# Correlation and comparison of magnetic and electric detection of small intestinal electrical activity

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Bradshaw, L. Alan, Suhail H. Allos, John P. Wikswo, Jr., and William O. Richards. Correlation and comparison of magnetic and electric detection of small intestinal electrical activity. Am. J. Physiol. 272 (Gastrointest. Liver Physiol. 35): G1159–G1167, 1997.—The small intestinal basic electrical rhythm (BER) was detected simultaneously with serosal electrodes and a transabdominal superconducting quantum interference device (SQUID) magnetometer in anesthetized rabbits. We induced mesenteric ischemia to correlate serosal electrode recording of changes in BER with the SQUID magnetometer. The BER frequency was obtained by spectral analysis of the data using Fourier and autoregressive techniques. There was a high degree of correlation ($r = 0.96$) between the BER frequency determined using the serosal electrodes and the BER frequency ascertained from SQUID data. Additionally, the effects of an electrical insulator on the external electric and magnetic fields were studied in the rabbit model. The presence of an insulator profoundly attenuates external electric potentials recorded by cutaneous electrodes but does not significantly affect external magnetic fields or serosal potentials. We conclude that SQUID magnetometers could noninvasively record small intestinal BER that was highly correlated with the activity recorded by invasive serosal electrodes. The advantages of magnetic field measurements have encouraged us to investigate clinical applications.

superconducting quantum interference device magnetometer; basic electrical rhythm; spectral analysis; volume conductor; small intestine; electrical control activity; electrical recordings

SMOOTH MUSCLE in the gastrointestinal tract displays two types of electrical activities. A high-frequency spiking activity known as the electrical response activity is associated with muscle contraction, whereas an oscillating slow wave, known as the electrical control activity or basic electrical rhythm (BER), is present continuously (8, 9, 24). The BER has typically been detected with invasive serosal electrodes that measure the local potential difference of a section of bowel. Recently, Chen et al. (6) reported detecting the human small bowel BER using cutaneous electrodes. To record small bowel BER, a band-pass filter was used to filter out all other biologically active tissues (stomach, heart, and colon). The results indicate that the small bowel potentials result in low-amplitude cutaneous potentials that give a low signal-to-noise ratio. Moreover, the studies by Chen et al. (6) involved subjects in whom the jejunum had been attached to the abdominal wall, providing for increased electrical contact between the bowel and the cutaneous electrode. Presumably, even lower signal-to-noise ratios than Chen et al. (6) reported would be obtained if the direct electrical contact between the bowel and the cutaneous electrode, provided by attaching the bowel segment to the abdominal wall, were broken.

Because magnetic fields are not attenuated by low-conductivity layers such as those found in the abdominal wall, another option is to measure the magnetic field produced by small bowel electrical activity (27). Biomagnetic fields are typically several orders of magnitude smaller than the magnetic field of the Earth, so a sensitive detection device is necessary. Superconducting quantum interference device (SQUID) magnetometers are able to detect the weak magnetic fields of biological origin. Previous studies have shown that SQUIDs can detect small intestine BER in vitro (25) and in vivo (11). Magnetoencephalography researchers routinely measure the magnetic field of the brain (27), which is at least an order of magnitude smaller than the magnetic field of the small intestine (21).

We present an experiment to examine the effect of a nonconducting layer placed between the small bowel and the abdominal wall on the transabdominal magnetic field, the serosal potential, and the cutaneous potential. We hypothesized that the magnetic fields of small bowel electrical activity recorded with the SQUID would correlate with the potentials measured with invasive electrodes and would not be attenuated by the placement of a nonconducting layer between the bowel and the abdominal wall. Transabdominal magnetic measurements are not expected to suffer from the same problems (attenuation and smoothing by electrically insulating layers) as cutaneous electrical recordings. A previous study utilizing a mathematical model for the magnetic fields and electric potentials from small bowel activity showed that layers of low conductivity do not affect the magnetic fields, but do attenuate cutaneous potentials (3).

## MATERIALS AND METHODS

Magnetic fields may be detected with SQUID magnetometers, which are basically magnetic flux detectors. Figure 1 shows a typical SQUID system. The term SQUID actually refers to only the cryogenic flux-to-voltage converter, but it has commonly been applied to the entire system, consisting of the flux-to-voltage converter, the superconducting pickup coils that serve as a direct current flux transformer, the connecting wires, and often the cryostat as well. The pickup coils are placed near the biomagnetic sample and are typically arranged in a gradiometer configuration with one pickup coil located a certain distance above a lower coil. The coils are wound in opposite directions so that the flux in the upper coil
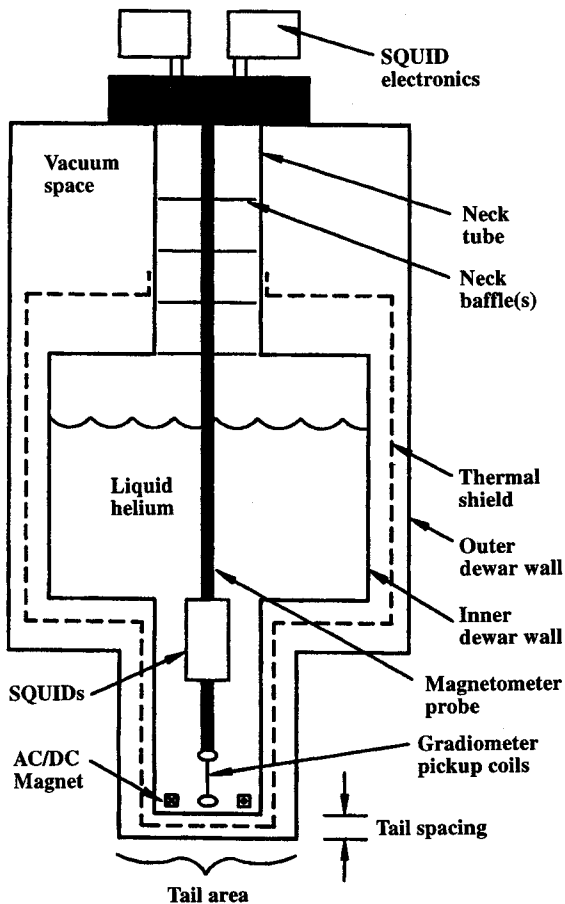
Fig. 1. Schematic diagram of a typical superconducting quantum interference device (SQUID) magnetometer system. Gradiometer pickup coils at bottom of Dewar couple magnetic flux to SQUID, which converts flux into measured voltage signal.

