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Artifact and head movement compensation in MEG

Medvedovsky M,[1] Taulu S,[2] Bikmullina R,[1] Paetau R[1,3,4]
[1]BioMag Laboratory, HUSLAB, The Hospital District of Helsinki and Uusimaa, Helsinki, Finland
[2]Elekta Neuromag Oy, Helsinki, Finland
[3]Hospital for Children and Adolescents, Department of Child Neurology, Helsinki University Central Hospital, Helsinki, Finland
[4]Department of Clinical Neurophysiology, Helsinki University Central Hospital, Helsinki, Finland

Corresponding author: Mordekhay Medvedovsky, BioMag laboratory, PO Box 340, FIN-00029; Email: marikmedv@yahoo.com

ABSTRACT

PURPOSE: Magnetoencephalography (MEG) is traditionally considered impractical if the subject's head moves during measurements. A novel approach to correct the head position and the associated movement-related artifacts does, however, exist: continuous head position monitoring and movement compensation (MC) realized by the signal space separation (SSS) or its temporal extension (tSSS). The latter is especially important for rejection of close-to-sensor artifacts. The goal of the present work was to study how MC-SSS and its temporal extension MC-tSSS would influence MEG results. **METHODS:** Somatosensory evoked MEG responses to electrical median nerve stimulation were recorded with 204 planar gradiometers and 102 magnetometers. We compared the localization error of the N20m source, the averaged baseline noise, goodness of fit and confidence volume on data processed by MC-SSS vs. MC-tSSS on a subject moving in a controlled manner. **RESULTS:** We defined two patterns of disturbances with MC-SSS: stimulus artifact increase and random noise increase mainly on the lowermost sensors in very low head positions (5-6 cm shift). Up to 5-cm head shift, MC-SSS decreased mean localization error from 3.91 to 2.13 cm, but at the same time increased noise on gradiometers from 3.4 to 5.3 fT/cm. The noise increment occurred simultaneously with signal enhancement as MC transformed the head position closer to the sensors. Replacement of SSS by tSSS reduced the noise on gradiometers from 5.3 to 2.8 fT/cm and on magnetometers from 1.4 to 0.8 fT, reduced the mean localization error from 2.13 to 0.89 cm and increased the goodness of fit from 61.5% to 76.5%. Thus, tSSS specifically suppressed the random noise and nearby artifacts without suppressing the signal and thereby improved the signal to noise ratio. **CONCLUSIONS:** Head position recalculation should be combined with a powerful artifact rejection method. We recommend limiting MC use up to 3 cm head shift and using tSSS-based MC.

Search Terms: magnetoencephalography, artifact, movement compensation, signal space separation method, spatiotemporal signal space separation method.

INTRODUCTION

While EEG recording is dependent on stable low-impedance contact between electrodes and scalp, MEG does not require scalp contact. In contrast to EEG, where electrodes are fixed on the head, in MEG, the head can move relative to the sensor helmet. The requirement of stable head position is one of the biggest limitations of clinical MEG especially in young children and during epileptic seizures. The head position can be measured by attaching at least three head position indicator (HPI) coils to head surface and providing currents of different frequencies above the frequency band of interest to the HPI coils. The magnetic fields produced by those currents can be measured and the location of the HPI coils (and therefore of the head) can be defined relative to the device coordinate system (Knuutila, 1985; Ahlfors, 1989; Incardona, 1992; Fuchs, 1995; Uutela 2000; de Munck 2001; Uutela, 2001). This procedure can be done continuously during the MEG recording. If the head changes position, the MEG signal at the deviant head position can be transformed to correspond to a reference position. A virtual magnetic signal is thus created, which corresponds, for example, to the primary head position (before the head movement). Such virtual signal can be calculated by transforming the measured data into a device-independent representation, for example by minimum norm estimate (MNE), and then recalculating the sensor-level signals (Uutela, 2001).

