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# THE VECTOR MAGNETIC FIELD OF THE HUMAN STOMACH AND SMALL BOWEL

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**Abstract**

*We recorded the vector biomagnetic field associated with gastrointestinal electrical activity in nine positions around the abdomen of 10 normal human volunteers using a vector SQUID magnetometer. Gastric activity with a frequency of 3.03 ± 0.18 cpm (mean ± SEM) was recorded with the magnetometer in the epigastrium. Small intestinal activity was also recorded in all abdominal positions with a frequency ranging between 9.0 ± 0.43 cpm in the lower abdomen to 10.5 ± 0.28 cpm in the upper abdomen. Different components of GI activity were evident within single magnetic field recordings. These different components could be elucidated by examining different projections of the magnetic field vector. These studies further demonstrate the ability of the SQUID magnetometer to detect gastrointestinal activity and also illustrate how different signal components associated with gastric and small intestinal activity may be separated.*

## Introduction

Gastric and small intestinal electrical activities were first recorded in 1922 by Alvarez using electrodes placed on the tissue surface (1). The basic electrical rhythm (BER), or slow wave, of both stomach and small bowel is characterized by an omnipresent slowly oscillating activity. Gastric BER typically has an oscillation frequency of about 3 cpm while small intestinal BER is slightly faster, ranging from 8-12 cpm. Additionally, multiple pacemaker sites and limited coupling between adjacent regions of intestine create a natural frequency gradient in the small intestine: the proximal duodenum displays a frequency of about 12 cpm. There is a stepwise decrease in BER frequency to the distal ileum where the frequency is typically about 8 cpm (3).

Bioelectric currents associated with gastrointestinal electrical activity produce magnetic fields that may be measured with a Superconducting QUantum Interference Device (SQUID) magnetometer. Our previous studies showed that a SQUID magnetometer measuring one component of the magnetic field was able to detect both gastric and small bowel activity and that noninvasive SQUID measurements correlate strongly with invasive serosal electrode measurements (2, 4). In those studies, we also observed the natural BER frequency gradient of the small intestine as more caudal recording locations displayed intestinal BER with progressively lower frequencies.

Although our previous studies recorded a single component of the magnetic field, the magnetic field is a vector quantity and has two other orthogonal components. The purpose of the present study is to investigate whether additional information about gastrointestinal electrical activity may be elucidated with the use of a vector magnetometer.

## Methods

Gastrointestinal activity of ten normal human volunteers was studied with a vector SQUID magnetometer (Conductus, San Diego). The SQUID sensors and pickup coils must be superconducting, so the components are housed in an evacuated dewar. The magnetometer is designed with three sets of gradiometric pickup coils that measure the x-, y-, and z- components of the magnetic field difference between the lower pickup coils near the base of the dewar and the upper coils fifteen centimeters above the lower set.

No dietary restrictions were imposed on the volunteers as we wished to compare these results with earlier fasting and fed studies as well as examining the vector nature of the signal. For each volunteer, the SQUID system was placed above the abdomen in nine regular locations covering a rectangular grid from 8 cm below the umbilicus and 5 cm to the left to 8 cm above the umbilicus and 5 cm to the right. Recordings were taken for two to three minutes while the subjects were asked to suspend respiration to reduce motion artifact. Signals were obtained with a sampling rate of 30 Hz and filtered from 0.01 Hz to 10 Hz. Autoregressive (AR) spectral analysis was used for the short-duration recordings, and frequency peaks corresponding to gastric and small bowel activity identified.

Frequently, recordings taken at a single position displayed at least two frequency peaks indicating the presence of both gastric and small bowel signal components. Additionally, multiple frequency peaks in the small bowel range suggested the presence of multiple intestinal sources. We utilized a vector projection technique to decompose the three recorded vector components into 32 vector projections directed evenly around a unit sphere according to

$$\vec{B}_i = \hat{i}B_x\sin\theta_i\cos\phi_i + \hat{j}B_y\sin\theta_i\sin\phi_i + \hat{k}B_z\cos\theta_i, \qquad (1)$$

for $i = 1, \ldots, 32$; $\phi_i$ and $\theta_i$ chosen to give 32 regular projections around a unit sphere (5). We could then identify which vector projections displayed maximal contributions from different gastrointestinal components and evaluate the degree of orthogonality between multiple signal components.

