

# Biomagnetic Techniques for Assessing Gastric and Small Bowel Electrical Activity

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**Abstract.** Recent advances in electrophysiology of the gastrointestinal tract have emphasized the need for methods of noninvasive assessment of gastric and small intestinal electrical activity (GEA and IEA). While the cutaneous electrogastrogram (EGG) may reveal the frequency dynamics of gastric electrical activity, other parameters important for characterizing the propagating electrical activity are not available from EGG recordings. Recent studies on the electroenterogram (EENG) are promising, but low-conductivity abdominal layers have complicated the identification of small intestinal electrical rhythms in cutaneous recordings. The magnetogastrogram (MGG) and magnetoenterogram (MENG) are able to characterize gastric and intestinal electrical activity noninvasively in terms of its frequency, power and characteristics of its propagation. Superconducting QUantum Interference Device (SQUID) magnetometers are used to detect the minute magnetic fields associated with electrical activity of the gastrointestinal syncytium formed by interstitial cells of Cajal and smooth muscle networks. Changes in GEA and IEA that occur in response to disease or abnormal conditions are reflected in MGG and MENG signals. Magnetic methods for assessing the electrical activity of the stomach and small bowel thus show great clinical promise.

## GASTROINTESTINAL ELECTRICAL ACTIVITY

Extracellular electrode recordings in the stomach and small bowel exhibit spontaneous, omnipresent rhythmic variation that depends on the location of the electrode. The slow wave, also known as electrical control activity or basic electrical rhythm, is present regardless of the contractile status of the tissue and modulates the appearance of smooth muscle contractions. Recently, the interstitial cells of Cajal (ICCs) located within the gastrointestinal musculature have been implicated as the originators and propagators of the slow wave [1-6]. ICC cells are connected by gap junctions to smooth muscle cells in the longitudinal and circular muscle layers, and the electrical activity propagates passively through these layers.

In the stomach, the slow wave originates at a location along the greater curvature and propagates nearly instantaneously around the circumference of the stomach. The slow wave then spreads aborally as a ring of depolarization at a velocity of about 11 mm/s in humans. The stomach's pacemaker generates a new slow wave as the previous one is terminating in the pylorus [7] at a frequency of about 3 cycles per minute (cpm).

The small intestine has several pacemaker regions. The proximal duodenum paces several cm of intestine at a frequency near 12 cpm, and each successively distal pacemaker runs at a slightly lower frequency.

The slow wave can be recorded using serosal electrodes. Cutaneous electrodes have been limited to the recording of frequency dynamics of the gastric slow wave in the electrogastrogram (EGG) [8], though efforts are underway to record the electroenterogram, the cutaneous signature of the intestinal slow wave [9-10]. Cutaneous electrical recordings are complicated by the volume conducting nature of the abdomen since the alternating high- and low-conductivity abdominal layers (muscle/fat/skin) distort and smear electric potentials [11].

The gastric and intestinal slow waves also produce magnetic fields that are not as affected by the conductivity ratios of abdominal tissue as electric potentials [11]. Gastric and intestinal magnetic fields are weak outside the body, typically in the range of 2-40 pT, but are detectable with Superconducting QUantum Interference Device (SQUID) magnetometers [12].

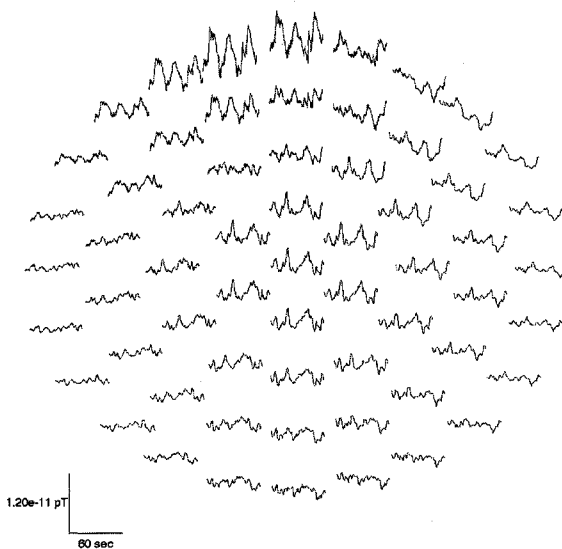
A SQUID magnetometer has been described as a magnetic-flux to voltage converter with unrivalled sensitivity [13]. Gastric and intestinal electrical activity may be measured by placing a SQUID near the abdomen of animal and human subjects [12, 14]. Multichannel SQUID magnetometers enable the characterization of spatial and temporal changes in the gastric and intestinal magnetic fields. In addition to the signal frequency, we can assess signal amplitude at multiple abdominal locations and investigate the propagation of electrical activity. All of these parameters are known to change in disease states like gastroparesis or mesenteric ischemia.

Gastroparesis results from the disruption of the normally well-coupled gastric syncytium. The normal 3 cpm propagating slow wave is altered with frequencies that might be either bradigastric (less than 2 cpm) or tachygastric (more than 4.5 cpm), and disrupted propagation resulted in delayed gastric emptying. The disease causes substantial pain, dangerous weight loss, and indigestion. Mesenteric ischemia causes an immediate decrease in the slow wave frequency, also occasionally accompanied by transient frequency increases. If mesenteric ischemia continues untreated, the resulting necrosis can be fatal. Thus, there is significant clinical interest in noninvasive techniques to assess the electrical activity of the stomach and small bowel.

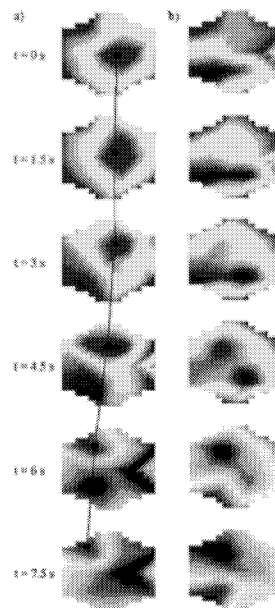
## **BIOMAGNETIC TECHNIQUES TO ASSESS NORMAL GEA**

The normal electrical activity of the stomach and small bowel is reflected in biomagnetic recordings. Figure 1 shows the magnetic fields recorded from a normal human subject using a multichannel magnetometer constructed by Biomagnetic Technologies, Inc. Signals from 61 normal-component detectors are displayed at their relative location. The upper part of the array exhibits the 3 cpm gastric slow wave while higher frequencies characteristic of intestinal slow waves are observed lower in the array. Frequency is an important indicator of

gastrointestinal electrical activity, and the frequency spectrum of the signals is nearly always computed as part of the analysis. Although Fast Fourier Transform is the most convenient and computationally efficient method for perform frequency analysis, we have used an autoregressive (AR) technique in situations where the signal stationarity was in question. The AR technique gives excellent frequency resolution [15]. These spectra can also be plotted at the detector locations to assess the spatial variation of GEA frequencies. We have used false-color plots of the frequency spectra in different frequency bands to visualize the aboral frequency gradient of the small bowel [16]. These plots could be quite useful to physicians interested in identifying the location of abnormal GEA frequencies typical of diseases like *mesenteric ischemia*.



**FIGURE 1.** Normal human gastric magnetic field data mapped to the coil location in a 61-channel biomagnetometer from Biomagnetic Technologies, Inc. Both gastric and intestinal slow waves are evident.

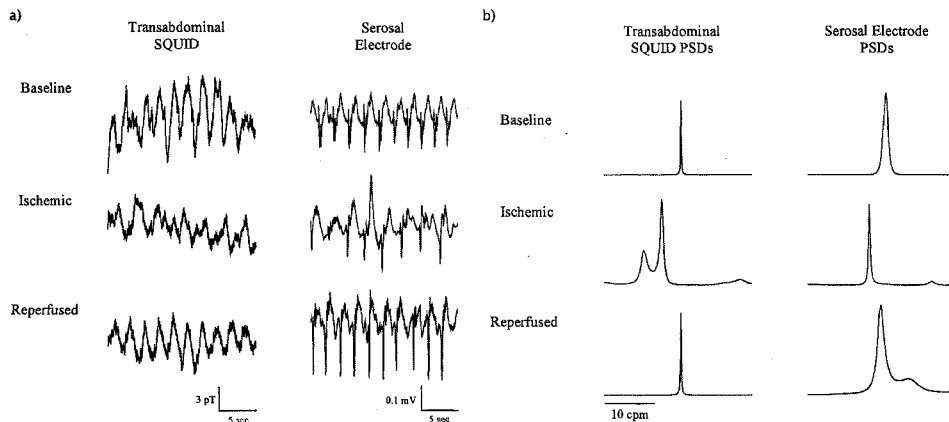


**FIGURE 2.** MGG data are represented as false-color maps at six successive time instants. In the first column, normal propagation is evident by the movement of the field maximum. In the second column propagation is disrupted by mechanical division of the stomach.