is subtracted from the flux in the lower coil, thus canceling out steady ambient magnetic fields, such as the Earth's field. Magnetic flux threading these superconducting coils induces current in the coils, which then couples this flux into the SQUID. The operation of the SQUID is to convert the flux to a voltage. Because of its extreme sensitivity, the SQUID system is the most sensitive flux-to-voltage converter known. Further details are provided in Jenks et al. (14).

MicroSQUID is a high-resolution, four-channel, first-order gradiometer designed to provide the high spatial resolution required in tissue studies. The pickup coils are 3 mm in diameter, arranged at the corners of a 4.4 mm × 4.4 mm square, and may be placed as close as 1.5 mm from a room-temperature sample (4). Although this magnetometer was designed for in vitro studies, it has been used to examine the signals from sections of prairie dog small bowel (25) and rabbit small bowel (10). The effect of mesenteric ischemia on the small bowel BER was subsequently studied with MicroSQUID. Those studies demonstrated that decreases in BER frequency during ischemia could be detected noninvasively using MicroSQUID (22).

*Experiment 1: Correlation of serosal electrode and transabdominal magnetometer recordings.* We performed simultaneous recordings of the serosal potential and transabdominal magnetic field from a segment of male New Zealand rabbit ($n = 6$) small intestine. The rabbits were fed a nonmagnetic diet consisting of lettuce and cabbage for at least 72 h before the experiments. The rabbits were anesthetized with intramuscular injections of ketamine (30 mg/kg) and acepromazine (5 mg/kg). A midline laparotomy was performed, and a serosal electrode platform was sutured to a segment of bowel. A snare consisting of monofilament nylon fishing line (Du Pont Stren 8 lb test) was threaded through a Teflon tube (Voltrex, 16 gauge) and placed around the vessels supplying the section of intestine under study. The snare could be pulled externally to induce ischemia and could subsequently be released to allow reperfusion. The section of small bowel with the electrode platform attached was then replaced in the abdominal cavity and attached to the abdominal wall, as shown in Fig. 2. In two experiments, bipolar Ag-AgCl cutaneous electrodes were placed on the abdominal surface on either

Fig. 2. Experimental setup for *experiment 1.* Electrodes in electrode platform placed beneath small bowel segment recorded serosal potential, while magnetometer outside abdomen recorded transabdominal magnetic field. In 2 experiments, cutaneous electrodes were also placed on abdominal surface. FFT, fast Fourier transform.
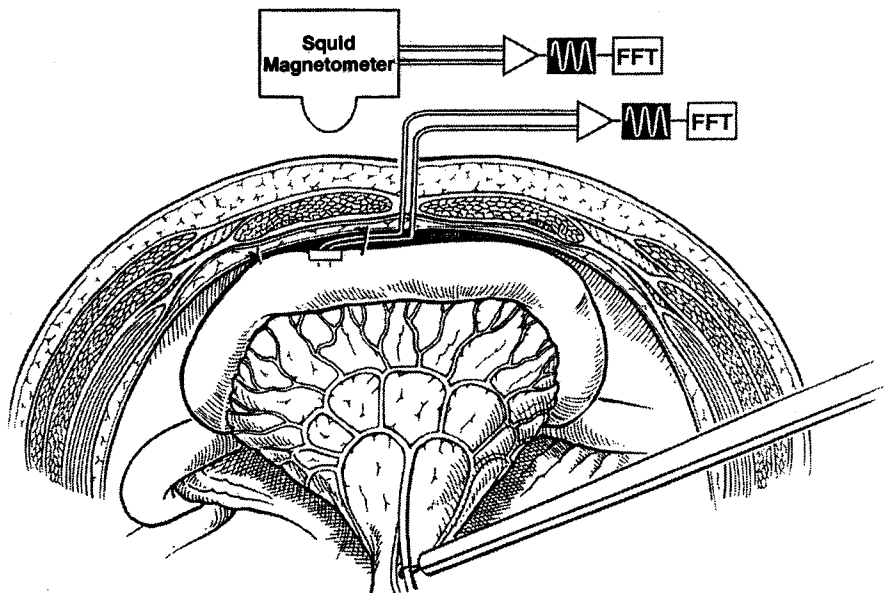
side of the electrode platform, and conductive jelly was applied to the electrodes. These cutaneous electrodes were not used consistently, because they tended to interfere with the SQUID recordings. The platform location was determined outside the abdomen by the location of the sutures at the ends of the platform. The magnetometer was centered over the position of the electrode platform. We recorded the signals using a Beckman amplifier system (model R612) with a data acquisition unit (MP100, Biopac Systems, Goleta, CA) and a laptop computer (Apple PowerBook 170) running data acquisition software (Acqknowledge 3.1.2, Biopac Systems). The electrode signals were band-pass filtered from 0.16 to 30 Hz, and the magnetometer signals were low-pass filtered at 30 Hz.

