Published in final edited form as:

IEEE Trans Biomed Eng. 2013 June ; 60(6): 1677–1684. doi:10.1109/TBME.2013.2240454.

Noninvasive Biomagnetic Detection of Isolated Ischemic Bowel Segments

Suseela Somarajan,

Department of General Surgery and Physics & Astronomy, Vanderbilt University, Nashville, TN 37232 USA

Summer Cassilly,

Department of General Surgery, Vanderbilt University, Nashville, TN 37232 USA

Chibuikwe Obioha,

Department of General Surgery, Vanderbilt University, Nashville, TN 37232 USA

L. Alan Bradshaw, and

Department of General Surgery and Physics & Astronomy, Vanderbilt University and Department of Physics, Lipscomb University, Nashville, TN USA

William O. Richards

Department of Surgery, University of South Alabama, Mobile, AL USA

Suseela Somarajan: suseela.somarajan@vanderbilt.edu; Summer Cassilly: summer.cassilly@vanderbilt.edu; Chibuikwe Obioha: dr.obioha@vanderbilt.edu; L. Alan Bradshaw: alan.bradshaw@vanderbilt.edu; William O. Richards: brichards@usouthal.edu

Abstract

The slow wave activity was measured in the magnetoenterogram (MENG) of normal porcine subjects (N=5) with segmental intestinal ischemia. The correlation changes in enteric slow wave activity were determined in MENG and serosal electromyograms (EMG). MENG recordings show significant changes in the frequency and power distribution of enteric slow wave signals during segmental ischemia, and these changes agree with changes observed in the serosal EMG. There was a high degree of correlation between the frequency of the electrical activity recorded in MENG and in serosal EMG ($r=0.97$). The percentage of power distributed in brady- and normoenteric frequency ranges exhibited significant segmental ischemic changes. Our results suggest that noninvasive MENG detects ischemic changes in isolated small bowel segments.

Index Terms

electroenterogram; magnetoenterogram; slow wave; SQUID magnetometer

I. Introduction

The slow wave of the small intestine is generated and propagated by interstitial cells of Cajal (ICCs) located within the gastrointestinal musculature. ICCs are electrically coupled to circular and longitudinal muscle layers by gap junctions [1–4]. The small intestine exhibits a stepwise gradient in slow wave frequency from about 12 cycles per minute (cpm) in the normal human duodenum to between 9 and 11 cpm in the jejunum and around 8 cpm in the ileum [5, 6]. Disease states such as ischemia and motility disorders of the small bowel are known to alter the normal enteric slow wave activity [7, 8]. Most methods of studying enteric slow wave activity have relied upon invasive techniques which have involved placing electrodes on either the mucosal or the serosal surface of the small intestine [9]. The difficulties in gaining access to the digestive tract have limited the development of invasive

techniques for recording slow wave activity. For this reason, noninvasive methods for monitoring intestinal slow wave activity and detecting the early signs of ischemia, have garnered interest in recent years [10, 11].

The cutaneous electroenterogram (EENG) records the cutaneous potentials associated with intestinal slow waves. Distortion and attenuation from alternating low- and high-conductivity layers in the abdominal volume conductor reduces the signal-to-noise ratio which limits the potential use of cutaneous electrode recordings in clinical settings [12]. Chen et al. measured electrical activity of the human small intestine using cutaneous electrodes and noted a very low signal-to-noise ratio. The signal required extensive filtering to remove physiological interferences such as gastric signals and respiration artifacts [10, 13]. Moreover, the patients used in the study had jejunostomy feeding tubes placed, which would unnaturally improve the conduction pathway between the bioelectric intestinal source and the cutaneous electrode. Recently, Prats-Boluda and colleagues have proposed the use of Laplacian abdominal surface recording for the identification of slow wave components of the EENG, but it remains to be seen whether these techniques overcome the limitations associated with a high body mass index particularly since the Laplacian operator tends to exacerbate noise in high spatial frequencies [14, 15].