Recently, a movement compensation (MC) method, based on signal space separation (SSS), was developed. The SSS method is based on Maxwell's equations and rejects the signals originating outside the sensor array (Taulu, 2005a,b), and simultaneously creates a device-independent representation of the data. SSS can be expanded into time domain to further attenuate the remaining interference signals. The method is called spatiotemporal signal separation (tSSS), previously also abbreviated as SSSt (Taulu, 2006); this method is especially useful in suppression of artifacts originating close to the sensors (Mäkelä, 2007). SSS- and tSSS-based movement corrections are in the following called MC-SSS and MC-tSSS, respectively. It is important to note that MEG measurements are disturbed by several factors: 1) external interference, that originates from sources localized outside the sensor array, 2) “brain noise” or random brain activity that differs from the interesting brain signal, 3) intrinsic sensor noise, 4) nearby (close-to-sensors) interference, e.g., head and neck muscle artifact or artifacts from moving EEG cables that quite often accompany clinical MEG recordings, and 5) different artifacts of non-magnetic origin, e.g., electric stimulus artifact. This last type of artifact is comparable to nearby artifacts in terms of interference suppression.

Noise increment was reported, when head position was corrected using MNE (Uutela, 2001), but the influence of MC on different categories of MEG artifacts was not studied in detail. The goal of our work was to study how MC-SSS and its temporal extension MC-tSSS can improve the MEG results. In the present work, we dealt only with stable deviant head positions, leaving out MEG recordings during actual movement.

METHODS

The study was performed according to recommendations of the local ethical committee. Somatosensory evoked magnetic fields to median nerve stimulation of one adult subject were recorded in a magnetically shielded room. MC-SSS and MC-tSSS were applied off line. Brain MRI was acquired with Philips 1.5T.

Stimulation protocol

Right and left median nerves were alternately stimulated with 0.2 ms rectangular electric current pulses at wrist. The stimulus amplitude was adjusted to reach the motor threshold without being painful. The interstimulus interval was 500 ms with a random jitter of ±50 ms.

MEG measurement protocol

The data were recorded with a 306 channel neuromagnetometer, Elekta Neuromag ® (204 planar gradiometers and 102 magnetometers), manufactured by Elekta Neuromag, Helsinki, Finland. The sampling frequency was 600 Hz and the signal band was 0.01-172 Hz. Before the recording sessions, the locations of three anatomical landmarks of the head (the nasion and the two preauricular points) and four HPI coils were digitized. The coils were located approximately in areas F3, F4, P3, P4 according to 10-20 EEG system. The coils were activated continuously throughout the measurement and produced signals in frequencies 154, 158, 162, and 166 Hz. Data were acquired with the head in reference head position (RHP) or in deviant head position (DHP). In RHP, the subject kept the head immobile, straight without turning or tilting the head to either side, and with the fronto-parietal scalp lightly touching the uppermost part of the sensor helmet. RHP was measured in five sessions. Left and right hand responses were averaged separately in every session, which resulted in 10 RHP trials, overall. DHP sessions started in RHP, after a few seconds, the subject changed the head position once and kept it stable during stimulation until 200-210 responses for each median nerve stimulation were collected and averaged on-line. We used six different types of DHP: 1) “strongly downward” (approximately 5-6 cm), 2) “moderately downward” (approximately 2-3 cm), 3) “strongly backward” (maximal possible chin upward position), 4) “moderately backward” (halfway of “strongly backward”), 5) “turn right” (maximal right turn of the head) and 6) “turn left” (maximal left turn of the head). Each DHP session was replicated (12 sessions overall), and separate right and left hand stimulations yielded a total of 24 DHP trials. Off-line MC-SSS and MC-tSSS were applied as described elsewhere: (Taulu, 2005; Taulu, 2006). The head position was defined in epochs of every 200 ms.