In these experiments, we recorded the signals from the serosal electrodes and magnetometer for at least 10 min to establish a baseline BER. After the baseline recording was obtained, we induced ischemia by pulling the snare and observed the BER for 30 min. We then released the snare and allowed the bowel to reperfuse, recording BER changes for at least 15 min after release of the snare.

Because we are interested in changes in frequency components of the signals we recorded, power spectral density (PSD) estimates for each of several epochs in the signal were computed so that we could create a time-frequency representation (TFR) of the data, showing the variation of the frequency content of the signal with time of recording. From these representations, the dominant frequency recorded during each epoch was extracted and used to track the changes in BER frequency with ischemia and reperfusion. Both classical Fourier [fast Fourier transform (FFT)] and modern autoregressive (AR) spectral analysis techniques were used for the TFR (2).

The Fourier power spectrum is appropriate for stationary signals that are not expected to change over the duration of the sample. Because the spectral resolution of the FFT is determined by the length of the sample, long sample durations are required for adequate resolution at low signal frequencies. However, signals from ischemic bowel are expected to change, and only short-duration samples may be assumed to be stationary. Thus we employ the AR spectral technique to identify frequency changes over short (1 min) time segments.

*Experiment 2: Effect of insulators.* We then studied the relationship among serosal potentials, magnetic fields, and cutaneous potentials. We conducted experiments on seven rabbits in which cutaneous electric, transabdominal magnetic, and serosal electric signals were measured with and without an electrical insulator between the bowel segment and abdominal wall. This method is similar to that used by Leifer et al. (17) to study the heart-lung boundary. A latex surgical glove was used as the insulator. A larger latex sheet was placed around the bowel segment under study and over the rest of the bowel to further eliminate the interference of electrical activity from the surrounding bowel. The surgical glove was inserted between the bowel segment and the abdominal wall so as to break the electrical contact between the surface of the small bowel and the inner abdominal wall. The serosal electrodes used in the ischemia studies were used in a similar manner for these experiments, and an additional bipolar electrode pair was inserted directly into the musculature of the abdominal wall of the rabbit to ensure a direct electrical contact between the small bowel and the recording electrodes, because the small bowel was sutured to the abdominal wall. The animal with the glove in place was positioned under the magnetometer, and simultaneous sero-

sal and cutaneous electrode and transabdominal magnetometer recordings were taken for 3–5 min. The glove was then carefully pulled out without reopening the abdomen, restoring the electrical connection between the small bowel and the abdominal wall. These experiments allow us, by examining the raw data as well as Fourier PSD and magnitude spectra, to determine the effect of insulators on the serosal and cutaneous potentials and on the transabdominal magnetic field.

## RESULTS

*Experiment 1: Correlation of serosal electrode and transabdominal magnetometer recordings.* Figure 3 shows the data obtained during a single experiment, and Fig. 4 presents PSDs of the Fig. 3 data computed using an AR technique. Thirty seconds of data are shown for samples during the baseline recording, 15 min after the snare was pulled, and 10 min after the bowel was reperfused. The baseline BER in both serosal electric and transabdominal magnetic recordings was 19.1 counts/min (cpm). Fifteen minutes after the onset of ischemia, the BER frequency had dropped (11.1 cpm in the serosal electrodes and 10.8 cpm in the SQUID), again indicated by serosal electric and transabdominal magnetic data. When the snare was released and the bowel was reperfused, the BER frequency returned to normal preischemic values. Ten minutes after reperfusion, the magnetometer detected the BER with a frequency of 14.7 cpm and the serosal electrode recorded BER frequency at 14.9 cpm.

The TFR of the signals obtained by taking the square root of the AR PSD (so that peaks correspond to power in the signal) reveal the time course of the decrease in BER frequency with the induction of ischemia and subsequent reperfusion (Fig. 5). Both serosal electric and transabdominal magnetic data show a baseline BER frequency of 19.1 cpm, with a gradual decrease during ischemia to 10.8 cpm in the magnetic recording and 11.1 cpm in the serosal electric recording 15 min after the onset of ischemia. After reperfusion, BER frequency again increased toward the preischemic values and was 14.7 cpm in the SQUID and 14.9 cpm in the serosal electrode 10 min after the snare was released. Two minutes of traces have been omitted from the magnetic TFR, when the snare was pulled and when it was released, because opening the door to the shielded room distorted the magnetic signals, resulting in falsely large low-frequency components to the PSD. Note that the PSD estimates are generally smaller during ischemia, although direct interpretation of the AR PSD amplitudes is not straightforward (19).