The magnetoenterogram (MENG) records the magnetic fields associated with intestinal electrical activity. Previous studies by several research groups have demonstrated that MENG overcomes many of the limitations of EENG [16–18]. MENG can differentiate physiological from non-physiological electrical activity [6], detect characteristics of slow wave propagation [19], identify uncoupling of the electrical syncytium [20] and distinguish spiking activity [21]. Studies in our laboratory have been the first to demonstrate the ability of MENG to detect changes in the slow wave frequency after the onset of global ischemia in animal models [11, 22]. To date, however, no studies have identified isolated ischemia in small bowel segments. We hypothesized that SQUID measurements of the intestinal magnetic field activity could distinguish segmental ischemia from normal activity. Furthermore, we expect that the ischemic changes in intestinal biomagnetic activity were similar to changes observed in serosal EMG. Clinical situations like strangulated segment of small bowel from internal hernias, volvulus or vascular occlusion are mimicked in this study design.

II. Procedure

A. Materials and Methods

All animal studies were reviewed and approved by the Vanderbilt Institutional Animal Care and Use Committee. Electrical potential and magnetic measurements were made simultaneously in adult pigs (N=5) with mean body weight of 36.8 ± 2 kg (mean $\pm$ standard deviation). We recorded serosal EMG using nonmagnetic silver electrode platforms and we measured MENG using the Tristan Model 637 Superconducting Quantum Interference Device (SQUID) magnetometer. The test subject was anesthetized and laparotomy was performed in order to place electrodes and snare suture, subsequently allowing induction of segmental ischemia on the small bowel. Ag/AgCl electrodes were sutured onto the serosal surface of the small intestine at the following sites: Platform I- four electrodes, located on the most distal portion of the segmental ischemic region in the jejunum (16" from the Ligament of Treitz); Platform II- four electrodes, located on the proximal segmental ischemic region of the jejunum (8" from the Ligament of Treitz); Platform III- four electrodes, placed at the Ligament of Treitz in the very proximal duodenum which is not ischemic; Platform IV- four electrodes, located on the distal ileum immediately proximal to the ileocecal junction and also not ischemic, and Platform V- sixteen electrodes, located directly in the middle of the segmental ischemic region in the jejunum (from 8" – 16" distal

to the Ligament of Treitz). We created mesenteric windows on the mesentery adjacent to the 8 inch bowel segment for the study and loosely placed a snare suture around the mesenteric vessels. We then closed the abdominal wound in layers.

To obtain biomagnetic recordings, the animals were placed underneath the SQUID magnetometer in a shielded room with the detection coils located directly above the serosal electrode platform. The SQUID has 19 normal-component sensors in a hexagonal, close-packed array that measure magnetic fields perpendicular to the body surface when a subject lies underneath the device. Ten additional sensors measure tangential components of the magnetic field at locations at the top, bottom, sides and in the middle of the normal-component sensor array. The SQUIDs convert magnetic flux into voltage signals, which are then amplified (Model 5000, Quantum Design), digitized, and stored on a PC. SQUID and electrode signals were time-synced during collection. Continuous recordings of electrical potentials and magnetic fields were obtained from the SQUID and the serosal electrodes. After baseline recordings were taken for 30 minutes, a second laparotomy was performed to permanently tighten the snare suture and induce segmental ischemia on the isolated small bowel segment. The abdominal incision was then closed in layers. We determined the length of ischemic bowel segment in these subjects by visual inspection. Minor variation in size of ischemic bowel segment between porcine subjects was not statistically significant ($p > 0.05$). All surgical procedures in this study were done by a trained surgeon who applied basic surgical techniques and principles to minimize tissue damage. The animals were studied for 60 minutes after induction of segmental ischemia in the jejunum, 8–16 inches from the Ligament of Treitz. Throughout the duration of the experiment, the respiration rate was held constant at 26 cpm using a mechanical ventilator. At several times during data collection, respiration was suspended to provide periods of reduced motion [19].

B. Data acquisition

Electrode signals were acquired at 256 Hz with the electrode amplifier and resampled to 30 Hz. SQUID signals were passed into a preamplifier stage (Model 5000, Quantum Design, San Diego) with a gain of 5 and a low-pass filter set to 1 kHz. Data were acquired at 3 kHz and subsequently down-sampled to 30 Hz. For all studies, the data acquired from 17 normal-component SQUID sensors were used; 2 sensors were not in service due to sensor malfunction.

