetic flux to voltage [7]. Magnetic fields incident upon superconducting pickup coils situated at the bottom of an insulating dewar induce current in the superconducting wire that is coupled to the SQUID. Hence, the SQUID is able to detect the very weak magnetic fields associated with bioelectric activity. These magnetic fields are typically several orders of magnitude smaller than the magnetic field of the earth, so special measures are taken to eliminate unwanted background interference, including use of a magnetically shielded room and/or winding of the detection coils in such a way as to subtract magnetic fields measured from distant sources from those measured from sources close to the magnetometer.

Previous results using both human and animal models indicate the ability of the SQUID to accurately and noninvasively measure gastrointestinal (GI) magnetic fields [2], [8], [9]. The BER frequency gradient of the human small intestine was measured magnetically as was the decrease in BER frequency associated with mesenteric ischemia in rabbits [2], [10], [11]. SQUID recordings correlate strongly with measurements using serosal electrodes [1].

These SQUID recordings of the spontaneous electrical activity of the stomach and small bowel differ from recording methods that utilize magnetic markers. Several other research groups are engaged in active research into gastric and intestinal transit times by having subjects ingest magnetic markers consisting of permanent ferromagnets [12]–[15]. Our measurements record the magnetic field associated with current flow in the biological tissue and do not require ingestion of a magnetic marker. In this study, we have measured human gastric and intestinal BER using a vector magnetometer to determine whether additional information is available in vector recordings that is not present in single-component recordings such as those previously reported [2].

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*L. A. Bradshaw is with the Living State Physics Group, Department of Physics and Astronomy and Department of Surgery, Vanderbilt University, Nashville, TN 37235 USA (bradshla@ctrvax.vanderbilt.edu).

J. K. Ladipo and W. O. Richards are with the Department of Surgery, Vanderbilt University, Nashville, TN, and Department of Surgery, Veterans Affairs Medical Center, Nashville, TN 37235 USA.

D. J. Staton and J. P. Wikswo, Jr. are with the Living State Physics Group, Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235 USA.

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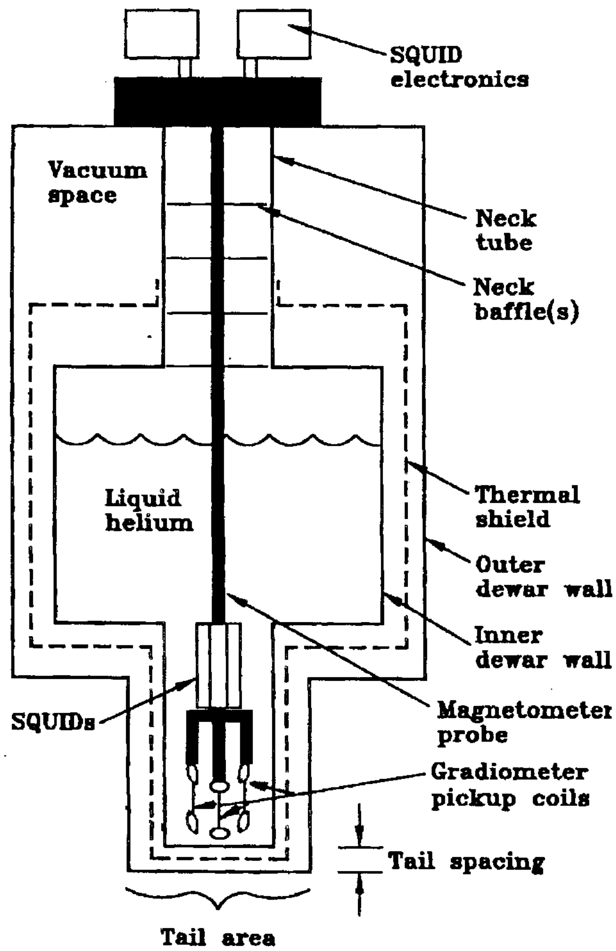

Fig. 1. Vector SQUID magnetometer. The vector SQUID magnetometer contains three orthogonal detection coils to record all three components of the magnetic field. The detection coils and SQUID's are immersed in liquid helium to keep them superconducting.

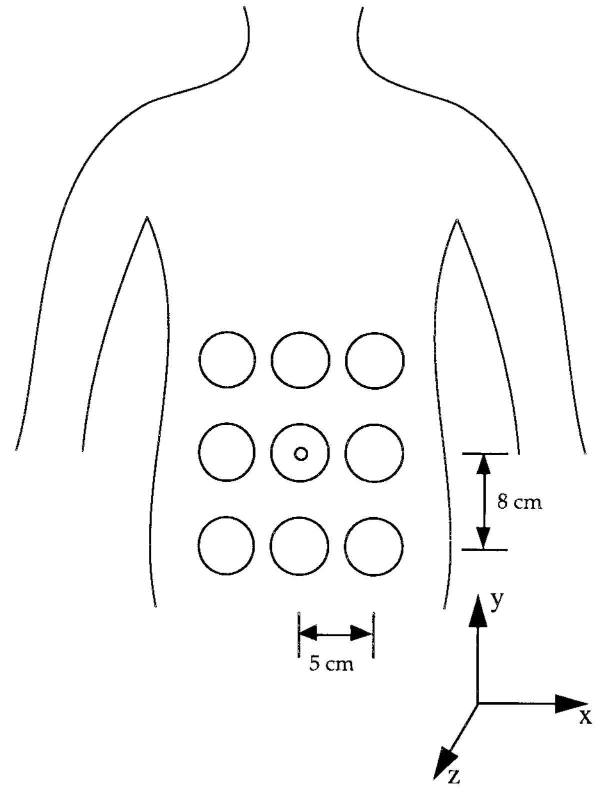

Fig. 2. Abdominal sections. Recordings were made over nine abdominal positions. The coordinate system used for analysis is also shown.

II. Methods

A. Data Acquisition

Our studies used a custom-fabricated SQUID magnetometer (Conductus, Inc., San Diego, CA) that provides simultaneous recordings of three orthogonal magnetic field components (Fig. 1). Its detection coils are in a first order vector gradiometric arrangement; magnetic flux threading a coil near the bottom of the sensor is subtracted from flux threading an identical coil, wound in the opposite direction, located 15 cm above the first. This gradiometric arrangement provides for elimination of uniform ambient magnetic fields that are incident on both detection coils, but does not reject magnetic fields from biological current sources near the bottom coil. Raw voltage signals from the three output channels of the SQUID flux-locked loop were first amplified by the SQUID controller (iMAG, Conductus, Inc., San Diego) and then filtered from direct current to 10 Hz. The signals were processed through an analog-to-digital converter using a data acquisition board (NB-MIO-16XL, National Instruments, Austin, TX) and a Macintosh computer (Apple Computer, Cupertino, CA). Signals were acquired with a sampling rate of 30 Hz using LabView (National Instruments, Austin, TX).