Figure 6 shows the average data over six experiments. BER frequencies detected magnetically were (with SE indicated) 18.2 ± 0.4, 13.9 ± 0.6, and 17.9 ± 0.9 cpm before, during, and after ischemia, respectively. The serosal electric BER frequencies were 18.2 ± 0.4 cpm during baseline, 14.0 ± 0.5 cpm 15 min into ischemia, and 17.4 ± 0.9 cpm on reperfusion. Paired *t*-test analyses indicate that the BER frequency recorded during ischemia falls significantly compared

Transabdominal
SQUID

Serosal Electrode

A

Baseline

B

Ischemic

C

Reperfused

5 pT

10 sec

5 mV

Fig. 3. Transabdominal magnetic and serosal potential recordings under normal conditions (baseline; *A*), 15 min into ischemic episode (*B*), and 10 min after reperfusing bowel (*C*). A decrease in basic electrical rhythm (BER) frequency during ischemia is obvious on visual analysis of both serosal electric and transabdominal magnetic data. A spiking potential characteristic of electrical response activity (ERA) is seen in both magnetic and electric recordings in *A*.
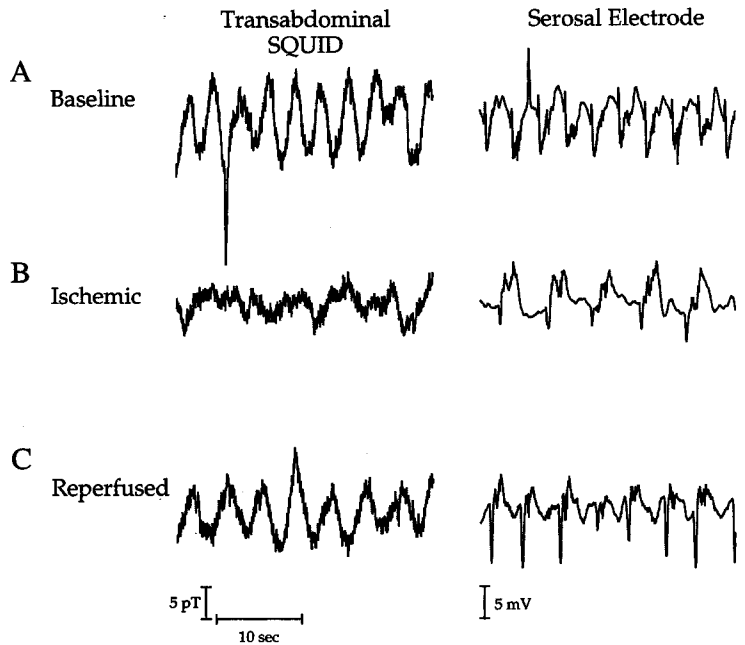
with that recorded during the baseline measurement ($P < 0.01$).

The instantaneous correlation between the frequencies recorded electrically and those recorded magnetically is of interest. The data in Fig. 5 suggest that both recording methods detect signals with the same dominant frequency, which is the BER frequency. One simple method of comparing the dominant frequencies

recorded is to take FFT over the duration of both signals and compare the frequencies of the dominant peaks. Figure 7 plots the peak frequencies indicated by FFT analysis of 3-min samples of serosal electrode data against those found magnetically. The samples were taken during baseline, 15 min into ischemia, and 7–10 min after reperfusion in each of the seven experiments, for a total of 21 observations. A linear least-squares fit

Transabdominal
SQUID PSDs

Serosal Electrode
PSDs

A

Baseline

B

Ischemic

C

Reperfused

Vertical
Scale
Normalized

0        10        20        30
*f*, cpm

0        10        20        30
*f*, cpm

Fig. 4. Autoregressive power spectral density (PSD) estimates of data in Fig. 3. *A*: dominant baseline frequency (*f*) indicated by SQUID and serosal electrode was 19.1 counts/min (cpm). *B*: during ischemia, SQUID PSD indicates drop in BER frequency to 10.8 cpm, whereas serosal electrode indicates 11.1 cpm. *C*: 10 min after reperfusion, SQUID-recorded BER frequency rose to 14.7 cpm, whereas serosal electrode detected BER frequency at 14.9 cpm. PSD are all scaled to their maxima.
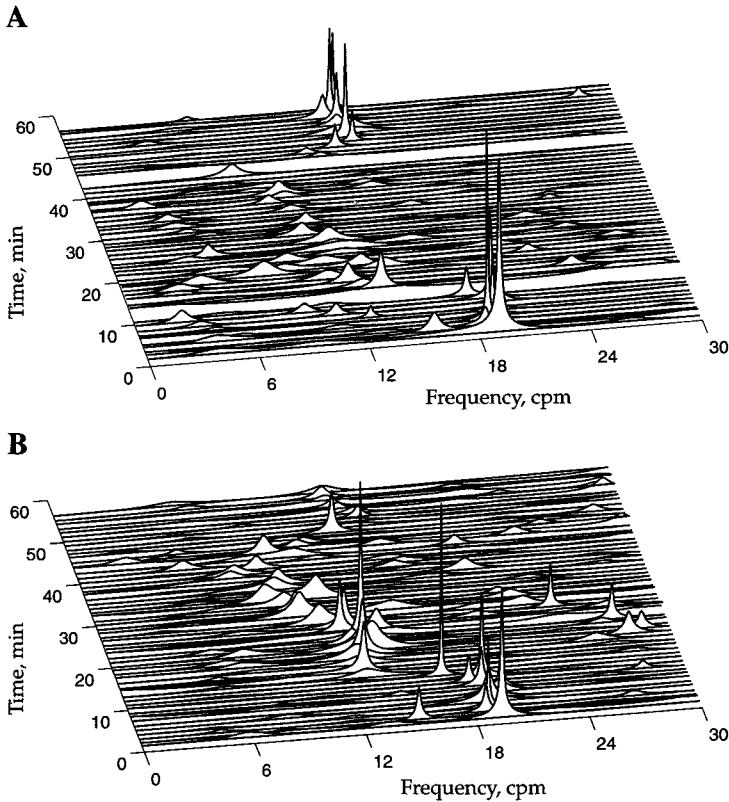
**A**