While spatiotemporal data mapping can often provide an excellent picture of the spatial variation of the signal and signal frequencies, we can also create false-color plots of the magnetic field data and observe their change over time. Figure 2a shows sequential false-color maps of the intensity of the magnetic field from a porcine subject. The signal maximum moves from the subject's right to left, consistent with

the aboral propagation of electrical activity. We can calculate the velocity of propagation by (1) computing the movement of the signal maximum or other signal characteristic, or (2) computing time lags from cross-correlation functions of the signals in two channels separate by a known distance. Preliminary results have shown that magnetic field propagation values obtained this way agree well with known propagation velocities [17].

The magnetic field is a vector quantity, and our studies have shown that additional information is present in the tangential components of the magnetic field [Unpublished data, 2003]. By projecting the magnetic field vector into different directions, we can focus on a particular feature of the signal or a particular signal frequency. We also showed that a single vector magnetometer was capable of reproducing electrical activity recorded by a 24-channel serosal electrode array with excellent fidelity [18]. Moreover, the magnetic field vector projection correlates to the direction of propagation of electrical activity the magnetic field is perpendicular to the direction of current.



**FIGURE 3.** Magnetic fields and serosal potentials are shown in (a) recorded from rabbit intestine during baseline, induced mesenteric ischemia, and reperfusion. The PSDs in (b) show that the slow wave frequency decreases during ischemia from 18 to 12 cpm and recovers to 15 cpm after reperfusion. Adapted from [14].

## BIOMAGNETIC TECHNIQUES TO ASSESS GEA DYSRHYTHMIAS

Alterations in the normal electrical activity of the stomach and small bowel are evident in SQUID recordings. Figure 2b shows the magnetic fields analyzed from recordings taken above a pig abdomen as in Figure 2a except that the stomach of the pig was mechanically divided. The well-defined propagation pattern is no longer apparent. Areas of activity continue to oscillate near the normal slow wave frequency, but any motion appears to be retrograde in nature. Frequency increases into tachygastric ranges were noted in this study. These maps are visualized much easier as

movies with sequential frames corresponding to successive time increments. Although the movies demonstrate the spatiotemporal response of the gastric magnetic fields to an abnormal condition such as mechanical uncoupling, they do not necessarily correspond with the actual electrical activity of the stomach, although in our case the propagation velocities we computed in the normal case were consistent with values obtained by other researchers [17].

Figure 3 shows the magnetic fields and serosal potentials that result from induced ischemia of a segment of the small bowel. In both the serosal electrode and in the transabdominal SQUID recording, the normal 18 cpm intestinal slow wave decreases to 12 cpm during ischemia and then recovers back to nearly 15 cpm after reperfusion of the bowel. AR power spectra confirm the changes in frequency (Figure 3b). We have also observed transient tachyarrhythmias associated with small bowel ischemia [19]. Presumably, these effects are caused by uncoupling of the syncytium formed by the ICC network as a result of the ischemic insult. Although further work is needed to verify such a hypothesis, these results suggest that multichannel magnetic studies may provide insight into the function and dysfunction of the ICC network.

Vector projections of the magnetic field are also useful in the identification of abnormal electrical activity. Previous studies showed that the vector projection closely reflected the frequency decrease during an episode of segmental ischemia while the normal component recording contained contributions from both normal and ischemic bowel [20]. Thus, the vector projection provides a substantial increase in the signal-to-noise ratio and aids in the discrimination of signals from multiple bowel sources. In another study, a single vector magnetometer produced projections that correlated highly with 24 gastric serosal electrodes and reflected spatiotemporal signal changes that occurred following a vagotomy [18]. This observation strongly suggests that additional information is available in the full vector recording of the gastrointestinal magnetic field as opposed to that available in any single component.

## FUTURE DIRECTIONS

The noninvasive assessment of functional activity in the stomach and bowel is clinically attractive. The ability of the biomagnetic method to identify spatiotemporal parameters of gastrointestinal electrical activity sets it apart as a unique means to obtain information otherwise available only through invasive diagnostic testing or surgery. Widespread implementation of this technique is limited because of the current cost of instrumentation and associated equipment, with multichannel magnetometers costing in the millions and with the current requirement for expensive magnetic shielding in hospital environments. Nonetheless, there is reason to be enthusiastic about future efforts with the decreasing price of SQUID electronics, the development of high-temperature superconductors and the introduction of new techniques for noise reduction that eliminates the need for shielding. In addition, efforts are underway to construct sophisticated, extensible and biophysically-realistic models of the GI system from the cellular ICC level to the systems level and to use these models to solve the inverse problem and determine the GI sources of the observed electromagnetic activity [21]. Results from our lab and others have convinced us of the inevitability of the

routine clinical use of biomagnetometers in the assessment of gastrointestinal electrical activity.

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