MEG data analysis

We used software provided by Elekta Neuromag Oy for off-line data analysis. The cortical responses to median nerve stimulation were averaged in epochs ranging from -100 to 500 ms in relation to the stimulus onset. After averaging, the responses were low-pass filtered at 80 Hz in order to exclude the HPI coil signals, and the epoch between -80 ms and 400 ms was analyzed. The baseline for noise estimate was defined between –60 ms and –20 ms. Equivalent current dipole (ECD) model was used for the inverse problem solution. We modelled the head with a spherical volume conductor. The time point of the magnetic N20-response (N20m) peaking at 22.5 ms after stimulus was chosen for least-squares dipole fit in all trials. No channels were excluded from the fitting procedure and the results of the first fit were accepted. The coordinates of the ECD location in the anatomical coordinate frame, goodness of fit, confidence volume, mean noise values from baselines of all gradiometers (with resolution 0.1 fT/cm) and separately from all magnetometers (with resolution 0.5 fT) were determined from averaged data for every DHP trial. At DHPs these parameters were determined for unprocessed, MC-SSS- and MC-tSSS-processed data; and, at RHP trials, only unprocessed data was used.

Statistical data analysis

We used MS Excel version 2003 to calculate mean values and standard deviations (SD) for the Cartesian ECD coordinates of the N20m-sources at the primary somatosensory hand area, SI, defined in ten RHP trials. Using these mean values as reference points; we created two different reference locations – one in each hemisphere. For both the right and left reference points (x0, y0, z0), we will use in this article the term SI_0. We determined the distance between the measured source location and the ipsilateral SI_0 on each axis and then calculated absolute distance for every DHP trial. For DHP we also calculated mean and standard deviation of absolute displacement from SI_0, separately for unprocessed, MC-SSS- and MC-tSSS-processed data. For statistical significance evaluation we used two-tailed paired Student's t-test. The difference with p-value of less than 0.05 was considered as statistically significant. We compared the absolute displacement from SI_0, the baseline noise level, goodness of fit and 95% confidence volume between unprocessed, MC-SSS- and MC-tSSS-processed data for DHPs. At first, we performed this analysis for all 24 DHP trials, and then, two of these 24 trials, with head down by 6 cm, were excluded due to the signal to noise ratio (SNR) being too weak for a meaningful analysis.

RESULTS

Source localization error

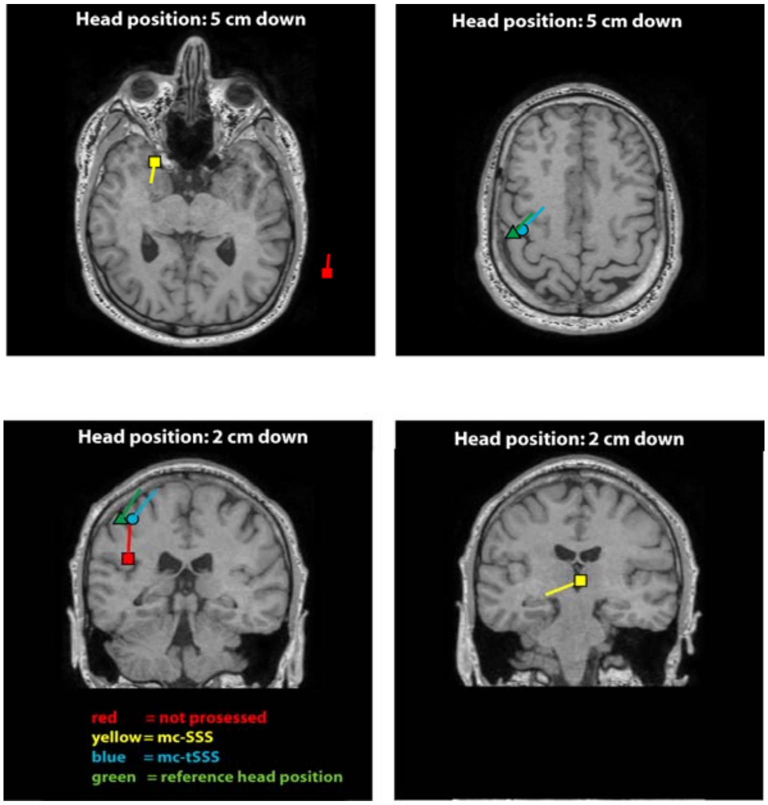
The distances between SI_0 and measured source location at deviant head positions are presented in Table 1. In 22 out of 24 trials with deviant head positions, the distance of the source locations was more than 1 cm, and in 16 trials, more than 2 cm from SI_0. After processing with MC-tSSS, the corrected source locations deviated less than 2 cm from SI_0 in 21 trials and less than 1 cm from SI_0 in 14 trials. In the three "unsuccessful" trials (more than 2 cm error) the head shift was extreme: twice with 6 cm downward shift and once with the neck strongly extended backward 0.5 radians associated with a linear 3-cm displacement downward (Table 1).