**B**
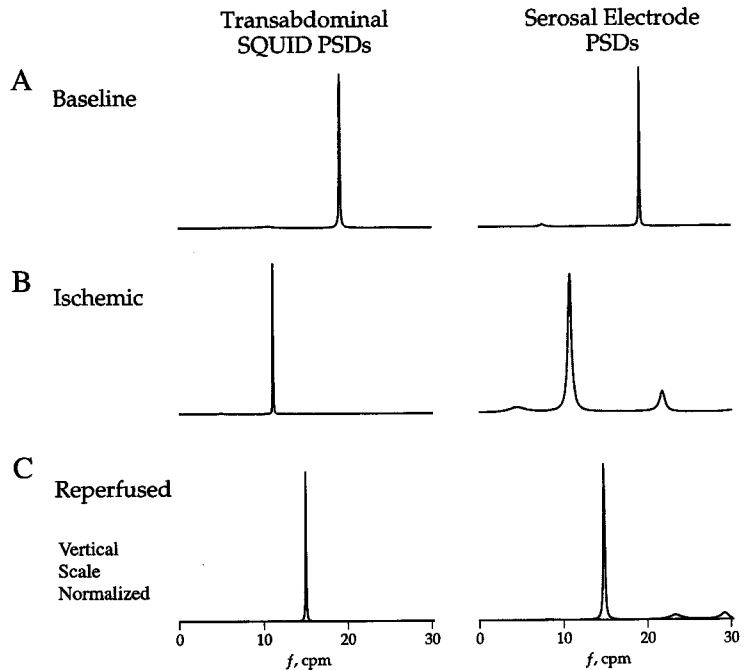


Fig. 5. Running power spectrum time-frequency representations (TFR) of signals from transabdominal SQUID (*A*) and serosal electrodes (*B*) computed each minute during experiment. Missing traces in SQUID TFR were omitted due to distortion of magnetic signal caused by opening door to shielded room. TFR show decrease of BER frequency during ischemia as well as subsequent rise on reperfusion.

is also shown. The magnetometer and serosal electrodes almost always detect the same dominant frequency; the correlation coefficient is 0.96.

*Experiment 2: Effect of insulators.* Figure 8 shows the transabdominal magnetometer, serosal electrode, and abdominal wall electrode recordings with the insulating layer in place and with it removed. The amplitudes of the magnetic signal and the serosal electric signal are unchanged, whereas the small bowel signal in the abdominal wall electrode is severely attenuated by the insulating glove.

A more quantitative determination of the degree of attenuation of the cutaneous potential by the nonconducting layer is not as simple as computing the power
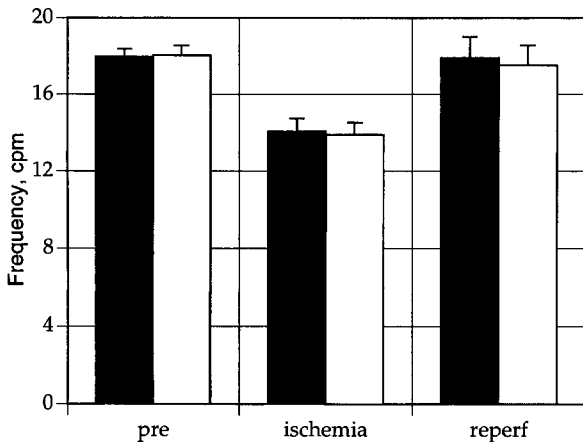


Fig. 6. Average BER frequencies during baseline (pre), ischemia, and reperfusion (reperf) detected by SQUID magnetometer (filled bars) and serosal electrodes (open bars) over 6 experiments are shown. Statistical relationships of data are given in text.
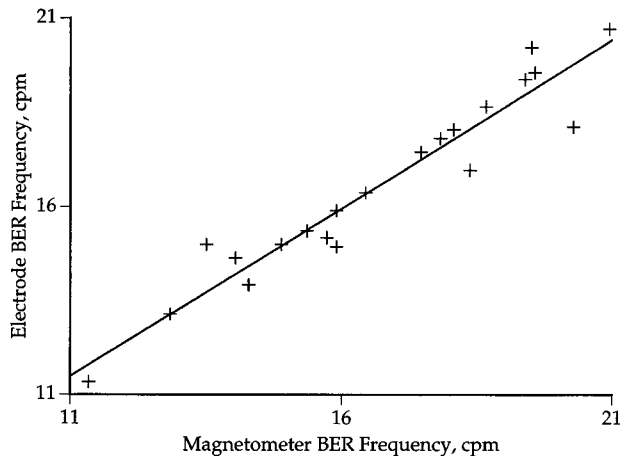