Nine normal human volunteers were positioned underneath the magnetometer inside a magnetically shielded room (Vaccuumschmelze). Informed consent was obtained from each volunteer and the study was approved by the Vanderbilt University Institutional Review Board. The subjects were asked to suspend respiration and lie quietly for a period of at least one minute during each recording. Each subject fasted for at least 8 h prior to the study [2]. Data were acquired from each of nine abdominal sections as indicated in Fig. 2 along with the coordinate system used for data analysis. For each recording, the magnetometer was oriented such that the coils measuring the x and y components of the signal tangential to the body surface were oriented in the sagittal and horizontal planes, and the coil measuring the z component normal to the body surface was oriented in the frontal plane.

B. Data Analysis

The data segments obtained were typically of short duration (~1 min) since many subjects could only hold their breath for a limited period. Using this technique, respiratory interference could be completely eliminated from the recordings. Autoregressive (AR) spectral analysis methods were preferred over traditional fast Fourier transform (FFT) methods because they provide excellent frequency resolution with as little as 30 s of data [16], [17]. The AR methods decompose the signal into its various frequency components and provide a power spectral density (PSD) estimate similar to that provided by the FFT. Chen *et al.* [18] also used AR spectral analysis on their electrogastrogram (EGG) data.

Recordings from all subjects showed interference from the magnetocardiogram, particularly in the upper abdominal sections. A median filter of order 30, corresponding to the approximate number of sample points per cardiac cycle, was used to eliminate cardiac interference. Clearly, this median filter also eliminates some higher-frequency information (higher than about 1 Hz), but the signals of interest in this study are well below 1 Hz.

Recordings of any component of the magnetic signal are expected to contain contributions from both small bowel and gastric electrical activity. Furthermore, different segments of the small bowel may exhibit different frequencies in the magnetic recordings. To make more complete use of the vector nature of GI magnetic fields, a vector projection technique was developed that is capable of optimizing the gastric signal or the small bowel signal recorded in a section and separating signals from distinct small bowel sources [19], [20]. The three recorded components B_x, B_y, and B_z, describe a vector whose projection in a particular direction is given by

$$B_{proj} = B_x \sin\theta \cos\phi + B_y \sin\theta \sin\phi + B_z \cos\theta \qquad (1)$$

where the azimuthal and tangential angles, ϕ and θ, are chosen to optimize the signal from a specific source.

The idea of using vector projections is based on the fact that the magnetic field from each source of current—the gastrointestinal electrical activity as well as the noise—has one specific direction (although the direction may vary with time). More likely than not, that direction does not happen to correspond to the orientation of a specific pickup coil or to the direction of the magnetic field vector from another signal component. Thus, we may separate physiological components of the signal from nonphysiological components, and distinguish between multiple physiological components. For example, we identify the gastric vector projection as the projection with maximal activity in the 2.5–4 cpm range. We identify the gastric BER frequency as the frequency corresponding to the maximum in the B_x, B_y, and B_z PSD's from 2.5 to 4 cpm. If we assume that the activity in this bandwidth is coherent across all three channels, then the values of the square roots of the PSD's at the gastric BER frequency are representative of the x-, y- and z-components of the gastric magnetic field vector. The azimuthal and tangential angles, ϕ and θ, are then obtained by coordinate transformation. Likewise, the small bowel projection is identified by the maximal signal in the 8–12 cpm range. Often, a signal will contain multiple contributions from small bowel activities with different frequencies and these may also be distinguished. For the purposes of this manuscript, we chose to concentrate on only the strongest small bowel component in each section. These projections are formed from the PSD's which are derived from data segments of one minute duration. It is possible that the projections vary over the analysis duration, and it should be noted that this analysis provides the projection averaged over the one minute duration. Once the vector direction of a particular signal component is determined, certain information may be obtained about the orientation of underlying current sources. This technique is very similar to the signal space projection techniques described by Tesche *et al.* [21].

A vector magnetic field recording at one location may provide more detailed information about underlying current sources than the recording of any single component. In order to evaluate the additional information content available in the vector magnetometer as opposed to a single-component instrument, we compute the normalized dot product of gastric and small bowel vector projections

$$\xi = \frac{\vec{\mathbf{B}}_g \cdot \vec{\mathbf{B}}_{sb}}{\left|\vec{\mathbf{B}}_g\right|\left|\vec{\mathbf{B}}_{sb}\right|} = \cos(\gamma) \qquad (2)$$

where we define ξ as the information content variable, $\vec{\mathbf{B}}_g$ represents the gastric magnetic field vector, $\vec{\mathbf{B}}_{sb}$ is the small bowel magnetic field vector, and γ is the angle between the gastric and small bowel magnetic field vectors. With this definition, ξ varies from zero to one, with zero indicating that the gastric and small bowel vectors are exactly perpendicular; one of the vectors would be missed completely by a single-component recording parallel to the other signal vector, while for another magnetometer orientation, the two signals would be inextricably combined. A value of one for ξ indicates that the vector projection that maximizes the gastric signal and that which maximizes small bowel signals are identical, and a single-component recording with the magnetometer placed correctly would optimally record both gastric and small bowel signals, but again, contributions to the magnetic field from gastric and small bowel sources could not be separated. Hence, any deviation of ξ from one indicates the amount of additional information provided by a measurement of the full magnetic field vector.

III. RESULTS

The vector projection technique is illustrated using a typical recording of each of the three magnetic field components that were recorded in one section and median filtered, as shown in Fig. 3. PSD's of the x-, y-, and z-components [Fig. 3(a)–(c)] indicate the separate gastric and small bowel BER frequencies, and the values of the square roots of the peaks in these three PSD's specify the projection that corresponds to maximal gastric and small bowel frequency content, as shown in Fig. 3(d) and (e).

The gastric projections in each of the nine abdominal sections of one volunteer are shown in Fig. 4(a), with the corresponding power spectra in Fig. 4(b). Notice that the gastric signal is most noticeable and strongest in the upper sections and is weaker in the lower sections. The small bowel projections in each section are similarly displayed with their power spectra in Fig. 5.

From these power spectra, the dominant signal frequency may be identified. The dominant frequencies in the 2.5–4 cpm range and in the 8–12 cpm range were computed.