Table 1. Localization error and noise at deviant head positions.

Head position		**Head shift, radian**	**Head shift, cm**	**Side**	**Localization error, cm**			**Noise, gradiometers, fT/cm (magnetometers, fT)**		
					No	MC-SSS	MC-tSSS	No	MC-SSS	MC-tSSS
1	Moderate downward		2 down	left	3.04	0.71	0.71	4.0 (2.0)	13.1 (1.0)	2.7(0.5)
2				right	5.93	0.83	0.83	3.5 (0.5)	3.2 (1.0)	3.1 (1.0)
3			2 down	left	2.67	1.09	1.09	3.1 (1.0)	8.7 (1.5)	2.2 (0.5)
4				right	2.27	0.83	0.83	2.6 (0.5)	2.6 (0.5)	2.5 (0.5)
5	Strongly downward		5 down	left	19.44	0.38	0.38	3.6 (2.0)	31.8 (5.0)	14.7 (2.0)
6				right	5.06	0.83	0.83	3.5 (0.5)	9.3 (1.5)	14.3 (2.5)
7			6 down	left	6.44	3.04	3.04	2.9 (1.0)	79.8 (11.0)	9.6 (2.0)
8				right	7.91	6.82	6.82	2.8 (0.5)	243.8(48.0)	11.0 (2.8)
9	Moderate backward	0.25 around x-axis	1 down	left	2.00	1.29	1.29	3.3 (1.0)	8.8 (2.0)	2.4 (0.5)
10				right	1.50	0.67	0.67	2.6 (0.5)	2.9 (0.5)	2.6 (0.5)
11		0.25 around x-axis	3 down	left	2.11	0.71	0.93	3.4 (2.0)	9.8 (1.5)	2.6 (0.5)
12				right	3.14	0.32	0.78	2.9 (0.5)	3.9 (1.0)	3.6 (0.5)
13	Strongly backward	0.6 around x-axis	3 down	left	6.91	0.77	0.65	4.0 (2.0)	17.1 (3.0)	5.1 (1.0)
14				right	6.73	6.94	0.35	3.9 (0.5)	6.0 (1.5)	6.0 (1.5)
15		0.5 around x-axis	3 down	left	6.40	2.35	2.61	2.8 (1.0)	5.3 (1.0)	4.4 (1.0)
16				right	7.24	1.58	1.32	3.0 (0.5)	4.5 (1.0)	4.4 (1.0)
17	Right turn	0.3 around z-axis	1 down	left	3.09	1.07	1.21	4.2 (2.0)	7.4 (2.0)	2.1 (0.5)
18				right	0.25	0.31	0.44	4.0 (0.5)	2.3 (0.5)	2.2 (0.5)
19		0.35 around z-axis	1 down	left	10.30	1.18	1.12	3.6 (2.5)	6.9 (1.5)	1.8 (0.5)
20				right	13.00	0.46	0.48	3.1 (0.5)	2.4 (0.5)	2.4 (0.5)
21	Left turn	0.1 around z-axis	No head origin	left	14.80	0.73	0.72	3.6 (2.0)	8.4 (1.5)	2.6 (0.5)
22				right	0.91	0.45	0.46	2.4 (0.5)	2.5 (0.5)	2.5 (0.5)
23		0.04 around z-axis	1 down	left	1.32	2.02	1.40	3.8 (2.5)	11.5 (2.0)	2.8 (0.5)
24				right	1.56	0.55	0.50	3.0 (0.5)	3.3 (1.0)	2.3 (0.5)

Figure 1 shows examples of MEG sources after application of MC-SSS and MC- tSSS at deviant head positions compared with MEG sources at reference head position co-registered with MRI.

Figure 1. The N20m modeled by equivalent current dipole and co-registered with MRI



For all 24 trials, the mean distance from SI_0 was significantly reduced from 3.99 cm (without processing) to 2.06 cm by MC-SSS and to 1.23 cm by MC-tSSS. For 22 trials up to 5 cm head shift, the results were as follows: 3.91 cm – unprocessed data, 2.13 – MC-SSS, 0.89 – MC-tSSS (Figure 2A). When considering all 24 trials, the difference between MC-SSS- and MC-tSSS- processed data was not statistically significant (p=0.1583), but after excluding 2 trials with extreme head shift (>5cm) this difference became significant (p=0.0273) (Figure 2A).

Noise

On data inspection, the most important disturbance factor was the stimulus artifact related oscillations present even after MC-SSS, which correctly removed the distortion caused by the deviant head position but could not compensate for nearby artifacts. The amplitude of this disturbance signal increased simultaneously with the N20 amplitude as the head is virtually transformed closer to the sensors. The stimulus artifact was eliminated by replacement of SSS with tSSS (Figure 3, A and B). With significant downward head displacement (5-6 cm) the lowermost sensors became especially noisy after MC-SSS (Figure 3C). This is due to the poor SNR of the brain signals corresponding to sources far away from the

MEG sensors during strong downward displacement. With no noise weighting applied, MC-SSS aims to maintain the original SNR and therefore increases random noise in the sensors that couple strongly to the field components that were poorly detected in the original measurement.

Figure 2: Effects of MC-SSS and MC-tSSS

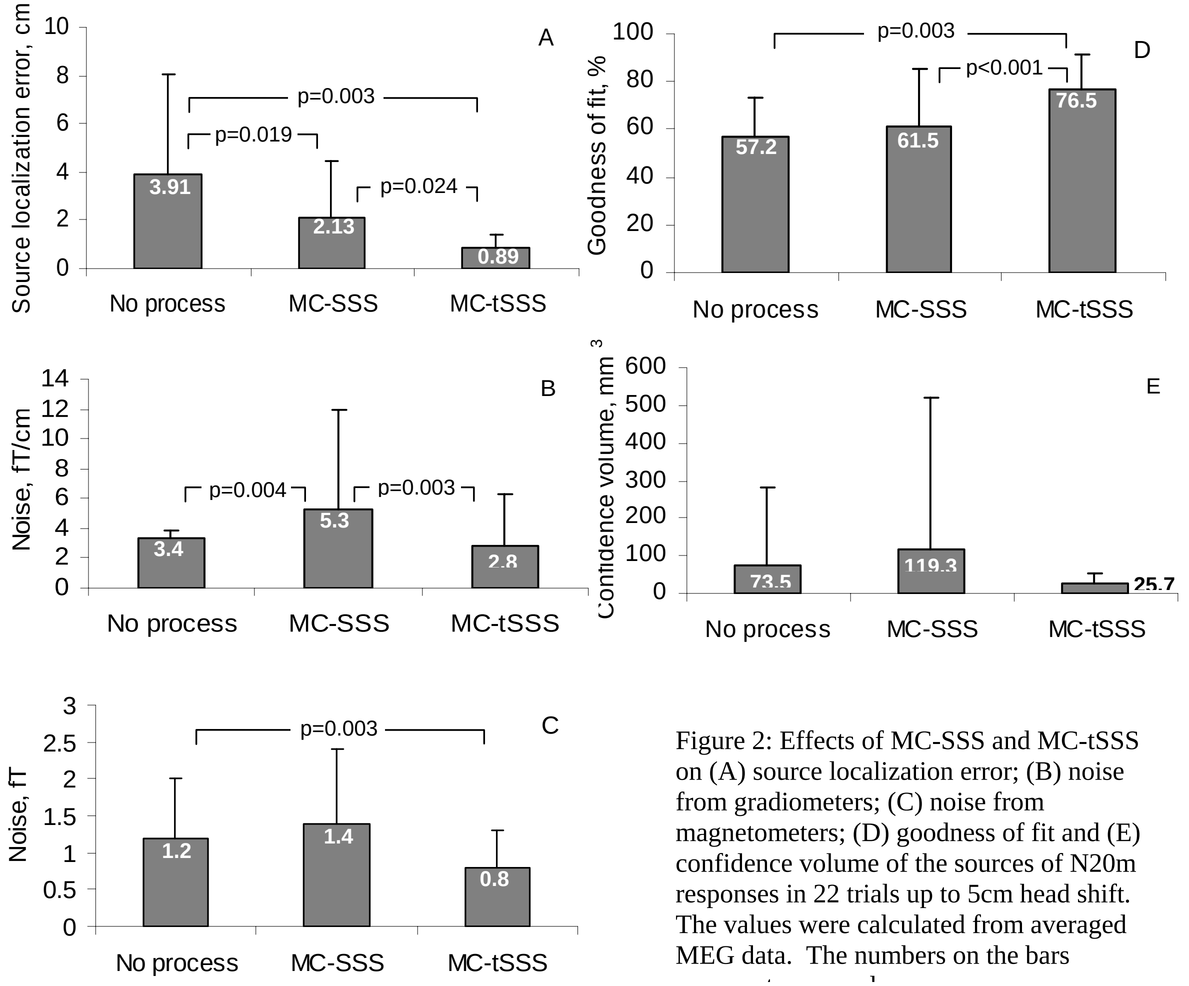


Figure 2: Effects of MC-SSS and MC-tSSS on (A) source localization error; (B) noise from gradiometers; (C) noise from magnetometers; (D) goodness of fit and (E) confidence volume of the sources of N20m responses in 22 trials up to 5cm head shift. The values were calculated from averaged MEG data. The numbers on the bars

The mean value of noise on gradiometers and to the lesser degree on magnetometers was increased by MC-SSS and reduced back by replacement of SSS with tSSS; the differences in the noise level between MC-SSS-processed and MC-tSSS-processed data did not, however, reach statistical significance in all 24 trials, but again with head origin shift up to 5 cm, the differences were statistically significant for both gradiometers and magnetometers (Figure 2, B and C). More than 10 fold increase of noise was produced by MC-SSS in the trials with 6 cm downward head displacement (Table 1). With significant (5-6 cm) downward head displacement, the noise was obviously stronger in lowermost sensors (Figure 3C). Figure 3 (B) demonstrates the influence of MC-SSS and MC–tSSS on the N20 signal and on the artifact. With application of MC-SSS (yellow line) amplitude of both signal and artifact are increased, so signal to noise ratio does not improve; but with application of MC-tSSS (blue line) the amplitude of N20 signal increases with simultaneous suppression of artifact and thereby signal to noise ratio improves.

Figure 3: Averaged somatosensory evoked responses with and without movement compensation

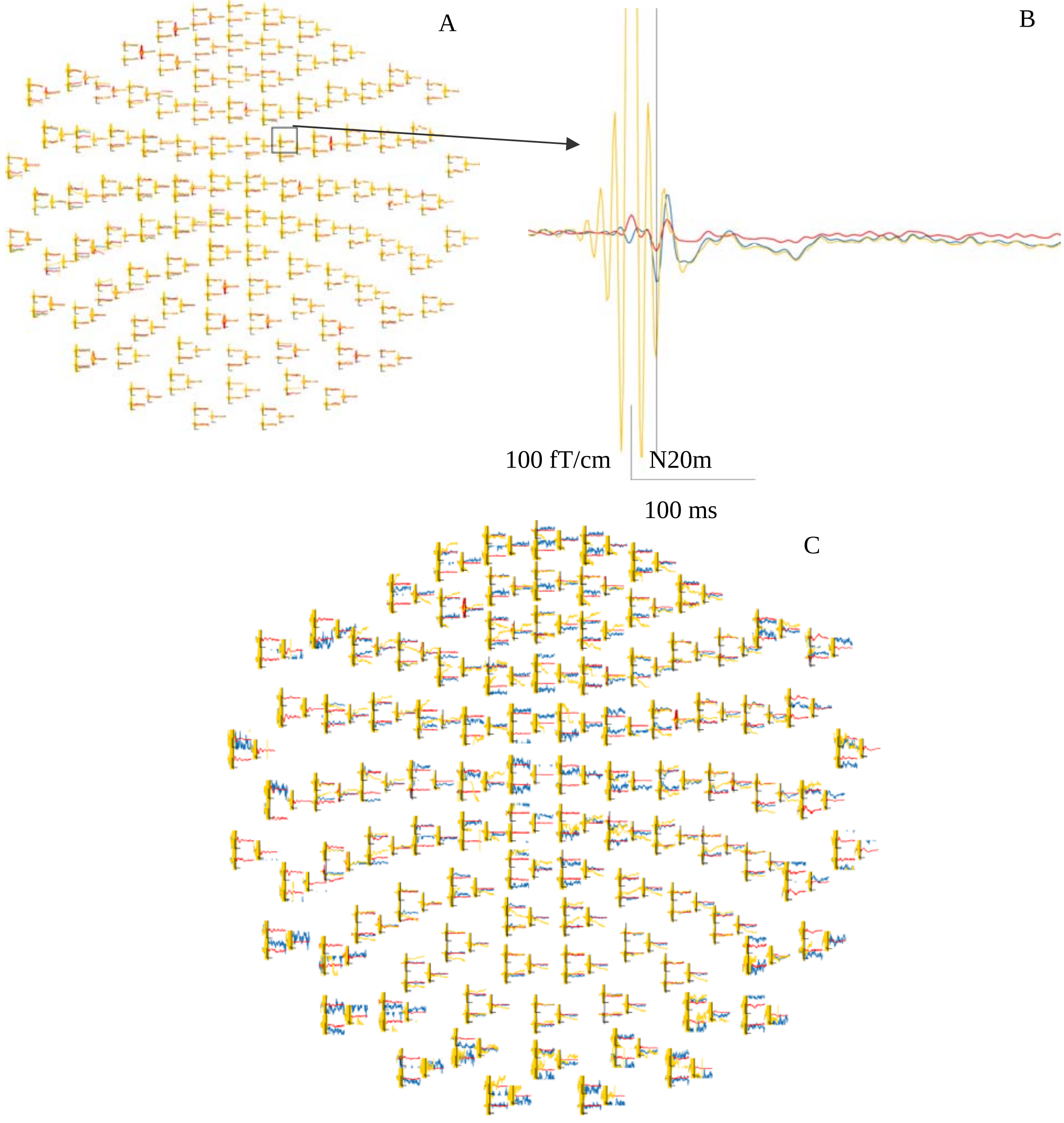


Figure 3: Red – unprocessed data. Yellow – MC-SSS processed data. Blue – MC-tSSS-processed data. (A) all 306 channels in the trial with head shift 2cm downward; (B) one channel in the same trial as A; and (C) all 306 channels in the trial with head shift 6 cm downward.

Goodness of fit

The mean goodness of fit value was not significantly increased by SSS-based MC but significantly increased by MC-tSSS (Figure 2D).

Confidence volume (95%)

The mean 95% confidence volume value was increased by MC-SSS, and decreased by MC-tSSS, but the difference was not significant (Figure 2E).

DISCUSSION

In our study, we investigated the utility of MC-SSS and MC-tSSS in MEG measurements with head position shifts. We demonstrated that use of MC-SSS increased stimulus artifact and, with substantial head shift (5-6 cm), increased random noise on lowermost channels. Substitution of SSS by tSSS suppressed stimulus artifact but was less efficient against random noise increase with strong head shift. Up to 5 cm head shift, replacement of SSS by tSSS reduced baseline noise on both gradiometers and magnetometers, reduced localization error and increased goodness of fit of N20 responses.

While determining the source location of sensory evoked responses, one often only includes channels having a strong response. However, the purpose of our study was not to localize sources of evoked responses; rather we used the evoked responses as a model to predict the error range for the clinical situation where sources of spontaneous epileptic activity are localized in pre-surgical workup using MC-SSS, and MC-tSSS approaches. Often, we have no firm a priori assumption of epileptic focus locations; therefore in our study we used all 306 MEG channels for each trial. We accepted the results of the first fit, which not always corresponded to the source of evoked responses, but everyday patient signals are also not always artifact-free. The principal difference between our experiments and epileptic source localization in clinical practice is the fact that we used averaged MEG signal, and the noise, being a random factor, is suppressed by averaging. We recognized two patterns of disturbances with MC-SSS.

The first pattern was increased amplitude of the stimulus artifact (Figure 3A). Signal averaging does not suppress the stimulus artifact, used as the trigger for averaging. In addition, being low-pass filtered, the power of stimulus artifact is distributed in time both forward and backward producing “spindle shape” complex of oscillations (Figure 3B – yellow line). It should be noted that this oscillation is due to temporal filtering only, not to MC-SSS processing. When those oscillations reach the time point of the response (in our experiments 22.5 ms), they contaminate the N20m signal and thereby impair the localization accuracy. When they reach the baseline (in our experiments -60 to -20ms), they influence the quantitative noise estimation. MC-SSS virtually brings both brain signals and artifacts closer to sensors so that their amplitudes increase. This pattern was present already with relatively small head shift of only 2 cm, it was not limited to the lowermost sensors (in contrast to the second pattern, see below), and the artifact was completely removed by tSSS (except of trials with 5-6 cm downward shift). Stimulus artifact belongs to the category of non-magnetic artifacts that are similar to nearby artifacts which, in addition to external interference, are specifically removed by tSSS. The practical solution for this pattern is to use MC-tSSS instead of MC-SSS. Replacement of SSS by tSSS in MC processing significantly improved the localization accuracy, decreased the noise and increased the goodness of fit. In clinical reality, different kinds of nearby artifacts are especially common (e.g., EEG cables or electrodes with some magnetic impurities, scalp and neck muscle artifact, metallic dental objects) and, apparently, their amplitude can be increased by head position correction, therefore the ability to suppress nearby artifacts is important for clinical MC applications.

The second pattern recognized was an increase of random noise on the lowermost sensors (Figure 3C). This pattern occurs in trials with very low head position (5-6 cm) and is only partially improved by tSSS. This noise behavior is due to the fact that by virtually shifting the head up from a very low position, the lowermost virtual sensors correspond to signals that were not detected in the actual measurement. To alleviate this problem, the poorly measured components of magnetic field should be suppressed in the transformation by a location dependent noise weighting. This is a subject of further studies. Presently, the practical solution is limitation of MC application to less than 5 cm head shift (taking safety margin, our recommendation is up to 3-cm shift). In addition, it is possible that the post-MC exclusion of lowermost noisy channels will be helpful in very low head positions, but the channel exclusion criteria should be elaborated in additional studies. The reasons to restrict MC application up to 3 cm are not only noise enhancement – with significant head shift some parts of the head can be far away from the MEG sensors, while other parts are still close, so that signal in some locations can be preferably recorded, while it can not be seen in others. That can for example lead to incorrect localization of initiating epileptic activity. By this reason the use of MEG data from the head positions with more than 3 cm shift is questionable even if the noise problem in lowermost sensors was solved. The main clinical significance of MC is not to reconstruct brain signal from extremely deviant head positions, rather to allow some (relatively small) movement during clinical data acquisition and thereby, to allow long-term MEG measurements, such as ictal recordings in epilepsy patients.

Increased disturbance amplitudes may be an undesirable side effect of brain signal recalculation in process of head position correction. To compensate this side effect, signal recalculation should be combined with an efficient artifact rejection method. Distant but not nearby artifacts can be rejected by SSS-processing which is included in SSS-based MC. We demonstrated that tSSS incorporated into the MC process can be more efficient than SSS and therefore tSSS-MC is preferable for clinical and research use.

With the head shift 5-6 cm down, the parameters of head position correction were less predictable (Table 1). Possible explanations are poor SNR, lowermost sensors noise enhancement and possible suboptimal HPI coil position localization. In order to improve the HPI process in the future, the coil amplitudes should be adjusted on-line to assure a good HPI result even with distant head positions.

According to results of our study we can formulate two recommendations for MC application: 1) use of tSSS-based MC and 2) limit use of MC up to 3 cm head shift. About the angular displacement the limitation is less clear, in one of the trials with angular head displacement 0.5 rad backward simultaneously with linear displacement 3 cm downward, the source localization error was between 2 and 3 cm, but additional studies are needed to define head displacement limits more certainly.

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