Fig. 7. Correlation between BER frequencies recorded by serosal electrodes and those recorded by SQUID magnetometer is evident in this plot ($r = 0.96$; mean difference $-0.117$ cpm; $P = 0.48$, paired $t$-test). Data points represent peaks detected in FFT of 21 samples of magnetic and electric data. A linear least-squares fit to the data points is also shown to emphasize degree of correlation.

Normal              Insulated

Transabdominal
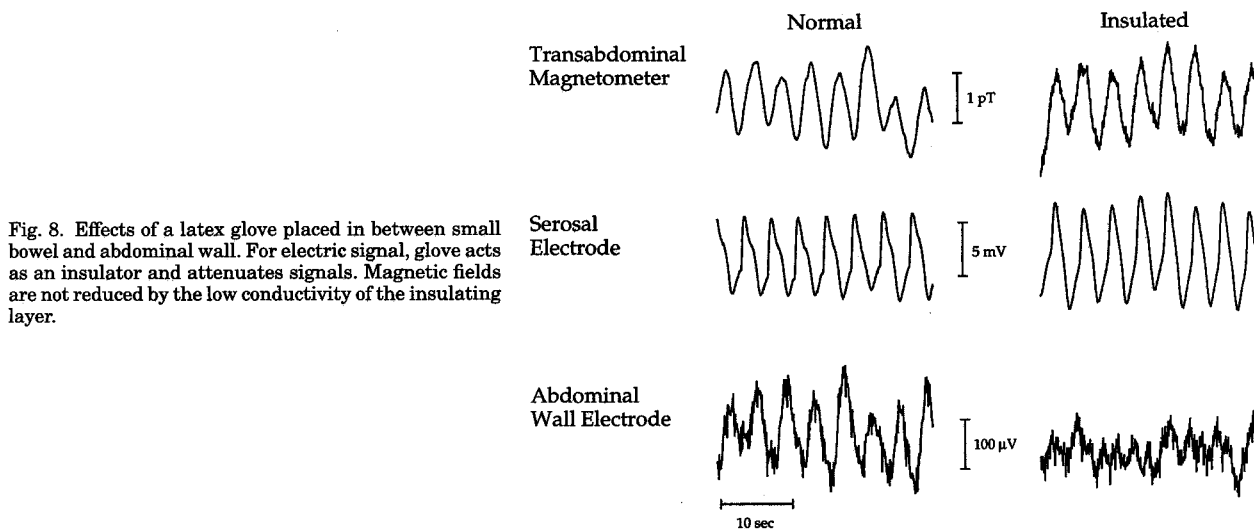Magnetometer

Serosal
Electrode

Abdominal
Wall Electrode

Fig. 8. Effects of a latex glove placed in between small bowel and abdominal wall. For electric signal, glove acts as an insulator and attenuates signals. Magnetic fields are not reduced by the low conductivity of the insulating layer.

in the signal with and without the glove in place. Other sources of bioelectric activity as well as measurement noise are included in such computations and hence are reflected in the power. A more preferable measurement of the degree of attenuation would account only for the power in the component of the signal due to the BER. In these experiments, no significant change in BER frequency is expected (no ischemic conditions exist), and so we may use Fourier analysis over a time interval of 3 min to identify the BER frequency with and without the nonconducting layer in place. Figure 9 shows Fourier power spectral estimates from *study 4* with the glove intervening and with it removed. A BER frequency of 15.6 cpm is identified in each of the recordings after the glove was removed. We can obtain the BER magnitude by taking the square root of the power at the BER frequency and examine changes in the BER magnitude with and without the insulating layer in place. The

changes in BER magnitude determined from the different recording methods during each of the seven experiments are provided in Table 1. The cutaneous electrode signal was attenuated by $-53.4 \pm 9.3\%$ ($P < 0.001$), whereas the magnetic signal and serosal potential are unchanged ($P = 0.11, P = 0.18$, respectively).

## DISCUSSION

Our studies show that there is a high correlation between transabdominal SQUID magnetometer recordings and serosal electrode recordings. Time-frequency analyses clearly showed a decrease in BER frequency during the course of ischemia and a subsequent return toward preischemic values after reperfusion. These data are in agreement with the earlier findings of Katz et al. (15), Schamaun (23), and Cabot and Kohatsu (5) that the BER frequency is reduced during ischemia.