A. Gastric Signals

For the gastric signal, one of the upper nine sections typically had a significantly stronger signal component in the

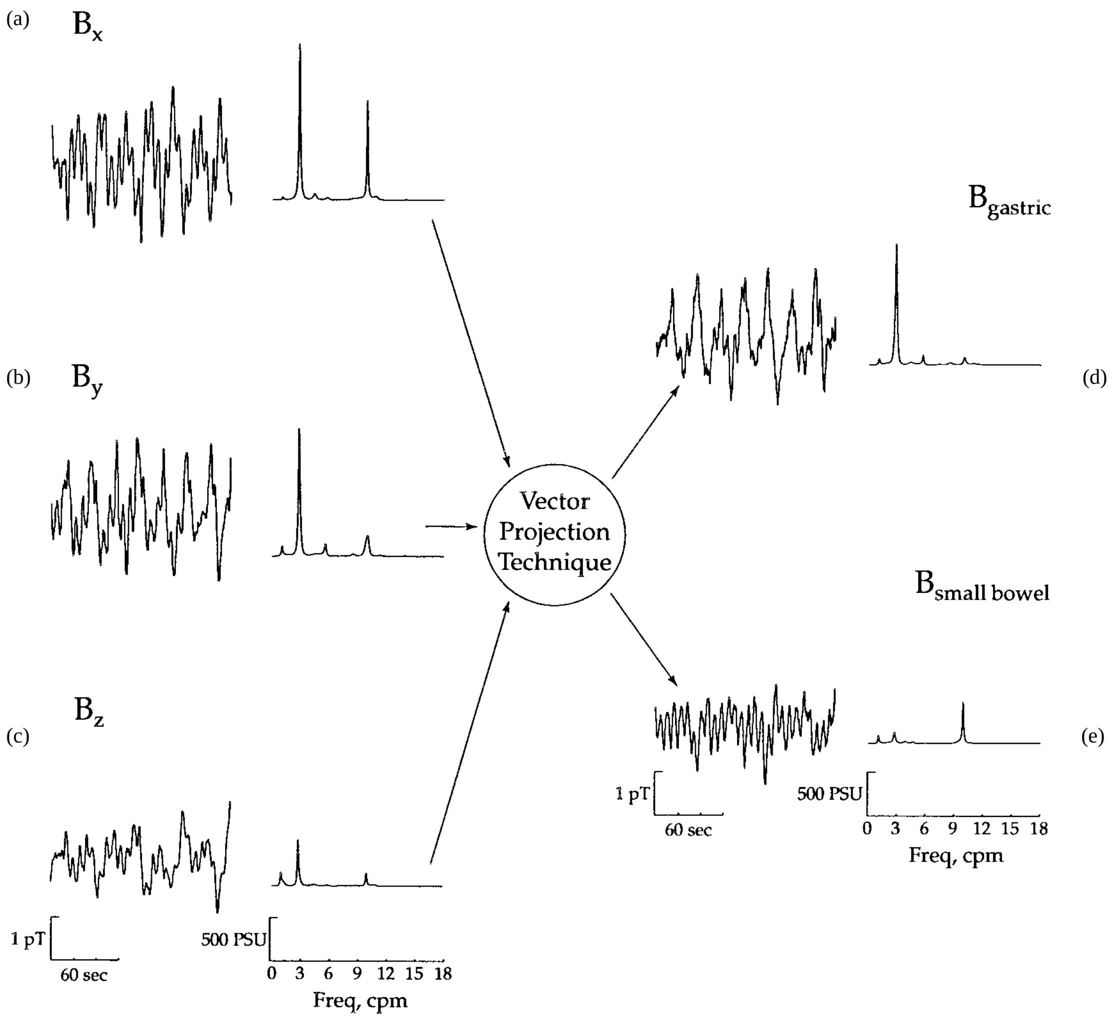

Fig. 3. Vector projection technique. The raw magnetic fields and their power spectra as measured over one abdominal location of a typical subject consist of the (a) x-, (b) y-, and (c) z-components of the magnetic field. These three components are projected into particular directions that optimize measurement of the (d) gastric and (e) small bowel signals by the vector projection technique, as can be seen in the differing heights of the main peaks in the two resultant power spectra. In this way, we may focus on a particular signal of interest while reducing interference from other signal and noise sources.

2.5–4 cpm range than did any of the other sections. In seven of the nine subjects, the central upper section had the strongest gastric signal, one subject showed greatest gastric activity in the left upper section, and one showed maximal gastric activity in the central middle section. The average gastric frequency recorded was 3.03 $\pm$ 0.18 cpm [mean $\pm$ standard error of the mean (SEM)]. The average signal strength is displayed in the contour plot of Fig. 6. As expected, the strongest signal is in the central upper section. Averaging the signal strength can lead to misleading results since the distance between the magnetometer and the stomach varied according to intersubject differences in abdominal wall thickness, so this figure must be interpreted accordingly. Nevertheless, the data do indicate that the gastric signal was strongest in the central upper section.

B. Small Bowel Signals

The small bowel activity did not show significantly stronger activity in any one section. Dominant frequencies were determined for each section in each subject. Overall, there was a wide variation of dominant frequencies in the nine sections. Fig. 7 shows the small bowel frequencies averaged over all subjects. Identification of the expected small bowel frequency gradient is complicated by the large signal variance between subjects and the necessity of moving the magnetometer between sections. However, small bowel frequency peaks for individual subjects show the BER frequency gradient more clearly. Fig. 8 displays the amplitude of the AR power spectrum in nine frequency bands with a width of 0.5 cpm. Activity in the 8 cpm map is primarily located in the lower abdomen, activity in the 9.5–10.5 cpm range is recorded more in the middle abdominal sections, and activity in the 11 and 11.5 cpm range is recorded in the upper sections of the abdomen, consistent with the known BER frequency pattern in humans.

C. Gastric Vector

The vector corresponding to the gastric or small bowel signal components was identified as the projection with the maximum spectral peak in the appropriate frequency range. The gastric vector projection can be expected to yield relevant information about gastric function since 1) the stomach is relatively fixed in position while the subjects suspend res-