C. Data analysis

All simultaneously recorded SQUID and serosal signals were subjected to spectral analysis. Recorded signals were loaded into MATLAB (Mathworks, Natick, MA, USA) and filtered using CWT (Continuous Wavelet Transform) digital filter based on Morlet wavelet with a bandpass of 9–120 cycles per minute (cpm). We computed power spectra using the Fast Fourier Transform. For SQUID signals, in addition to filtering, we also applied the Second-Order Blind Identification (SOBI) signal processing algorithm to reduce the interfering noise signals [6, 23]. After applying SOBI, primarily sinusoidal signals in the normal enteric frequency range (9 – 20 cpm) and artifact-related components were identified [6]. Enteric SOBI signals were reconstructed onto the sensor array, allowing us to localize enteric sources. The mean frequencies of both serosal EMG and MENG recordings were calculated during baseline and ischemic periods for each animal. The results are expressed as mean $\pm$ standard error of the mean (SEM). The paired Student's t test was used to compare baseline and ischemic frequencies. Statistical significance was set at $p < 0.05$. Correlation between the magnetic and electrical frequencies was determined by calculating the correlation coefficient (r) value. In addition, we determined the percentage of power distributed (PPD) in the power spectra in frequency ranges defined as bradyenteric (lower than two standard deviations from the mean baseline enteric frequency determined by serosal and magnetic

recordings) and tachyenteric (higher than two standard deviations from the mean baseline enteric frequency) [24].

III. RESULTS

Since respiration and other artifactual signals can dominate enteric signatures in the MENG, we used enteric SOBI components reconstructed to the sensor array to identify enteric slow waves, as outlined in figure 1 [6]. A typical bandpass filtered MENG signal during baseline is shown in figure 1a.1. SOBI components computed from the filtered MENG are shown in figure 1a.2 and the corresponding power spectra are shown in figure 1a.3. Figure 1a.4 represents the reconstructed power spectra which show how the MENG-SOBI components are distributed around the sensor array. The SOBI components used in the reconstruction are marked with *. Figure 1b.1- b.4 represents the CWT filtered MENG signals, MENG-SOBI components, MENG-SOBI frequency spectra and its reconstructed power spectra during ischemia. We used dominant frequencies from serosal potential measurements made from the five specific sites along the small intestine as a standard to validate the reconstructed SOBI-MENG components. The resulting reconstructed SOBI-MENG signals have peak frequencies characteristic of the frequency of serosal EMG recorded on bowel segments near each sensor. Based on the approximate location of the SQUID array in reference to the subject's anatomy, the central part of the SQUID array corresponded with jejunum, the upper part of the array to duodenum and the lower part of the sensor array to the ileum components.

A typical set of baseline CWT-filtered serosal EMG signals and power spectra obtained from each bowel section is shown in figure 2a. The dominant frequencies obtained by reconstructing enteric MENG-SOBI component on to the sensor array enable the identification of different small bowel sections, as shown in Fig. 2(b).

Baseline recording showed a consistent enteric slow wave frequency in duodenum, jejunum, and ileum in all five test subjects in both serosal and SQUID recordings. The jejunal slow wave frequency determined from SOBI-MENG decreased from 15.2 ± 0.4 cpm at baseline to 10.0 ± 0.2 cpm after 30 minutes of ischemia ($p < 0.001$), as illustrated in figure 3a. The slow wave recorded in serosal EMG decreased in frequency from a mean baseline value of 15.3 ± 0.6 cpm to 10.3 ± 0.2 cpm after 30 minutes of ischemia ($p < 0.001$), also shown in figure 3a. There was no difference between serosal EMG and MENG slow wave frequencies in baseline ($p = 0.53$) or ischemia ($p = 0.50$).

Figure 3b illustrates the serosal EMG and MENG recordings attributed to ileum and duodenum components at baseline and at different time points during ischemia. As expected, there was no significant difference in the ileal or duodenal frequency components before or after induction of ischemia. The mean slow wave frequency of the ileal component recorded in the serosal EMG was 10.2 ± 0.1 cpm in baseline and 10.3 ± 0.3 cpm after 30 minutes of ischemia ($p = 0.88$). For the MENG slow wave frequency, the ileal component was 10 ± 0.2 cpm in baseline and 10.3 ± 0.1 cpm after 30 minutes of ischemia ($p = 0.42$). There was no difference between serosal EMG and MENG slow wave frequencies in baseline ($p = 0.49$) or ischemia ($p = 0.96$). The mean slow wave frequency recorded in the non-ischemic duodenal serosal electrode was 15.7 ± 0.4 cpm at baseline and 16.3 ± 0.5 cpm after 30 minutes of ischemia ($p = 0.07$). The mean MENG slow wave frequency of the non-ischemic duodenal component was 15.0 ± 0.6 cpm in baseline and 15.9 ± 0.7 cpm after 30 minutes of ischemia ($p = 0.08$). There was no difference between serosal EMG and MENG slow wave frequencies in baseline ($p = 0.14$) or ischemia ($p = 0.29$).

Figure 4 plots the jejunal peak frequencies indicated by FFT analysis of 2-minute samples of serosal electrode data (EMG) against those determined by reconstructed MENG-SOBI components. The samples were taken during baseline and 30 minutes into ischemia. The SQUID magnetometer and the serosal electrodes detect the same dominant frequency; the correlation coefficient is 0.97.

The percent power distribution (PPD) in frequency ranges associated with normal slow waves, bradyenteria and tachyenteria may indicate functional changes in the enteric slow wave. In this study, bradyenteric PPD for jejunum component increased significantly during ischemia in both serosal EMG ($p < 0.001$) and MENG ($p < 0.01$). Both MENG and EMG recordings have significantly less power in the normal frequency range during ischemia ($p < 0.01$ for MENG; $p < 0.001$ for EMG). There was no significant change in power at tachyenteric frequencies ($p = 0.33$ for MENG; $p = 0.43$ for EMG) during ischemia, as seen in figure 5.

IV. DISCUSSION AND CONCLUSIONS

Our research group first recorded MENG from the intestinal slow waves in animals [25, 26] and subsequently in human subjects [27]. Unlike serosal EMG, which measures the electrical activity at a specific location, MENG using SQUID magnetometers detect and differentiate magnetic signals from different areas of the abdominal cavity. Our group has investigated the effect of ischemia on small bowel electrical activity using non-invasive biomagnetic techniques [28–31]. Frequency, amplitude and propagation velocity of the intestinal slow waves were observed to decrease during ischemia [32]. These studies demonstrated that intestinal ischemia may be detected noninvasively at an early stage using MENG measurements. Although intensive research effort has been directed on non-invasive detection of ischemic bowel, identification of isolated ischemic bowel segments has not been previously reported.

The ability of SQUID to spatially identify slow wave activity of the stomach and different parts of the small intestine is instrumental in identifying these ischemic bowel segments while simultaneously detecting normal bowel magnetic fields. In our previous studies, Siedel, et al. utilized approximately 47 inches of the free-lying small bowel in the rabbit model to detect global mesenteric ischemia by ligating the superior mesenteric artery [29]. The present study demonstrates the first noninvasive detection of an isolated ischemic bowel segment of approximately 8 inches in the swine model. We detected significant decreases in slow wave frequency with MENG channels directly above the affected segment that were highly correlated with similar changes in serosal EMG.

Previous studies in our lab showed that the 8-element noise array in the Tristan 637 magnetometer were insufficient for separating and classifying signals from distinct intestinal sources in raw magnetic field data [9]. In order to identify segments of ischemic bowel, our studies utilized CWT-filtered and SOBI-separated MENG signals. We found that Second Order Blind Identification (SOBI), a blind source separation technique, allowed the separation and identification of enteric slow wave signals from noisy, artifact-contaminated SQUID measurements [6], and to identify ischemic and normal intestinal slow wave components from raw or filtered SQUID data. We select SOBI components to retain or to eliminate based on frequency content and signal periodicity, and reconstruct the noise-reduced SQUID signal at each sensor location. This spatial reconstruction of SOBI components allows us to distinguish normal and ischemic bowel segments. We conclude that the use of SOBI to isolate noise from intestinal signals and to separate normal from ischemic signals is the most useful signal processing technique for identification of pathologic intestinal magnetic fields to date in our investigation of this diagnostic modality.

A previous study by Tang et al. used SOBI to identify and localize neuronal sources using MEG (magnetoencephalography) components [33]. In our study, the spatial distribution of the coils and the use of SOBI allowed us to detect the normal duodenum, ischemic jejunum and normal ileum. Since normal ileum and ischemic jejunum components are in approximately the same frequency range, the selection of appropriate sensors in the magnetometer array is critical for the identification of these components. Central array channels exactly above platform V were used to identify the jejunal components. In all five animal models we observed magnetic field baseline changes in response to segmental ischemia in the central array sensors. The lower array sensors record exactly the same ileal frequency before and during ischemia. However, the overlap in frequency observed could lead to the incorrect identification of closely-apposed normal bowel as ischemic, suggesting that concomitant structural studies may be necessary.

Our study demonstrated a strong correlation between the enteric slow wave frequency determined by invasive serosal electrodes and those recorded by non-invasive SQUID magnetometer. We observed a significant increase in the percentage of power distributed in bradyenteric frequencies in both serosal and MENG recordings during ischemia. Bradshaw et al. observed a similar PPD effect in uncoupled gastric musculature [20]. A previous study by Seidel et.al reported the detection of intestinal tachyarrhythmias during small bowel ischemia in rabbit models using serosal EMG recordings [34]. In our study, in addition to our analysis in the normal enteric frequency range, we also analyzed higher frequencies (between 20 and 60 cpm) to identify tachyarrhythmias during segmental ischemia. Interestingly, we did not observed changes in tachyenteric signals during ischemia in porcine subjects in either serosal or MENG recordings.

Our findings suggest that noninvasive MENG can identify signatures of isolated ischemia in bowel segments as small as 8 inches in length with surrounding normal bowel. These magnetic signatures agree with serosal electrode recordings.

With respect to clinical application, the relative mobility of intestinal loops and its mesentery in the abdominal cavity of most human provide a significant challenge due to lack of fixed spatial location maps. However, we believe that we can create and average the distribution of normal small intestinal slow wave signal characteristics at anatomic fixed points of human intestine like ligament of Treitz and ileocecal junction. We can compare against these values to determine, diagnostic signature of intestinal ischemia in suspected individuals. We will continue to investigate the application of SOBI and other related noise-reduction techniques to localize ischemic bowel for early noninvasive detection of this life-threatening disease.

Acknowledgments

The authors greatly appreciate the assistance of the staff of Light Lab Surgical Research Center, Vanderbilt University. We gratefully acknowledge the work of Dr. J. Erickson who developed the SOBI algorithm for the analysis of gastrointestinal slow wave activity. The authors would also like to thank N. Muszynski for editorial assistance.

Funding for this study was provided by grants from the National Institute of Health (R01 DK58697, R01 DK58197 and R01 DK064775).

References

1. Langton P, Ward SM, Carl A, et al. Spontaneous Electrical-Activity of Interstitial-Cells of Cajal Isolated from Canine Proximal Colon. *Proceedings of the National Academy of Sciences of the United States of America*. Sep; 1989 86(18):7280–7284. [PubMed: 2550938]

2. Horowitz B, Ward SM, Sanders KM. Cellular and molecular basis for electrical rhythmicity in gastrointestinal muscles. *Annual Review of Physiology*. 1999; 61:19–43.
3. Sanders KM, Koh SD, Ward SM. Interstitial cells of Cajal as pacemakers in the gastrointestinal tract. *Annual Review of Physiology*. 2006; 68:307–343.
4. Thuneberg L. Interstitial-Cells of Cajal - Intestinal Pacemaker Cells. *Advances in Anatomy Embryology and Cell Biology*. 1982; 71:1–130.
5. Christen J, Schedl HP, Clifton JA. Small Intestinal Basic Electrical Rhythm (Slow Wave) Frequency Gradient in Normal Men and in Patients with a Variety of Diseases. *Gastroenterology*. 1966; 50(3): 309. [PubMed: 5905350]
6. Erickson JC, Obioha C, Goodale A, et al. Detection of Small Bowel Slow-Wave Frequencies From Noninvasive Biomagnetic Measurements. *Ieee Transactions on Biomedical Engineering*. Sep; 2009 56(9):2181–2189. [PubMed: 19497806]
7. Cabot RM, Kohatsu S. Effects of Ischemia on Electrical and Contractile Activities of Canine Small-Intestine. *American Journal of Surgery*. 1978; 136(2):242–246. [PubMed: 686270]
8. Leahy A, Besherdas K, Clayman C, et al. Abnormalities of the electrogastrogram in functional gastrointestinal disorders. *American Journal of Gastroenterology*. Apr; 1999 94(4):1023–1028. [PubMed: 10201477]
9. Bradshaw LA, Allos SH, Wikswo JP, et al. Correlation and comparison of magnetic and electric detection of small intestinal electrical activity. *American Journal of Physiology-Gastrointestinal and Liver Physiology*. May; 1997 272(5):G1159–G1167.
10. Chen JD, Schirmer BD, Mccallum RW. Measurement of Electrical-Activity of the Human Small-Intestine Using Surface Electrodes. *Ieee Transactions on Biomedical Engineering*. Jun; 1993 40(6):598–602. [PubMed: 8262544]
11. Golzarian J, Staton DJ, Wikswo JP, et al. Diagnosing Intestinal Ischemia Using a Noncontact Superconducting Quantum Interference Device. *American Journal of Surgery*. Jun; 1994 167(6): 586–592. [PubMed: 8209933]
12. Bradshaw LA, Richards WO, Wikswo JP. Volume conductor effects on the spatial resolution of magnetic fields and electric potentials from gastrointestinal electrical activity. *Medical & Biological Engineering & Computing*. Jan; 2001 39(1):35–43. [PubMed: 11214271]
13. Lin ZY, Chen JDZ. Recursive Running Dct Algorithm and Its Application in Adaptive Filtering of Surface Electrical Recording of Small-Intestine. *Medical & Biological Engineering & Computing*. May; 1994 32(3):317–322. [PubMed: 7934257]
14. Bradshaw LA, Wikswo JP. Spatial filter approach for evaluation of the surface Laplacian of the electroencephalogram and magnetoencephalogram. *Annals of Biomedical Engineering*. Mar; 2001 29(3):202–213. [PubMed: 11310782]
15. Prats-Boluda G, Garcia-Casado J, Martinez-De-Juan JL, et al. Identification of the slow wave component of the electroenterogram from Laplacian abdominal surface recordings in humans. *Physiological Measurement*. Sep; 2007 28(9):1115–1133. [PubMed: 17827658]
16. Allescher HD, Abraham-Fuchs K, Dunkel RE, et al. Biomagnetic 3-dimensional spatial and temporal characterization of electrical activity of human stomach. *Digestive Diseases and Sciences*. Apr; 1998 43(4):683–693. [PubMed: 9558020]
17. Buist ML, Cheng LK, Yassi R, et al. An anatomical model of the gastric system for producing bioelectric and biomagnetic fields. *Physiological Measurement*. Aug; 2004 25(4):849–861. [PubMed: 15382826]
18. Estombelo-Montesco CA, de Araujo DB, Silva ACR, et al. Dependent component analysis for the magnetogastrographic detection of human electrical response activity. *Physiological Measurement*. Sep; 2007 28(9):1029–1044. [PubMed: 17827651]
19. Bradshaw LA, Irimia A, Sims JA, et al. Biomagnetic characterization of spatiotemporal parameters of the gastric slow wave. *Neurogastroenterology and Motility*. Aug; 2006 18(8):619–631. [PubMed: 16918726]
20. Bradshaw LA, Irimia A, Sims JA, et al. Biomagnetic signatures of uncoupled gastric musculature. *Neurogastroenterology and Motility*. Jul; 2009 21(7):778–E50. [PubMed: 19222760]

21. Irimia A, Richards WO, Bradshaw LA. Magnetogastrographic detection of gastric electrical response activity in humans. *Physics in Medicine and Biology*. Mar 7; 2006 51(5):1347–1360. [PubMed: 16481699]
22. Richards WO, Garrard CL, Allos SH, et al. Noninvasive Diagnosis of Mesenteric Ischemia Using a Squid Magnetometer. *Annals of Surgery*. Jun; 1995 221(6):696–705. [PubMed: 7794074]
23. Belouchrani A, AbedMeraim K, Cardoso JF, et al. A blind source separation technique using second-order statistics. *Ieee Transactions on Signal Processing*. Feb; 1997 45(2):434–444.
24. Bradshaw LA, Sims JA, Richards WO. Noninvasive assessment of the effects of glucagon on the gastric slow wave. *American Journal of Physiology-Gastrointestinal and Liver Physiology*. Nov; 2007 293(5):G1029–G1038. [PubMed: 17884978]
25. Staton DJ, Soteriou MC, Friedman RN, et al. First magnetic measurements of smooth muscle in vitro using a high-resolution DC-SQUID magnetometer. *Proceedings in 13th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 1991; 13(2):550–551.
26. Golzarian J, Staton D, Wikswo JP, et al. 1st Biomagnetic Measurements of Intestinal Basic Electrical Rhythms (Ber) In vivo Using a High-Resolution Magnetometer. *Gastroenterology*. Oct; 1992 103(4):1385–1385.
27. Richards WO, Bradshaw LA, Staton DJ, et al. Magnetoenterography (MENG) - Noninvasive measurement of bioelectric activity in human small intestine. *Digestive Diseases and Sciences*. Dec; 1996 41(12):2293–2301. [PubMed: 9011432]
28. Allos SH, Staton DJ, Bradshaw LA, et al. Superconducting quantum interference device magnetometer for diagnosis of ischemia caused by mesenteric venous thrombosis. *World Journal of Surgery*. Feb; 1997 21(2):173–7. discussion 177–8. [PubMed: 8995074]
29. Seidel SA, Bradshaw LA, Ladipo JK, et al. Noninvasive detection of ischemic bowel. *Journal of Vascular Surgery*. Aug; 1999 30(2):309–319. [PubMed: 10436451]
30. Hegde SS, Seidel SA, Ladipo JK, et al. Effects of mesenteric ischemia and reperfusion on small bowel electrical activity. *J Surg Res*. Jan; 1998 74(1):86–95. [PubMed: 9536980]
31. Goodale A, Obioha CB, Erickson J, et al. Partial mesenteric ischemia alters biomagnetic slow wave. *Gastroenterology*. Apr; 2008 134(4):A673–A673.
32. Garrard CL, Wikswo JP, Staton D, et al. Noninvasive Measurements of Small-Bowel Electrical-Activity. *Gastroenterology*. Apr; 1994 106(4):A502–A502.
33. Tang AC, Pearlmutter BA, Malaszenko NA, et al. Independent components of magnetoencephalography: Localization. *Neural Computation*. Aug; 2002 14(8):1827–1858. [PubMed: 12180404]
34. Seidel SA, Hegde SS, Bradshaw LA, et al. Intestinal tachyarrhythmias during small bowel ischemia. *American Journal of Physiology-Gastrointestinal and Liver Physiology*. Nov; 1999 277(5):G993–G999.

Figure 1.

Figure 1: a.1) CWT-filtered MEG signals from 17 sensors during baseline period, a.2–a.3) MEG-SOBI components and its corresponding power spectra, a.4) Reconstructed power spectra showing how the MEG-SOBI components are distributed around the sensor array. (The SOBI components used in the reconstruction are marked with *).

Figure 1: b.1) CWT-filtered MEG signals during ischemia, b.2–b.3) MEG-SOBI components and its corresponding power spectra, b.4) Reconstructed power spectra showing how the MEG-SOBI components are distributed around the sensor array.

Figure 2.

Figure 2a: Representative baseline serosal electrode recordings made simultaneously from various sites along the small bowel (top row). Signals are CWT-filtered in the band 9–120 cpm. Corresponding power spectra (bottom row). The dominant frequencies of duodenum, jejunum and ileum components were 16, 15.7 and 10.5 cpm respectively.

Figure 2b: Reconstructed MENG-SOBI components (top row) and its corresponding frequency spectra (bottom row). The dominant frequencies of duodenum, jejunum and ileum components were identified as 16, 15.8 and 9.4 cpm respectively.

Figure 3.

Enteric slow wave frequency (mean $\pm$ SE) determined by MENG and serosal EMG in five porcine subjects before and during segmental ischemia. (a) Dominant frequencies of EMG and MENG-SOBI components in jejunum show a distinct decrease during ischemia. (b) EMG and MENG-SOBI components in non-ischemic ileum and duodenum did not exhibit a significant difference in dominant frequency before or during ischemia.

Figure 4.

Correlation between enteric slow wave frequencies recorded by serosal EMG to those recorded by SOBI-MENG. The peak frequencies are strongly correlated (correlation coefficient, $r = 0.97$). A linear fit to the data is also shown to emphasize the degree of correlation.

Figure 5. Percent power distributed (PPD) in brady-, normo- and tachyenteric frequency ranges for ischemic jejunum for (a) serosal EMG recording and (b) MENG recordings.