Normal              Insulated
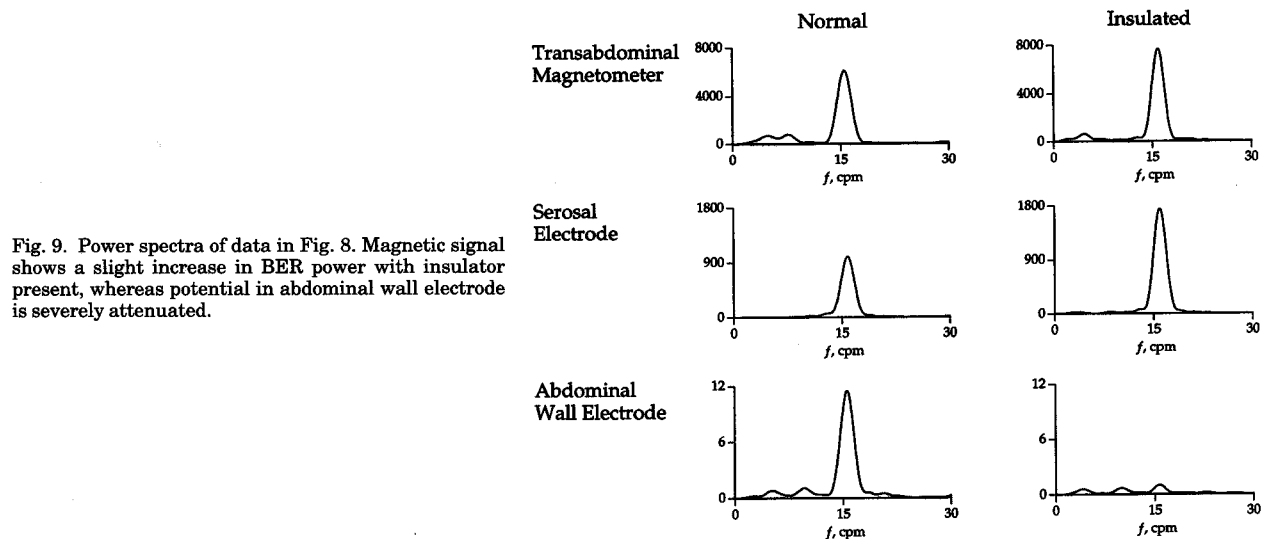
Transabdominal
Magnetometer

Serosal
Electrode

Fig. 9. Power spectra of data in Fig. 8. Magnetic signal shows a slight increase in BER power with insulator present, whereas potential in abdominal wall electrode is severely attenuated.

Abdominal
Wall Electrode

Table 1. *Percentage change in spectral magnitude at BER frequency with insulating layer placed between bowel and abdominal wall*

| Study | Serosal Electrode | Magnetometer | Cutaneous Electrode |
|---|---|---|---|
| 1 | −6.1 | −31.1 | −36.5 |
| 2 | 51.7 | 12.4 | −20.1 |
| 3 | 20.9 | −18.9 | −56.3 |
| 4 | 32.3 | 12.2 | −70.4 |
| 5 | 14.1 | −22.7 | −44.9 |
| 6 | 24.7 | −13.2 | −48.9 |
| 7 | −29.7 | −29.3 | −96.5 |
| Mean ± SE | 15.4 ± 10.0 ($P = 0.18$) | −12.9 ± 6.9 ($P = 0.11$) | −53.4 ± 9.3 ($P < 0.001$) |

BER, basic electrical rhythm.

Both serosal electrodes and the SQUID magnetometer were able to track BER frequency changes associated with ischemia.

Our studies utilized Fourier (FFT) and AR spectral analysis techniques. Other spectral estimation techniques that may be used include AR moving average (ARMA) models, adaptive AR and ARMA models (7, 16), eigenanalysis methods such as multiple-signal classification and eigenvector analysis (19), linear TFRs such as the short-time Fourier transform and the wavelet transform, or quadratic time-frequency estimators such as the spectrogram and the exponential distribution (18, 13). We prefer the AR spectral analysis technique because of its computational efficiency and accuracy. One drawback to the AR analysis is that it is not a true spectral estimator. For a sinusoid, the area under the spectral curve is linearly proportional to the signal power as with typical PSD estimators, but the peaks in the AR PSD are proportional to the square of the power (19). For this reason, some researchers display the square root of the AR PSD. Deviations of real signals from sinusoids further complicate the amplitude estimation. Thus the AR method is useful for locating frequencies dominant in the sample but may not contain useful information about the power at given frequencies.

Although the correlation between SQUID and serosal electrode signals and their dominant frequencies was high, we should consider potential sources of the minimal differences between frequencies detected electrically and those detected magnetically. Only a small section of the bowel is secured to the abdominal wall, and thus the rest of the bowel may move in response to peristalsis or small movements of the animal during the experiment. Another possible explanation for observed differences between electric and magnetic dominant frequencies may be that the serosal electrodes are constrained to record only the activity of the bowel section immediately adjacent to the electrode, whereas the magnetometer may record the activity of normal or partially ischemic bowel in a somewhat larger region. In the case of the cutaneous electrodes, the region of sensitivity is determined by the separation of the cutaneous electrodes and the effects of the insulating layers and is much larger than that of the SQUID, so that cutaneous electrical recordings provide rather poor discrimination of multiple sources. The PSD estimation procedure can also contribute error to the determination of the dominant frequency, and hence it is of great importance to use accurate spectral estimation techniques.

A pair of serosal electrodes will record the electrical activity in the immediate vicinity of the small bowel, but cutaneous electrodes reflect the summed contribution of various electrically active tissues, such as the stomach and the heart. Also, tissues of low conductivity between the smooth muscle of the small intestine and the recording electrodes affect the signal in two ways: they smooth the high-frequency content and attenuate the signal strength (1). This presents problems in the recording of the scalp electroencephalogram, where many cortical and subcortical sources contribute to the signal and the skull is a low-conductivity layer that smooths and attenuates the volume current. Similarly, in recordings from the abdomen, layers of fat effectively insulate the volume current from smooth muscle sources. In humans, the abdominal wall contains layers of preperitoneal and subcutaneous fat. Cutaneous gastric signals must arise from current sources with sufficient strength to be detectable across the fat of the abdominal wall. The omentum, which covers portions of the small intestine, introduces an additional layer of low conductivity, which makes it difficult to detect cutaneous electrical signals in normal subjects without extensive filtering (6).

Magnetic detection of the smooth muscle electrical activity avoids problems inherent in electrical recording. Conductivity discontinuities affect the electric potential fields more than the magnetic fields (12). In the human abdomen, there are at least six interfaces at which the conductivity discontinuity is large: the interfaces between intestinal smooth muscle and omentum, omentum and peritoneum, peritoneum and preperitoneal fat, preperitoneal fat and abdominal muscle, abdominal muscle and subcutaneous fat, and subcutaneous fat and skin. The combined effect of these interfaces drastically alters the potential from weak intestinal sources more than it alters their magnetic field.

Data from *experiment 2*, seen in Table 1, confirm these observations. The presence of an insulating layer drastically reduces the cutaneous potential by >50% ($P < 0.001$) but does not alter the serosal potential ($P = 0.18$) or the transabdominal magnetic field ($P = 0.11$). We observed a substantial amount of variation in the percent change of the BER spectral magnitude on removal of the insulating layer for all recording modalities, reflected by the large standard error. For instance, BER magnitude recorded by the serosal electrode decreased by 29.7% in one experiment and increased by 51.7% in another; no change in BER magnitude is expected in serosal electrode recordings. These variations may reflect normal physiological fluctuations, errors in the power spectrum estimation, or changes in the bowel location on removal of the insulating layer. Although we have no control over normal signal variability, we did take precautions to avoid spectral errors and bowel location changes. Three-minute samples of data

were used for the Fourier spectral estimates from which the BER magnitude was determined, but the averaging effect of the FFT might alter the power spectrum if the signal exhibits changes during the 3 min. The insulating layer was pulled out carefully to avoid disturbing the setup, but slight disturbance was inevitable. Notwithstanding the seemingly large variations in the percent change of BER magnitude in the serosal electrodes and SQUID during individual experiments, they were statistically unchanged ($P = 0.18$ and $P = 0.11$, respectively). Our data indicate that the presence of insulating layers attenuates the volume current flowing from small bowel sources and complicates electrode recordings taken outside the insulated region. The BER magnitude decrease recorded in the cutaneous electrodes with the insulating layer in place was statistically significant ($P < 0.001$). These results suggest that the low conductivity of the omentum and other abdominal fat layers will inevitably make cutaneous electrode recordings difficult on human subjects. Magnetic fields are relatively unaffected by insulating layers, so the transabdominal magnetic recordings would still able to detect the electrical activity of the human small bowel noninvasively.

*Considerations for SQUID recordings.* Some issues associated with implementation of SQUID technology remain to be resolved before SQUIDs are widely introduced into the clinical environment. The need for a shielded room in which to measure the small magnetic fields as well as the need for liquid helium to keep the SQUID and pickup coils cryocooled are considerations that must be addressed by advances in SQUID technology. Problems with the recording technique such as motion of magnetic contaminants must also be addressed. Furthermore, the removal of unwanted environmental noise, such as power line interference and other ambient magnetic fields, and the elimination of undesirable biomagnetic contributions to the gastrointestinal signal from cardiac sources may require sophisticated hardware and software algorithms.

There is reason to believe that SQUID technology will soon address many of these issues. Advances in SQUID magnetometers, gradiometer design, noise cancellation, and digital SQUID technologies offer the hope of sensitive magnetic measurements in noisy ambient environments, which would eliminate the need for an expensive shielded room (26). SQUIDs fabricated from high-transition-temperature superconductors may simplify the cryogenic requirements and drastically reduce the cost by eliminating the need for liquid helium.

To this point, our studies have concentrated on the use of the SQUID magnetometer to noninvasively detect changes in the BER associated with intestinal ischemia. There are other potential clinical applications of the biomagnetic method to gastrointestinal activity. Our studies in human volunteers have demonstrated the ability to detect the normal frequency gradient of the small intestine BER (21). Diseases affecting the smooth muscle electrical activity may be amenable to noninvasive magnetic field recordings as

an aid in diagnosis. Intestinal pseudo-obstruction, paralytic ileus, bowel transplantation, mechanical obstruction, dysmotility syndromes, Roux syndrome, gastroparesis, and irritable bowel syndrome may all be associated with changes in electrical activity that might be detectable using this technology.

This research shows that magnetic detection of small bowel electric activity is a promising technique. Further studies are expected to demonstrate its potential for clinical applicability. It offers information comparable to that obtained by serosal electrodes and superior to the recordings of cutaneous electrodes. SQUID magnetometers may in fact offer the first reliable technique for noninvasive detection of the electrical activity of human small bowel.

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