## Results

Figure 1 shows sixty seconds of the sequential recordings for one subject at the nine abdominal positions. The slower 3 cpm variation of the gastric component of the signal is evident in the upper tracings near the stomach while the faster 8-12 cpm small bowel oscillations are apparent in lower sections. In 8 of the 10 subjects, the maximal gastric signal was recorded in the epigas-



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trium. One subject showed maximal activity in the gastric frequency range in the left upper section, and the other had maximal gastric activity in the recording above the umbilicus. The gastric frequency recorded in all volunteers was 3.03 ± 0.18 cpm. Different frequencies of the small bowel BER were recorded at the different locations (mean 9.99 ± 0.14 cpm). Examination of the dominant frequencies recorded in the small bowel range generally showed higher BER frequencies in the uper abdomen (10.5 ± 0.28 cpm) and lower frequencies in the lower abdomen (9.0 ± 0.43), consistent with the natural BER frequency gradient of the small intestine. These differences are statistically significant ($p=0.01$).

The AR frequency spectra show that many recording locations displayed both gastric and small bowel components and several also displayed multiple small bowel contributions. Individual projections of the vector magnetic field could be identified in which gastric signal was maximized, and the same was true for the multiple small bowel signal components. Figure 2 shows the vector projections from the recording above the epigastrium that maximize the gastric component at 2.8 cpm and a small bowel component at 11.7 cpm.

The magnetic fields of these different components of the signal are not all oriented in the same direction. The degree of orthogonality of the signals in two projections can be determined by examining the dot product of the two vector directions (effectively, the cosine of the angle between two vectors). These dot products will assume values from 0 to 1, with 0 indicating that the vectors are completely orthogonal and 1 indicating that they are parallel. The mean dot product between gastric and small bowel magnetic field vectors was 0.497 ± 0.033, suggesting that the relative orientations of gastric and small bowel magnetic field vectors is approximately random; they are neither exactly parallel nor exactly orthogonal.

## Discussion

Biomagnetic measurement of gastrointestinal magnetic fields is an effective way to noninvasively measure the electrical activity of the GI system. These studies show that the vector magnetic field provides additional information to that obtained with single component measurements. Gastric and small bowel components can be separated with the vector projection technique as can multiple small bowel sources. We recorded the gastric signal with an average frequency of 3.03 ± 0.18 cpm and the small bowel activity at 9.99 ± 0.14 cpm.

In one sense, the effectiveness of the vector recording can be evaluated by looking at the dot product of the magnetic field vectors between small bowel and gastric signal components. We determined this value to be 0.497 ± 0.033 which suggests that the components not completely parallel or completely orthogonal. For this reason, any single component of the magnetic field would be unable to record both gastric and small bowel activity maximally. The vector magnetic field is needed to fully separate the different components of gastrointestinal electrical activity.

## Acknowledgements

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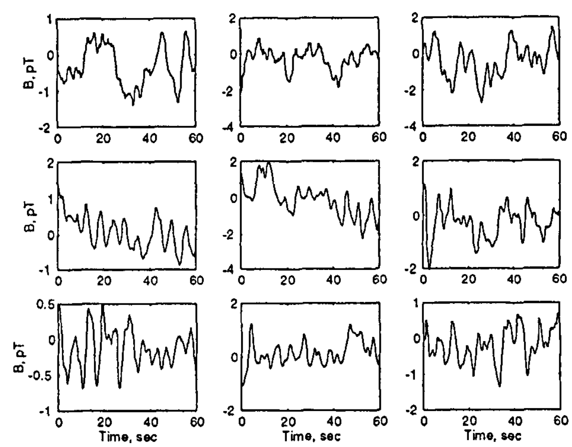


*Fig. 1. The z-component of the vector SQUID recordings in each of nine abdominal sections show gastric activity at 2.8 cpm in the upper abdomen and small intestinal activity in the lower abdomen. The x- and y- components were also recorded.*

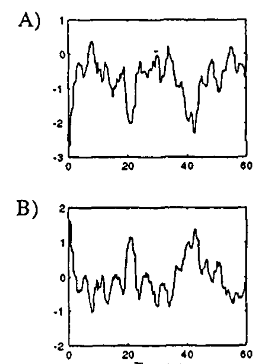


*Fig. 2. Gastric (A) and small intestinal (B) magnetic field vector projections were derived from recordings above the epigastrium (upper middle tracing of Fig. 1) by finding the vector orientation that maximized the signal in the relevant frequency ranges.*