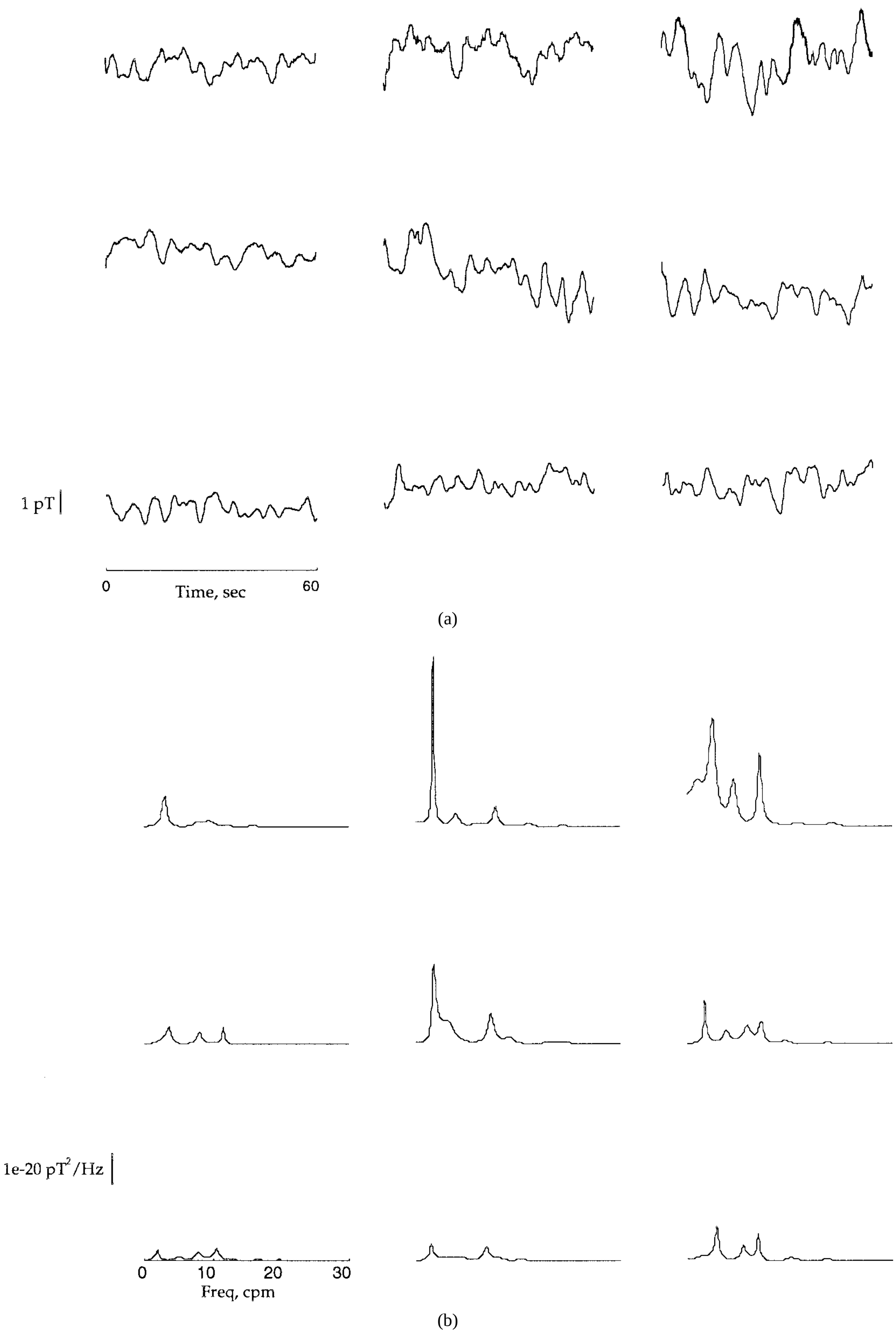

Fig. 4. Gastric signals. (a) The gastric projections of the magnetic field recorded at all nine abdominal locations are shown for a typical subject. Characteristic 3-cpm slow waves are especially apparent in upper abdominal sections near the epigastrium. (b) The autoregressive (AR) power spectra corresponding to the signals in (a). Peaks near 3 cpm are indicative of gastric activity.

piration and 2) the magnetometer was positioned above the same location in each subject. The vector projections in the xy plane for the signal in the 2.5–4 cpm range determined at each recording location and averaged over all nine subjects are plotted in Fig. 9. The average direction of the gastric magnetic field vector was 96.0 $\pm$ 33.7° (mean $\pm$ S.D.) measured counter-clockwise from the positive x-axis. The magnetic field vector could also be projected in the other planes (xz and yz). The xy plane is used here since we assume that gastric current sources may be approximated by chains

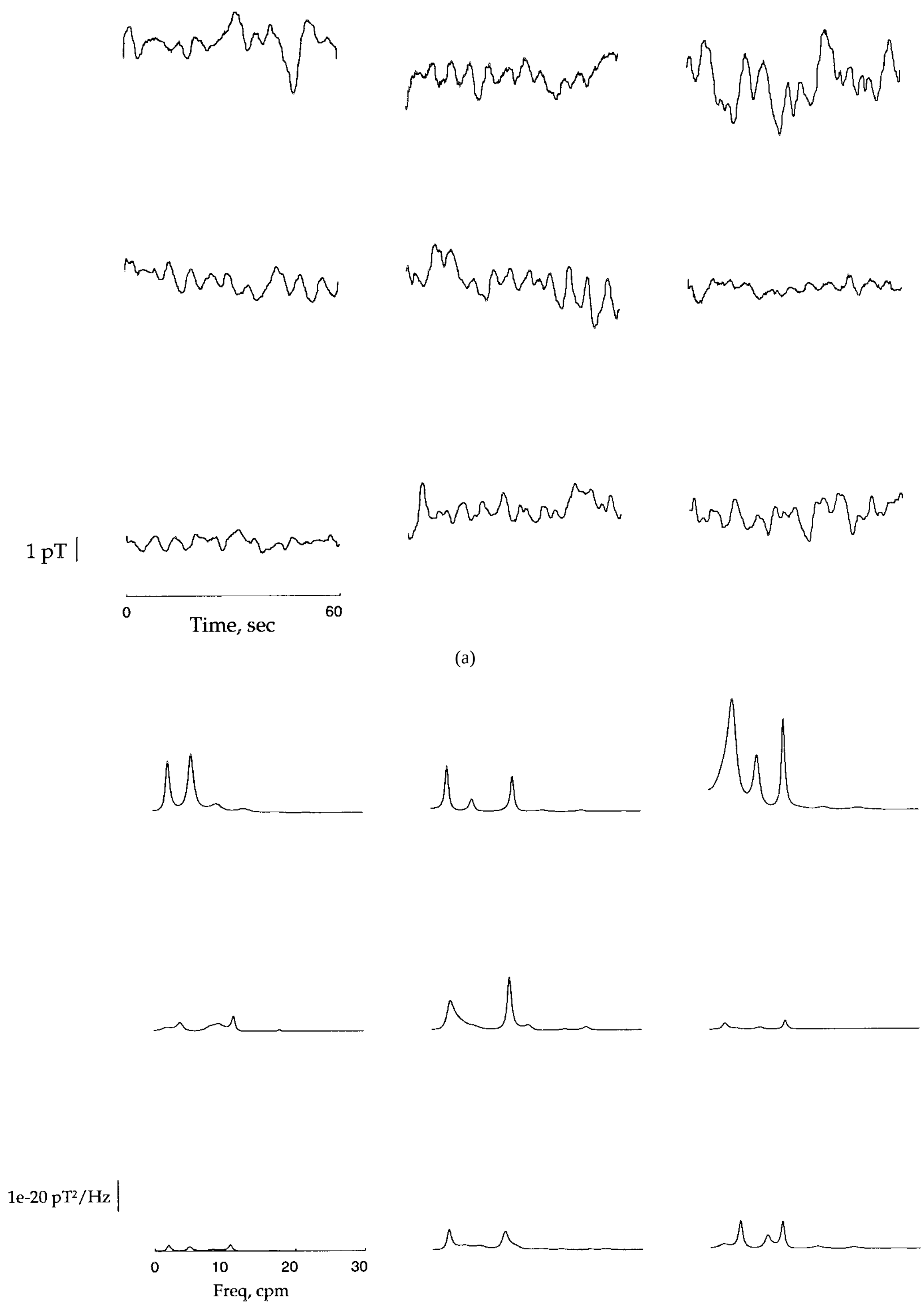

Fig. 5. Small bowel signals. (a) The small bowel projections of the magnetic field recorded at all nine abdominal locations are shown for a typical subject. Slow waves characteristic of intestinal activity are evident. (b) The AR power spectra corresponding to the signals in (a). Peaks in the 8–12 cpm range indicate small intestinal activity. Some sections exhibit multiple peaks indicating different GI sources.

of current dipoles (see Section IV). Peaks in the tangential components of the magnetic field of a current dipole occur directly above the dipole, in contrast to the situation with the normal component of the magnetic field, which is zero directly above a current dipole. The average gastric vector is by far strongest in the central upper section, and is oriented in a cephalad direction. In addition, relatively little variance was observed in intrasubject recordings taken on five different occasions (mean S.D. $= 22.1°$).

D. Small Bowel Vectors

The vector magnetic field was also projected into the direction of optimal signal in the small bowel frequency range for each recording section. The small bowel vector projections

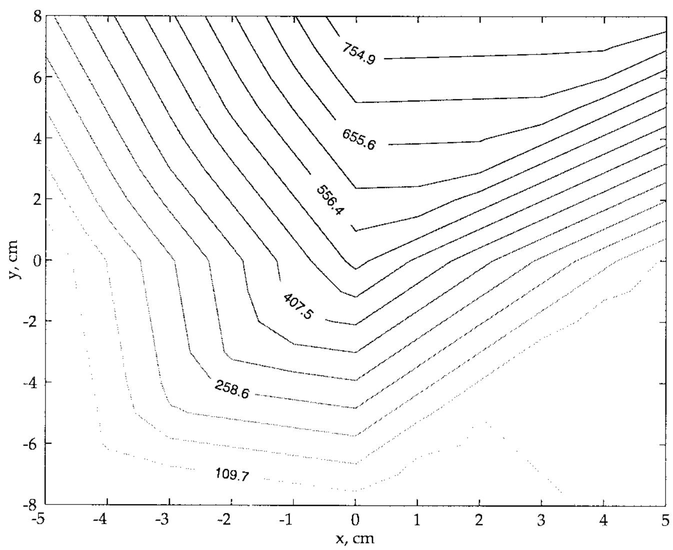

Fig. 6. Gastric signal strength. The average spectral strength contours of the gastric magnetic field vector signal in all nine subjects are plotted over the entire abdomen with darker lines corresponding to greater strength. Some contours are labeled by the spectral value they represent. The activity is strongest in the central upper section, the approximate location of the stomach.

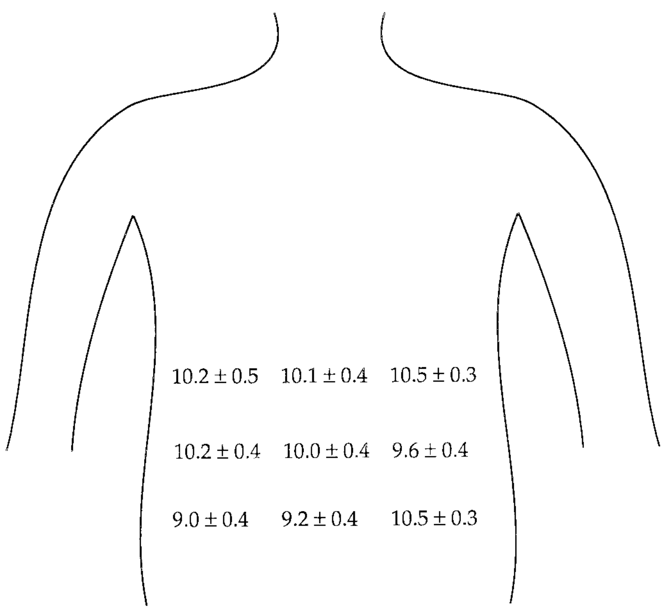

Fig. 7. Small bowel BER frequencies. The average BER frequency recorded in each abdominal section is tabulated. Generally, there is a trend toward lower BER frequency with lower abdominal sections, consistent with the known BER frequency gradient. However, the error bars are quite large since there was a considerable variation in the frequencies recorded between subjects.

were of limited use since the precise position of the intestine during the study is variable both within and between individual subjects, and since the recordings from different abdominal sections were not simultaneous. Small bowel vectors were consistently smaller in magnitude than the gastric vectors and showed no preferred direction. Intrasubject differences in small bowel vector direction were also large. The mean small bowel vector direction recorded in all nine sections for all subjects was 84.4 $\pm$ 106.4° (mean $\pm$ S.D.).

E. Information Content in Vector Magnetogastrograms (MGG's) and Magnetoenterogram (MENG's)

Although small bowel magnetic field vectors are difficult to interpret from single-channel vector recordings since the bowel is not stationary, the dot product of the gastric magnetic field vector and the small bowel magnetic field vector at a particular recording location gives an indication of the information content in the vector signal. If the dot product of two vectors is one, the vectors are oriented in the same direction, while a dot product of zero indicates that the two vectors are orthogonal. We computed the dot products of the gastric and small bowel magnetic field vectors in each of the nine sections. The mean dot product between the gastric magnetic field vector and the small bowel magnetic field vector recorded in all nine locations over all nine subjects was $\xi = 0.344 \pm 0.079$ (mean $\pm$ SEM), indicating that the gastric magnetic field direction is significantly different from the small bowel magnetic field direction ($p < 0.001$). Since these two vectors are oriented in different directions, the vector recording of gastric and small bowel activity provides information not available in single-component magnetic measurements. Furthermore, the vector projection technique, which allows us to project the recorded magnetic field along an arbitrary direction, provides for a dramatic improvement over single component recordings in that projections can often be chosen to maximize the contribution of one signal source and minimize another.

IV. Discussion

The cutaneous EGG was first recorded in 1922 by Alvarez [22], who noted characteristic 3-cpm slow waves. Since then, several studies have concentrated on the EGG and, in particular, changes in the EGG during abnormal gastric activity [23]. However, the utility of the EGG has been called into question on the basis that only frequency dynamics can be ascertained [24]. Changes in EGG amplitude may reflect displacement of the stomach with respect to recording electrodes. Determination of gastric propagation is also problematic in cutaneous EGG [25]–[27]. The study by Chen *et al.* [25], for example, found that the propagation direction could be reliably obtained, but propagation velocity could not be determined consistently. The recording of small bowel BER with cutaneous electrodes is even more troublesome. Layers of tissue (omentum, fat, muscle, fasica, and skin) situated between the small bowel sources and the abdominal surface attenuate potentials and smooth their high frequency content resulting in low signal-to-noise ratio (SNR) and poor spatial discrimination [28], [29]. Since magnetic fields are mediated by the magnetic permeability of tissue, which is nearly the same as that of free space, magnetic fields reflect underlying current sources with higher SNR's and in greater spatial detail [30].

Our previous studies have shown the feasibility of measuring the magnetic field associated with human gastrointestinal electrical activity using a SQUID magnetometer and discussed some of the potential clinical problems that could be addressed [2]. Other studies have demonstrated that measurement of the cardiac vector magnetic field provides more information than measurement of individual magnetic field components [31].

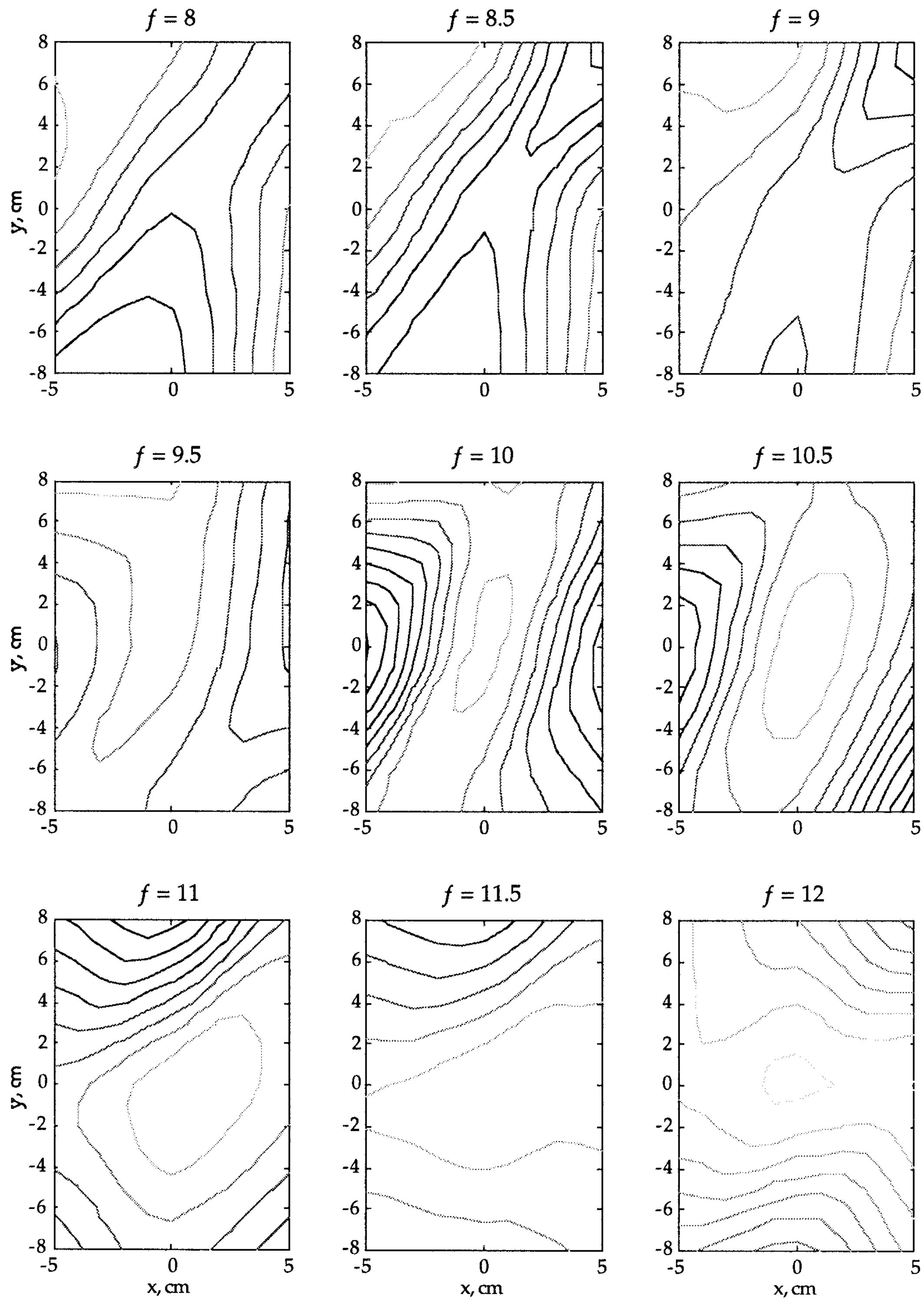

Fig. 8. Small intestinal activity. Strength contours determined by spectral analysis of intestinal activity in nine different frequency bands are plotted around the abdomen from recordings in a typical subject. Each plot represents the activity in a 0.5-cpm frequency band centered at the frequency indicated in the plot. Darker lines indicate stronger activity. The maps in the lower frequency bands show activity in the lower part of the abdomen, and maps in the higher frequency ranges show activity in the upper part of the abdomen. The results are consistent with the known BER frequency gradient of the small intestine.

We have used a vector SQUID magnetometer to measure the vector magnetic field of normal human gastrointestinal electrical activity. The results agreed with previous single-channel data [2], and additional information was apparent in the vector recordings. The gastric magnetic field showed a BER frequency of 3.03 ± 0.18 cpm ($N = 9$), and the intestinal magnetic fields showed the expected variation at different recording locations. Although we observed the expected trend toward lower BER frequencies in lower abdominal sections, there was a large amount of variance between subjects. One reason that the averaging procedure does not work for the small intestinal BER is that the location of the small bowel

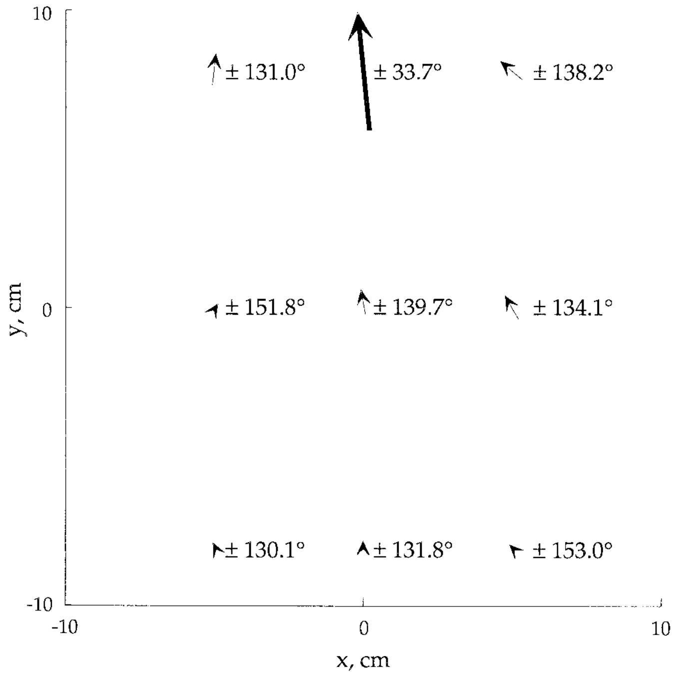

Fig. 9. The gastric vector. The magnetic field vectors at the gastric frequency are represented by arrows in each of the nine sections with the standard deviation indicated. The size of the arrow indicates the strength of the vector. The average magnetic field vector associated with the gastric projection was strongest in the central upper section and generally oriented in a cephalad direction (96.0 ± 33.7). Vectors of magnetic fields at the gastric frequency in other sections are much smaller and are randomly oriented.

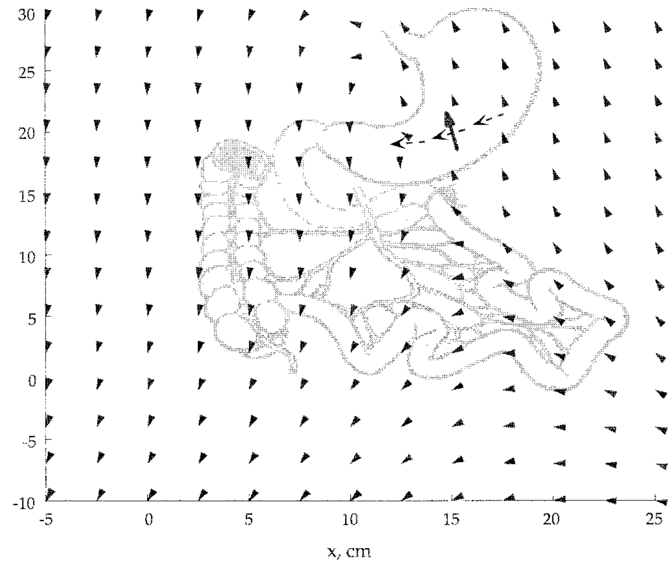

Fig. 10. Gastric magnetic field (GMF) vector model. A simple current dipole model approximates gastric electrical activity with three current dipoles (dashed arrows) aligned along the longitudinal axis of the stomach. The dipoles have oscillating amplitudes at 3 cpm, and phase differences to simulate uniform aboral propagation. Arrows representing magnetic field vectors are computed at 182 locations in a 14 × 13 grid. The size of the arrows corresponds to the strength of the vector. The GMF vectors calculated from the three-dipole model show that activity is strongest directly above the current dipole pattern, and that the vector is oriented in a perpendicular direction to the current flow according to the right-hand rule. Only two arrow sizes are evident in the figure because the vector is so much stronger directly above the propagation pattern. The model suggests that our experimental results are consistent with aboral current propagation along the axis of the stomach, assuming that gastric electrical activity may be modeled by current dipoles.

varies from subject to subject. Thus, one segment of the intestine oscillating at, say 11 cpm may be located in the right upper section in one subject and the central middle section in another. Identification of the BER frequency gradient in each subject was much less problematic; we clearly saw a decrease in small bowel BER frequency using spatial maps of the frequency content as in Fig. 8. Although these maps may be somewhat distorted due to the potential movement of the bowel during repositioning of the magnetometer between sections, they do record the gross frequency changes characteristic of the BER frequency gradient. Our single-channel vector measurements at different abdominal locations do not provide enough information to reliably isolate specific intestinal segments according to their BER frequency. However, a multichannel vector magnetometer would provide for an inverse mapping that could potentially determine gastrointestinal sources from external measurements of the magnetic field and provide for more accurate intersubject comparisons [30].

One significant finding of the present study is the determination of the direction of the stomach's magnetic field and, by inference, the direction of gastric electrical propagation. By measuring the gastric magnetic field vector, one can infer the direction of propagation. As expected, the magnetic field vector of gastric activity was strongest in the epigastrium. On average, the gastric vector was oriented cranially (96.0 ± 33.7°, mean ± S.D.). The variance from the mean gastric vector direction is small in comparison with the variance of small bowel vector directions (84.4 ± 106.4°, mean ± S.D.) and may represent normal biological variance. Our results indicate that while description of small bowel magnetic fields by single vectors may be of limited diagnostic value, a single gastric magnetic field vector represented the gastric activity consistently.

We created a computer simulation to model the vector magnetic field associated with electrical activity propagating along a certain direction. Although an appropriate source model for gastric electrical activity has not been fully elucidated, the propagating dipole model has received a considerable amount of attention in the literature [32], [33]. We will employ that model in this work as well though we must admit that further research is necessary to identify an accurate model for gastric activity. Fig. 10 shows three current dipoles (dashed arrows) representing gastric sources oriented along a hypothetical stomach. The dipole magnitudes are programmed to oscillate at 3 cpm with their phases differing by an amount consistent with propagation of a single slow wave from the greater curve to the pylorus over 20 s. The resulting gastric magnetic field vectors measured by a hypothetical 182-channel magnetometer array are also shown. The magnetic field strength is clearly strongest at one location and the vector at that location projected into the xy plane is oriented toward the head. Thus, the magnetic field vector above three propagating dipoles is oriented perpendicular to the direction of propagation according to the right-hand rule. The results of this simple simulation show that our experimental findings are consistent with the propagation of current along the stomach axis. It is important to note the low standard deviation of the mean orientation of the gastric magnetic field vector. In fact, the gastric magnetic field vector was clearly oriented in the cephalad direction for all subjects, despite the fact that the subjects had a wide variety of body frames.

To provide a quantitative assessment of the additional information content of vector MGG and MENG as opposed to single component recordings, we computed the dot product of the gastric and small bowel magnetic field vectors ξ. Our data showed that these vectors are indeed oriented in different directions. If the vector projections maximizing gastric and small bowel magnetic fields were identical, then a vector magnetometer would provide no additional information, since the different GI signals might be recorded with equal fidelity using a single-component instrument. We found that there is a significant difference between the gastric and small bowel magnetic field directions, so the vector magnetometer allows separation of the two contributions and hence optimization of each recording. In a sense, the further the average dot product is from one, which would indicate that the vectors were oriented in the same direction, the more useful is the vector recording. The average dot product in this study was $\xi = 0.344 \pm 0.079 (p < 0.001)$. Therefore, a single-component recording of the magnetic field necessarily cannot distinguish useful information since only one direction is recorded. The single-component magnetometer records the projection of two different vectors onto a single axis, such that the projection operation corresponds to the rejection of information describing the differences in the two contributions. Furthermore, a single-component recording is insensitive to dipolar sources that are oriented normal to the plane of the pickup coil, and a vector instrument would be needed to detect such a source. Cutaneous electrodes above the stomach are sensitive to activity from a wide region with numerous bioelectrically active tissues. Although magnetic detection devices are also sensitive to sources distributed over a wide area, the vector magnetic field recording may be projected by means of simple coordinate transformations into particular directions associated with magnetic fields from specific electrical activities. In this way, much of the measurement noise as well as extraneous bioelectric activity may be rejected from gastric or small bowel magnetic field recordings. While the cutaneous EGG may measure biologically active tissues other than the stomach, the vector magnetic field may be projected into the direction of the gastric magnetic field, thus greatly reducing contributions from other biologically active tissues and noise sources.

Most biomagnetometers in use today employ a multichannel array of SQUID-based single-component detectors. Our results indicate that measurement of a single vector magnetic field contains more information than measurement of any single component, information that is crucial for distinguishing sources at different locations or with different orientations. However, it remains to be demonstrated whether multichannel single-component measurements might have information content similar to vector measurements. It is theoretically possible that appropriate manipulation of multichannel single-component recordings through, for example, the signal-space projection technique [21] could provide enough information to distinguish physiological components as long as they were not silent to the magnetic field component recorded. As an example, a current dipole in the x–y plane could be specificized by several z-component measurements at different locations above the source plane. However, if the current dipole were oriented in the z-direction, it would have no signature in a z-component recording, and either an x- or y-component recording would be required to detect it.

Instrument noise is always a concern in measurements of biomagnetic activity. This is particularly true in the case of gastrointestinal signals since the frequencies of interest are below 1 Hz. Many SQUID sensors exhibit $1/f$ noise with a 3-dB point around 1 Hz. Also, environmental noise, primarily interference from large moving metal objects can also degrade the signal. The AR PSD is quite effective in identifying these noise components of the signal which are typically much smaller in magnitude than the GI signals. Fortunately, the gastric signal, which is the lowest frequency of physiological interest in this study (about 0.05 Hz), also has a relatively large magnitude and is always detectable. The small bowel signal has a smaller magnitude, but a higher characteristic frequency and is also always observed. We have previously demonstrated that MENG signals correlate highly with electrical activity detected by serosal electrodes [1] and that these signals are not the result of motion artifact by magnetic contaminants in the bowel [2]. It is important to recognize that while these signals are at much lower frequencies than are typical for biomagnetic measurements, the shielding factor of the magnetically shielded rooms often used in biomagnetism are also surprisingly low at these frequencies. Hence, it may be easier to eliminate the magnetic shield for these measurements than for signals at higher frequencies where the effectiveness of the shields is much greater.

Disease states are known to change the direction of gastric electrical activity propagation [34]. Whereas determination of propagation direction from raw cutaneous EGG signals has been difficult, vector MENG would be expected to determine abnormal propagation patterns easily. In our study, the single channel vector measurement (three vector components) clearly reveals propagation information. No pathologic propagation patterns were noted in the normal volunteers. Multichannel vector magnetic measurements would improve the determination further.

This study suggests that examination of magnetic fields detected by SQUID magnetometers may offer the first reliable noninvasive assessment of the condition of the gastrointestinal musculature by allowing for examination of the basic electrical activity. In addition to the ability to detect and quantify frequency dynamics of the signals, spatial variations that result from propagating activity are also apparent. We showed that a vector SQUID magnetometer can measure the vector magnetic field from both stomach and small intestinal activity, and that there is significant information present in the full vector that may not be obtained by a single channel measurement. Our studies utilized a vector magnetometer that records the vector at only one location. A multichannel vector instrument measuring GI activity at multiple abdominal locations might allow noninvasive determination of the gastric propagation velocity as well as the direction of propagation as determined in this work. Propagation velocity has never been measured noninvasively. Presumably, intestinal BER propagation velocity could also be observed with a multichannel vector SQUID magnetometer. Also, the multichannel instrument would allow more specific characterization of the current sources associated with gastric activity since simultaneous magnetic field measurements can be used for an inverse analysis. The precise nature of gastrointestinal current sources has yet to be elucidated, and SQUID magnetometers represent an additional tool for researchers to consider in this endeavor.

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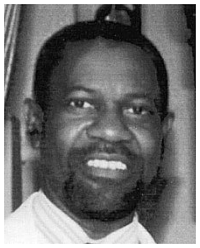
L. Alan Bradshaw received the B.S. degree in physics from Abilene Christian University, Abilene, TX, in 1990 and the M.S. and Ph.D. degrees in 1992 and 1995 from Vanderbilt University, Nashville, TN. He continued his dissertation work in gastrointestinal biomagnetism under a National Institutes of Health (NIH) National Research Service Award from 1996–1998.

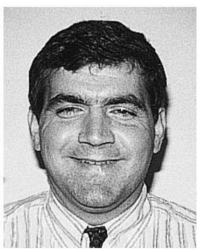
He now serves as Director of the Biomagnetism Laboratory and was appointed as a Research Assistant Professor in the Department of Physics and in the Department of Surgery at Vanderbilt University. His research interests include magnetic and electric detection of gastrointestinal activity and mathematical modeling of bioelectric activity.



J. K. Ladipo was born in 1951 in Lagos, Nigeria. He obtained the M.B. and B.S. degrees (bachelor of medicine, bachelor of surgery) in 1977 from the Medical School of the University of Ibadan, Nigeria. His residency training was at the University College Hospital, Ibadan, Nigeria.

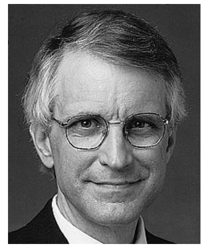
From 1995–1997, he was a Surgical Research Fellow at Vanderbilt University Medical Center, and currently works as a Senior Lecturer, College of Medicine of the University of Ibadan and Consultant Surgeon at the University College Hospital, Ibadan, Nigeria. His areas of interest are surgical gastroenterology and gastrointestinal electrophysiology.

Dr. Ladipo is a Fellow of the West African College of Surgeons (FWACS) and Fellow of the International College of Surgeons (FICS).



Daniel J. Staton received the Ph.D. degree in physics from Vanderbilt University, Nashville, TN, in 1994.

He served as an American Heart Research Fellow at Vanderbilt from 1994–1996 and as a Medical Physics Resident at the University of Alabama Birmingham, Department of Radiology, from 1996–1998. He is presently a Radiological Medical Physicist, affiliated with Radiological Physics Consulting, Inc., Winston-Salem, NC.



John P. Wikswo, Jr. (S'75–M'75) was born in Lynchburg, VA, in 1949. He received the B.A. degree in physics from the University of Virginia, Charlottesville, in 1970, and the M.S. and Ph.D. degrees in physics from Stanford University, Stanford, CA, in 1973 and 1975, respectively.

He was a Research Fellow in cardiology at the Stanford University School of Medicine from 1975 to 1977, where he continued his work on determining the relationship of the electric and magnetic fields of the heart and developing instrumentation and analysis techniques for magnetocardiography. He joined the faculty in the Department of Physics and Astronomy at Vanderbilt University, Nashville, TN, as an Assistant Professor of Physics in 1977. He is now the A.B. Learned Professor of Living State Physics. He is a fellow of the American Physical Society. His current research is directed toward using electric and magnetic measurements and electromagnetic theory for studying the propagation of electrical activity in nerve and muscle cells and for nondestructive testing. He has published more than 84 research articles and 17 book chapters, and more than 150 conference papers, abstracts and reports. He holds ten patents.

William O. Richards was born in Ann Arbor, MI, in 1953. He received the M.D. degree from the University of Maryland, Baltimore. After finishing his residency in general surgery in 1984, he completed a research fellowship in GI physiology at Vanderbilt University in 1987.

He is currently a Professor of Surgery at Vanderbilt University School of Medicine. His current research interests include the electrophysiology of gastrointestinal smooth muscle.