EEG Versus MEG Localization Accuracy: Theory and Experiment

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Summary: We first review the theoretical and computer modelling studies concerning localization accuracy of EEG and MEG, both separately and together; the source is here a dipole. The results show that, of the three causes of localization errors, noise and head modelling errors have about the same effect on EEG and MEG localization accuracies, while the results for measurement placement errors are inconclusive. Thus, these results to date show no significant superiority of MEG over EEG localization accuracy. Secondly, we review the experimental findings, where there are again localization accuracy studies of EEG and MEG both separately and together. The most significant EEG-only study was due to dipoles implanted in the heads of patients, and produced an average localization error of 20 mm. Various MEG-only studies gave an average error of 2-3 mm in saline spheres and 4-8 mm in saline-filled skulls. In the one study where EEG and MEG localization were directly compared in the same actual head, again using dipoles implanted in patients, the average EEG and MEG errors of localization were 10 and 8 mm respectively. The MEG error was later confirmed by a similar (but MEG-only) experiment in another study, using a more elaborate MEG system. In summary, both theory and experiment suggests that the MEG offers no significant advantage over the EEG in the task of localizing a dipole source. The main use of the MEG, therefore, should be based on the proven feature that the MEG signal from a radial source is highly suppressed, allowing it to complement the EEG in selecting between competing source configurations. A secondary useful feature is that it handles source modelling errors differently than does the EEG, allowing it to help clarify non-dipolar extended sources.

Key words: MEG; EEG; Localization.

Introduction

Among the various properties of the EEG and MEG which make them useful, we here consider the specific property of source localization. Mostly, we consider the localization of a focal (confined) source in the human brain. Because most focal sources in the brain can be approximated by a dipole when viewed from the surface of the head, we therefore consider EEG and MEG localization of a dipole. We here review the theoretical and experimental studies performed to date for these two localizations. In addition, we briefly consider non-dipolar sources.

For both theory and experiment, we subdivide the review by first considering the work done on EEG only, then on MEG only, and lastly on EEG compared with MEG. We state, wherever possible, the localization errors found in each study.

Review of Theoretical Studies (by BNC)

From the theoretical and computer modelling point of view, there are three causes of EEG or MEG localization error of a dipole source. The first cause is noise in the recorded EEGs and MEGs, which is the extra unwanted signal in the recorded waveform, for example due to interfering brain signals or instrumental noise. The second cause is measurement placement error, which are the spatial displacements of EEG electrodes or the MEG coil from their intended location on the scalp (for the MEG it also means an angular displacement of the coil from the intended orientation). The third cause is head modelling error; this is produced by the differences between the complex geometry of the actual head and the simple models used to represent it, such as a sphere. In addition to these three errors, there is the error of approximating the neural source by a dipole, called the source modelling error; these are caused by the differences between complex, extended sources in the brain and the dipole used to represent them. These causes are all considered in the following review. Table I is a summary of this review, and may be followed along with the review.

We first consider the studies of localization accuracy of EEG only, of which there are many. While studies of the effects of noise have been performed (Kavanagh et al.

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Table I. Summary of theoretical and computer modelling studies of localizing accuracy. These are divided into three groups: those which investigate the localization accuracy of EEG-only; those which investigate MEG-only; and those which directly compare EEG VS. MEG localization accuracy. The four rows indicate the causes of localization error. Different studies are separated by a semi-colon.

	EEG ONLY	MEG ONLY	EEG VS. MEG
NOISE	Inconclusive	Inconclusive; Preferred direction	Same; MEG 35% better
MEASUREMENT PLACEMENT ERRORS	5-10% or 4-7 mm	2 mm	————
HEAD MODELLING ERRORS	Skull: 7 mm; Cavity: 10 mm; Layers: 4 mm	Shape: 15 mm; Shape: 16 mm	Fissures: 8 mm both; Shape: 10 mm both; Layers: 8 mm EEG, 10 mm MEG; Bumps: 10 mm EEG, 5 mm MEG
SOURCE MODELLING ERRORS	————	Dipole generally centered	Depends on nature of error

1978; Darcey et al. 1980; Gaumond et al. 1983), the applicability of these studies to actual EEG measurements is not certain because random noise was assumed in the studies while actual noise may be both random and correlated. Correlated noise would be produced by an interfering source which is nearby and which is active at the same time as the source of interest. A study (Kavanagh et al. 1978) of measurement placement errors shows that location errors that are likely to exist under typical experimental conditions can cause localization errors of 5-10% in source parameter estimation; these translate to an error of about 4 to 7 mm in the dipole depth. One study (Ary et al. 1981) of head modelling errors has shown that neglecting the skull layer in a spherical model of the head can produce localization errors of as much as 7 mm. A similar study (Stok 1987) has found that physiologically reasonable ranges of errors in the conductivities and thickness of the skull and scalp layers in a spherical model of the head produce localization errors which are a maximum of 6% of the actual dipole location. For sources in the cortical region of the brain at a radius of about 70 mm, this would indicate a maximum localization error of approximately 4 mm. Another head modelling error study (He et al. 1987) has shown that a cavity in the brain can cause localization errors as large as approximately 10 mm for sources close to the cavity. In summary, the theoretical and computer modelling studies of EEG show localization errors of a dipole of up to about 10 mm.

A number of theoretical and computer modelling studies of MEG-only localization accuracy have also been performed. As with the EEG noise studies, the applicability of the MEG noise studies to actual measurements is not certain. However, one computer study of noise (Hari et al. 1988) has found MEG localization is more accurate in the direction perpendicular to a dipole source than in the direction parallel to such a source; this confirmed an earlier, purely theoretical observation (Cohen and Cuffin 1983). A study of the effects of MEG measurement placement errors (Cuffin 1986) shows that typical experimental placement errors cause a localization error of about 2 mm using single-channel MEG detectors. We are not aware of studies with multi-channel detectors. Studies of head modelling errors have shown that the irregular shape of the inner surface of the skull can produce localization errors as large as 15 mm

(Hamalainen and Sarvas 1987), and that the irregular shape of the actual head can produce localization errors as large as 16 mm (Meijs et al. 1988). In addition, a study of source modelling errors (Okada 1985) found that for most extended or multiple sources, MEG localization places the dipole to within several mm of the geometrical center of such sources. In summary, the theoretical and computer modelling studies of MEG only indicate about the same localization errors as for the EEG, say about 10 mm.

Several theoretical and computer modelling studies directly comparing EEG and MEG have been performed to date. In the first such study (Cuffin and Cohen 1979), the sensitivity patterns of EEGs and MEGs to sources in the cortical region of the brain were compared. The sensitivity of unipolar (referential) EEGs and unipolar MEGs were found to be quite different and difficult to directly compare. However, bipolar MEGs and EEGs were found to be comparable. The MEGs were sensitive to sources over a somewhat smaller (≈ 30%) area than were the EEGs; this indicates that the MEG should localize somewhat more accurately, other factors being equal. In studies of noise, the effects were found to be nearly the same on EEG and MEG localization accuracy in one study (Cuffin 1985a), but another study (Stok 1987) has found the effects to be approximately 35% smaller for the MEG than the EEG. Several studies of the effects of head modelling errors have been performed. One study (Cuffin 1985b) has found that large fissures in the brain will produce localization errors up to 8 mm for both EEG and MEG. A computer modelling study (Cuffin 1990) has shown that the general non-spherical shape of the head produces localization errors of less than 10 mm for both the EEG and MEG. An eccentric spheres model of the head has been used in a recent study (Cuffin 1991a) to investigate the effects of large scale variations in skull and scalp thickness. It was found that such variations can produce EEG localization errors as large as approximately 8 mm; the MEG localization errors were somewhat less than this amount (within 10 %). Effects of local variations in skull and scalp thickness have also been investigated in a recent computer modelling study (Cuffin 1991b); it was found that these variations can produce EEG localization errors up to 10 mm and MEG errors which are less than half that amount.

Concerning source modelling errors, a computer modelling study (Cuffin 1985a) found that the relative effects on EEG and MEG localization accuracy depend on the nature of the modelling error. For sources in the form of lines, i.e., a number of dipoles in a line one behind the other, or side by side, EEG accuracy is better than MEG accuracy for side-by-side sources while the reverse is true for in-line sources. This study has also found that for some extended (non-focal) or multi-focal sources, the differences in EEG and MEG localizations are significant and could be helpful in identifying the presence of such sources. For example, for a side-by-side source which is 40 mm wide, the MEG localization is 8 mm deeper than with EEG localization.

In summary, the comparative MEG-EEG studies performed to date indicate that, with the exception of some head modelling errors, the factors investigated produce localization errors of approximately the same amount for both EEG and MEG.

Thus, we summarize all the theoretical and computer modelling results as follows. While the studies of noise that have been performed do not provide information on the absolute amount of localization errors caused by this factor, they do indicate that the effects of noise on MEG localization accuracy range from nearly the same to somewhat less (≈ 35%) than the effects on EEG accuracy. Not enough studies of measurement placement errors have been performed to compare the effects on EEG and MEG localization accuracy; more studies need to be done. The head modelling error studies performed to date indicate that the effects of these errors range from nearly the same for EEG and MEG to significantly less for the MEG. Finally, the source modelling error studies indicate that the relative effects of such errors on EEG and MEG localization accuracy depends on the nature of the error. The studies also indicate that for some source modelling errors, differences in the EEG and MEG localizations may be useful in indicating the presence of such sources. In conclusion, the theoretical and computer modelling studies performed to date indicate that MEG localization accuracy is not significantly better than EEG accuracy. However, this conclusion is only as valid as is the representation of the actual head by the models used in the studies. Therefore, experimental verification of at least some of these results is required.

Review of Experimental Studies (by DC)

There are some common elements for all the experimental work listed here. The experimental dipole always consists of two electrodes a short distance apart, where a brief pulse of current is repeatedly passed between them; this simulates a repetitive neural signal, and allows signal averaging to be used for the EEG and/or MEG. For the MEG, the electrodes are non-magnetic and the wires to the dipole are twisted together in order to produce no extra magnetic field. Localization accuracy is determined by first measuring the EEG and/or MEG over the head model or actual head due to this dipole, then solving these for the apparent source by solving the inverse problem, and finally comparing the location of the apparent source with the true source location. The distance between them is the error of localization. The

Table II. Summary of experimental studies of localizing accuracy. The studies are divided into the same three columns as in Table I. The three rows indicate increasingly better experimental "heads". Av.= average; † using only low-noise dipoles in order to compare with Cohen et al. 1990.

	EEG ONLY	MEG ONLY	EEG vs. MEG
SALINE SPHERE	1 study; Av. of 10 mm	5 studies; Av. of 2-3 mm	1 study; 2-3 mm vs. 2-3 mm
SALINE SKULL	1 study; