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Comparison and Analysis of Inter-Subject Variability of Simulated Magnetic Activity Generated from Gastric Electrical Activity

Rie Komuro¹, Leo K. Cheng¹, and Andrew J. Pullan^{1,2}

¹Bioengineering Institute, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand ²Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

Abstract

Electrogastrograms (EGGs) produced from gastric electrical activity (GEA) are used as a non-invasive method to aid in the assessment of a subject's gastric condition. It has been documented that recordings of the magnetic activity generated from GEA are more reliable. Typically, with magnetic measurements of GEA, only activity perpendicular to the body is recorded. Also, external anatomical landmarks are used to position the magnetic recording devices, SQUIDS, (Superconducting Quantum Interference Devices) over the stomach with no allowance made for body habitus. In the work presented here, GEA and its corresponding magnetic activity are simulated. Using these data, we investigate the effects of using a standard SQUID location as well as a customized SQUID position and the contribution the magnetic component perpendicular to the body makes to the magnetic field. We also explore the effects of the stomach wall thickness on the resultant magnetic fields. The simulated results show that the thicker the wall, the larger the magnitude of the magnetic field holding the same signal patterns. We conclude that most of the magnetic activity arising from GEA occurs in a plane parallel to the anterior body. We also conclude that using a standard SQUID position can be suboptimal.

Keywords

Electrogastrogram; Magnetogastrogram; Magnetic field; SQUID

INTRODUCTION

A survey made by the National Institute of Diabetes and Digestive and Kidney Diseases in 1996 estimated that 60 to 70 million people were affected by digestive diseases in the United States.¹ Extensive efforts are thus being made to develop reliable methods to diagnose such diseases including investigating non-invasive options.

For the last few decades, the study of electrical activity of the stomach recorded on the body surface (the EGG) has progressed, and the EGG is now used, albeit infrequently, to provide insight into the functioning of a subject's stomach. However, there are some difficulties with recording and interpreting the EGG because of the fact that recordings can suffer from

interference due to respiration, skeletal muscle activity, and electrical activity from the other organs such as the heart.^{10,15,18}

The magnetic field (MF) generated from gastric electrical activity (GEA) is also considered to be informative. It has been shown that magnetic activity generated from GEA can be reliably recorded by a Superconducting Quantum Interference Device (SQUID).^{4,18,19} During a recording, the SQUID does not directly contact the subject, and the results are considered to be more reliable than electrical recordings made with cutaneous electrodes.

Most multichannel SQUID recordings of GEA activity are obtained and/or analyzed in the direction perpendicular to the anterior body. In Bradshaw et al.,⁵ single site recordings of the three components of the MF vector have been made. The SQUID was moved to nine locations around the expected stomach location to obtain a complete map of MGG generated from GEA. The results were presented only for the plane parallel to the anterior body based on their assumption that the most of the MGG occurs in the plane.

To record magnetic activity arising from GEA, SQUIDs are typically positioned just above a subject lying in the supine position. Such SQUIDs are usually positioned over a subject without specific knowledge of the subject's stomach location or specific anatomy. Due to the variability of the stomach position within a torso, such positioning may not yield the optimal recording location. Furthermore, the SQUIDs, by their design, usually sample the 3D magnetic field only in the direction perpendicular to the subject. For these subjects, the importance of the activity in the other directions is, however, unknown. The SQUID described in Bradshaw et al.,⁴ the most frequently used SQUID for magnetic recordings of GEA, has channels at nineteen different locations. At five of the positions the SQUID is able to measure a three-component vector field, while only a single component can be measured at the remaining 14 positions.

To improve our understanding of the relationship between GEA and MGGs, we carefully analyzed detailed simulation results of the MF arising from GEA to determine (i) whether the magnetic activity in the direction perpendicular to the anterior body provides a good representation of the full 3D GEA magnetic field and (ii) how sensitive the recorded data are to the SQUID location. In addition to these issues, the effects of the stomach wall thickness on the simulated MF were investigated.

MODEL CONSTRUCTION AND METHODS FOR SIMULATION

Using our in-house software CMISS (<http://www.cmiss.org/>), magnetic activity was simulated using three different anatomically realistic stomach and torso models. These models were constructed from CT images of three male volunteers (37 ± 7 years) and are termed Subjects A, B, and C. Subjects underwent a 4-h fast prior to SQUID recordings and then were fed a standard 300 kcal meal. Following a further set of SQUID recordings, sixteen ounces of oral contrast (containing 10 g hypaque sodium powder, Amersham Health) was ingested over a 1-h period prior to the imaging to enhance appearance of the stomach in the CT images. For the work presented here, only the CT images were required.

In order to construct the stomach and torso models for each subject, first, the CT images were digitized, and an initial linear model constructed. A bicubic Hermite C^1 surface mesh was then created from the digitized data using iterative fitting procedure that minimized the distance between the data points and model.^{3,17} The fitted surface mesh was then uniformly extruded inward by 2.66 mm to represent the serosal wall of the stomach. This thickness was an average value derived from the literatures.^{12,13} The wall was then divided into five layers to represent the alternating smooth muscle and layers of interstitial cells of Cajal (ICC). A high resolution trilinear finite element mesh was then embedded within the elements of the geometric mesh^{9,16} to create computational points at the element vertices. Normal GEA was simulated for each of the stomach models by solving the monodomain equation:

$$\nabla \cdot (\sigma \nabla V_m) = A_m \left(C_m \frac{\partial v_m}{\partial t} + I_{ion} \right), \quad (1)$$

where σ is the tissue conductivity, V_m is the transmembrane potential, A_m is the surface to volume ratio of the membrane, C_m is the membrane capacitance, I_{ion} is the sum of all ionic currents that are calculated from the cellular models, and t is time. The Aliev cell model² was used to represent the I_{ion} term. The following are the cellular equations of the Aliev model for the normalized transmembrane potential u and slow current v :

$$\frac{du}{dt} = ku(u - a)(1 - u) - v, \quad (2)$$

$$\frac{dv}{dt} = \varepsilon \{ \gamma(u - \beta) - v \}, \quad (3)$$

where k is the maximum membrane conductance, a is the normalized threshold potential, ε controls the excitability of the system, γ is the recovery rate constant, and β is used to shift the cellular equilibrium from an excitatory to an oscillatory state.^{7,11}

Using the simulated GEA, we computed the magnetic activity external to the torso at nineteen positions.⁸ First, multiple temporally and spatially varying dipoles were calculated during the GEA simulation. The equivalent dipole sources are calculated from:

$$\mathbf{J} = -\sigma \cdot \nabla V_m, \quad (4)$$

The dipole sources were then used to compute the magnetic fields that corresponds to the locations of the SQUID channels presented in Bradshaw et al.⁴ and utilized to record MGGs at Vanderbilt University. The three principal directions of the coordinate system used herein are subject's right-to-left (x), front-to-back (y), and bottom-to-top (z) of the torso (Fig. 1). The names and locations of the channels of the MGG SQUID at Vanderbilt University are shown in Fig. 2.

SIMULATION OF MAGNETIC ACTIVITY GENERATED FROM NORMAL GEA

The torso and stomach geometries constructed from the CT images for each of the three subjects are shown in Fig. 3. The torso geometries were fitted with a root mean square

(RMS) error of 1.1 ± 0.3 mm while the stomachs had an RMS error of 0.9 ± 0.3 mm. Each subject-specific stomach model had a total of 432 nodes, 320 elements, and 245,784 grid points. The average grid spacing over the three subjects varied from 0.668 to 1.128 mm. Normal GEA was simulated for 200 s for each of the three models. A single simulated slow wave cycle for each subject is shown in Fig. 3.

A total of 320 temporally and spatially varying dipoles were then used to represent the GEA, and these were employed to compute electrical potentials on the body surface and magnetic fields at the SQUID channel locations.

Effect of SQUID Location

For each torso geometry, we calculated magnetic fields at two different SQUID locations. In the first set of results, the SQUID was positioned according to the recording protocols used at Vanderbilt University,^{6,14} which involves using fixed external anatomical markers. This SQUID location is termed the *Standard SQUID Location* in what follows. The second location was chosen to cover the entire stomach given a prior knowledge of the stomach position. This is termed the *Customized SQUID Location*. It is worth noting that, in practice, the Standard SQUID Location is used because the stomach location with the torso is typically not known *a priori*.

Standard SQUID Location

In our models, the position of the Standard SQUID Location was determined relative to the xiphoid as per the method used at Vanderbilt University with human subjects. When the MGG is recorded at Vanderbilt University, the operators position the SQUID over the location believed to correspond to the center of the stomach. The Standard SQUID Location was then determined from an average of five experiment subjects; the center of the SQUID was placed as close as possible to the body in the y-direction and 60 mm and -46 mm in the x and z-directions away from the xiphoid, respectively, i.e., 60 mm to the subject's right and 46 mm toward the feet. The standard SQUID locations of the corresponding stomach models for Subjects A, B, and C are shown in the left column of Fig. 4.

During the simulations, the MF at the nineteen SQUID channels was computed. The right column in Fig. 4 shows the MF for the three components for each geometry using the Standard SQUID Location for one slow wave. The range of the MF was between -0.023 and 0.034 pT for the x component, -0.015 and 0.019 pT for the y component, and -0.039 and 0.033 pT for the z component. As shown in the graphs, most of the MF in the y-direction, which is generally the only direction recorded in practice, was much weaker when compared to the other two components. This is true even when the channel was located directly over the stomach; for example, channel 33 for Subjects B and C (Fig. 4).

There was also some variation in the phase of the x and z components of MF between the subjects. For Subjects A and C, there was a half cycle difference between the x and z components at the channels where a strong MF was recorded (e.g., channel 9). On the other hand, for Subject B, the difference was much less, for instance, channel 9. These differences occurred due to the shape and orientation of the stomachs with their respective torsos.

Customized SQUID Location

Magnetic activity was also simulated using the Customized SQUID Location. The left column in Fig. 5 shows where the SQUID was located for each subject. The SQUID location was chosen so that the center of each stomach was located close to the center of the SQUID and the entire stomach was covered by the SQUID channels. The MF for each of the three subjects is shown in the right column of Fig. 5.

For Subjects A and C, the Standard and Customized SQUID Locations were very similar. However, for Subject B, the Customized SQUID Location was approximately 56 mm lower in the z -direction than the Standard SQUID location. This means that the stomach of Subject B was located further below the xiphoid when compared to the other two subjects.

As was shown with the Standard SQUID Location, the MF in the y -direction was much weaker than those in the other directions calculated using the Customized SQUID Location. The range of the MF was between -0.023 and 0.040 pT for the x component, -0.016 and 0.020 pT for the y component, and -0.036 and 0.034 pT for the z component.

Effect of Inter-Subject Variability

Figure 6 shows the magnetic activity at the nineteen SQUID channels for one slow wave with the Customized SQUID Location. The direction of the magnetic field at each channel is denoted by the direction of the arrow, and the magnitudes are given by the length of the arrow. At each time instance, a “dominant” direction can be calculated. In order to determine this over time and space, the average MF for the nineteen channels was calculated at each second using the method below.

Let $\mathbf{C}_{it}$ and $\mathbf{B}_{it}$ be the center and vector of the MF for channel i at time t , respectively. Then the average center $\overline{\mathbf{C}}_t$ and average vector $\overline{\mathbf{B}}_t$ of the MF at time t are defined as:

$$\overline{\mathbf{B}}_t = \frac{\mathbf{B}_{1t} + \mathbf{B}_{2t} + \cdots + \mathbf{B}_{ct}}{c},$$

and

$$\overline{\mathbf{C}}_t = w_{1t} \cdot \mathbf{C}_{1t} + w_{2t} \cdot \mathbf{C}_{2t} + \cdots + w_{ct} \cdot \mathbf{C}_{ct}$$

with $w_{it} = \frac{\|\mathbf{B}_{it}\|_2}{\sum_{j=1}^c \|\mathbf{B}_{jt}\|_2}$, where c is the number of channels, and $\|\cdot\|_2$ is the Euclidean norm.

To generate the averaged activity, the length of the vector was taken to be proportional to the vectors, and the center was defined by a weighted sum of the centers for all the channels, where the weight w_{it} is proportional to the magnitude, and the sum of all weights is 1. An example of this averaged activity is shown by the arrow in Fig. 7.

In order to investigate the relative importance of the magnetic activity in the direction perpendicular to the anterior body, we plotted the angle of the average MF to each of the

three directions for the three subjects with the two SQUID locations (Fig. 8). The plane of the SQUID channels and the y component of the average MF were almost always orthogonal. This means that the magnetic activity occurred primarily in the plane perpendicular to the recording direction for both the Customized and Standard SQUID Locations.

The individual channel traces of the MF in Figs. 4 and 5 showed a phase shift for the x and z components of the MGG. To determine why the shift was smaller for Subject B, we analyzed the MF in the x-z plane. Figure 9 shows the trajectory of the terminal point of the MF vector at channel 33 for one slow wave with the Customized SQUID Location for all the three subjects. While the terminal point traced clockwise for Subject A, it ran counterclockwise for Subjects B and C. The direction of rotation matched that of the dipole on the stomach.

The track for Subject B encircled a much larger area than those for Subjects A and C. Since the magnetic field is perpendicular to the electrical current, the larger the area surrounded by the trajectory, the larger the y component of the electrical current. The stomach of Subject B is oriented more in the coronal plane than those of Subjects A and C, and therefore we expect that the y component of the electrical current at channel 33 for Subject B to be larger than those for Subjects A and C. This provides an explanation why the phase shift was smaller between the MF in the x and z-directions at some channels for Subject B.

Effect of Thickness on Stomach Wall

The results shown up to this point have used a constant stomach wall thickness of 2.66 mm. As mentioned previously, this figure was obtained as average value derived from the literatures. The thickness of human stomachs *in vivo* has been examined by Henry et al.¹² and Huh et al.¹³ For measurements, they used CT and endoscopic ultrasound, respectively, and five or six points were selected at each of multiple transverse slices of the stomach. From their data, they determined the total stomach wall thickness to be 2.35–5.43 mm. This thickness included both the serosal and mucosal surfaces. Huh et al.¹³ also determined the average mucosa thickness and the average wall thickness as 3.92 ± 0.16 mm and 1.26 ± 0.07 mm, respectively (mean $\pm$ standard deviation). Thus the electrically active part of the stomach wall is expected to vary between 2.43 and 2.89 mm.

To investigate the effect stomach wall thickness has on the MF, we increased the thickness for Subject A to extreme values of 4 and 5 mm and computed the MFs. Figure 10 shows the MF for the three components at three selected channels, which have strong MFs. The results illustrate that the thicker the stomach wall, the larger the magnitude of the MF. The maximum percentage difference between the MFs of the stomach with thickness 2.66 and 4 or 5 mm was as follows:

	x component	y component	z component
4 mm	1.09 ± 0.60	0.66 ± 0.42	0.64 ± 0.25

	x component	y component	z component
5 mm	1.67 ± 0.72	1.14 ± 0.44	1.02 ± 0.33

DISCUSSION

We have used three anatomically realistic models to simulate gastric electrical activity. This electrical activity has then be used to compute the magnetic fields near the body surface. The magnetic fields have been calculated at a standard location relative to the xiphoid and a customized location which was established using *a priori* knowledge about the stomach location.

SQUID technology is still an emerging field, and techniques to best utilize this technology are being continually developed. Our simulations should help to improve the understanding of what is measured by the SQUID when recording MGGs. The simulations have allowed us to examine the effects of the channel locations free from other artifacts such as cardiac activity, respiration artifacts, and background noise. The simulations have also allowed magnetic fields to be calculated for all three components at any location—something that is not widely recorded with existing SQUIDS used in MGG measurements.

There have been a number of assumptions made in our computational model, and these should be kept in mind when examining the results. For example, the thickness of the stomach was assumed to be a constant, and our stomach model was made up of five idealized layers. The torso model used here was homogeneous, and all the internal organs apart from the stomach were assumed to have the same electrical properties. The electrical activity of the smooth muscle and ICCs was represented using a relatively simplistic modified FitzHugh-Nagumo model, and we have assumed that the dipole sources provide an accurate representation of the underlying GEA. Despite these assumptions, we believe that the key results presented here reflect reality.

Using our simulations, we have illustrated the effect the SQUID location has on the resulting MF for each component. Specifically, we have shown that y component of the MF is much smaller than the components in *x* and *z*-directions and is the most sensitive. This result supports the analysis in Bradshaw et al.,⁵ where only the results on *x*–*z* plane were analyzed. For each SQUID location, we picked a channel that was located at a similar position relative to the stomach so that we could compare similar recordings of the MF. Since the Standard and Customized SQUID Locations were similar for Subjects A and C, channel 33 was picked for these two subjects for both locations. For Subject B, from Figs. 4 and 5, channel 35 with the Customized SQUID Location was around the same location relative to the stomach as channel 5 was with the Standard SQUID Location, so those two channels were selected for Subject B. To further investigate how the MF is affected by the two different SQUID recording locations, we computed the normalized difference between two similar recording locations, using the formula below. For each component *x*, *y*, *z* at time *t* ($t_1 - t_2$):

$$\frac{|B_{xt}^{cust} - B_{xt}^{std}|}{\max_{t_1 \leq t \leq t_2} |B_{xt}^{cust}|}, \frac{|B_{yt}^{cust} - B_{yt}^{std}|}{\max_{t_1 \leq t \leq t_2} |B_{yt}^{cust}|}, \frac{|B_{zt}^{cust} - B_{zt}^{std}|}{\max_{t_1 \leq t \leq t_2} |B_{zt}^{cust}|},$$

where $B_t^{cust} = (B_{xt}^{cust}, B_{yt}^{cust}, B_{zt}^{cust})$ and $B_t^{std} = (B_{xt}^{std}, B_{yt}^{std}, B_{zt}^{std})$ are the MF at time t for the customized and standard locations, respectively.

The normalized differences with $t_1 = 140$ and $t_2 = 160$ s are plotted in Fig. 11. For Subjects A and C, the normalized difference of the y component was much larger than the other two components. For Subject B, the normalized difference in the z-direction was as large as that in the y-direction. However, the scale of the graph is different from those for the other two subjects; the values of the differences for Subject B were much less than those for Subjects A and C. The results shown in Fig. 11 compound the issue highlighted in Figs. 4, 5, and 8. In essence, if one only records the vertical direction (y component) of the MF during an MGG study, then firstly only a small proportion of the full MF is reflected in such a recording and, secondly, this component is proportionally the most sensitive. Thus, when dealing with recorded MGGs, we would need to be very careful before using the magnitudes of the MF to make any judgement about the underlying GEA. Currently, most analysis of MGGs are done via examination of the frequency dynamics, with little, if any, reference to the magnitudes of the MF.

It was shown that increases in the stomach wall thickness can result in relatively large increases in the magnitudes of the MF; as shown above, the average normalized differences between the MF from the stomach with wall thickness 2.66 and 5 mm is larger than that with thickness 2.66 and 4 mm for all the three components. The results from the different thickness models indicate just how sensitive recorded MGGs are to stomach anatomy. Accurately simulating MGGs requires not only detailed knowledge of stomach and body habitus but also specific knowledge of the stomach wall thickness.

In summary, we sought to address two questions associated with recorded MGGs: whether the x and z components of the MGG were also important, and whether using a Standard SQUID Location was appropriate. Using detailed simulations, we have shown that the magnetic activity was weakest in the y-direction (the most routinely recorded direction), compared to the x and z -directions.

Also, the y component was more sensitive to the SQUID location than the x and z components, which means the SQUID location mainly affects the activity in the y-direction. These results indicate that it is important to record and analyze the activity not only in the y-direction but also the x and z -directions.

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Figure 1.
Coordinate system used in the simulations shown relative to the supine subject.

Figure 2.

Names and locations of the channels for the SQUID used at Vanderbilt University.⁴ The channels labeled 5, 17, 18, 26, and 33 are capable of recording all three components of the magnetic field, whereas the other channels record only the y component of the magnetic field.

Figure 3.

Anatomically realistic models of three subjects. Stomach location within the torso (left column) and simulation results of normal slow wave electrical activity for one slow wave (140–160 s) are shown for each subject. Torso models on the left are shown using the same scale. The presented stomach models for each subject are seen from the front using the same scale. The range of potential on the stomach was between -70 (blue) and -40 mV (red).

Figure 4.

Standard SQUID Location in relation to the stomach for the three subjects (left) and their simulated MF (right) resulting from the GEA shown in Fig. 3. The 19 recording channels have been positioned in the x - z plane. The MF is plotted for one slow wave (140–160 s) for the x (blue dash-dotted), y (red solid), and z (black dashed) components. The dotted black line in each graph of the MF indicates 0. It can be clearly seen that the MF in the y -direction is weaker than that in the other two directions.

Figure 5.

Customized SQUID Location in relation to the stomach for the three subjects (left) and their simulated MF (right) resulting from the GEA shown in Fig. 3. The 19 recording channels have been positioned in the x - z plane. The MF is plotted for one slow wave (140–160 s) for the x (blue dash-dotted), y (red solid), and z (black dashed) components. The dotted black line in each graph of the MF indicates 0. As in Fig. 4, the MF in the y -direction is weaker than that in the other two directions.

Figure 6.

Directions and magnitudes of the simulated magnetic field at the 19 recording channels with the Customized SQUID Location for one slow wave (140–160 s) for each subject.

Figure 7. Simulated average MF (shown by the arrow) and potentials on the torso for Subject A using the Customized SQUID Location. The range of potential is between -0.045 (blue) and 0.062 mV (red).

Figure 8.

Angles of the mean MF relative to the x , y , and z -axes using the Standard (top) and Customized (bottom) SQUID Locations for one slow wave (140–160 s) for Subjects A (blue solid), B (red dashed), and C (black dash-dotted).

Figure 9.

Trajectories of the terminal point of the MF vector at channel 33 in the x - z direction for one slow wave (140–158 s) using the Customized SQUID Location for Subjects A (blue solid), B (red dashed), and C (black dash-dotted). The origin (0,0) is the center of channel 33. Points at 140 and 158 s are indicated by an asterisk and diamond, respectively. The time of 158 s was chosen as the end instead of 160 s because it is easier to see the start and end points of the graphs. Each of the arrows indicates which direction the trajectory goes.

Figure 10.

Effect of stomach wall thickness on the magnetic fields located at channels 9, 33, 35. The wall thickness was increased from 2.66 mm (red dashed) to 4 and 5 mm (black dashed, and blue solid, respectively).

Figure 11.

Normalized differences between the MF with the Standard SQUID Location and the MF with the Customized SQUID Location for components x (blue dash-dotted), y (red solid), and z (black dashed) for one slow wave (140–160 s) at a specific channel. For Subjects A and C, channel 33 was picked for both SQUID locations, and channels 35 and 5 were selected with the Customized and Standard SQUID Locations, respectively, for Subject B.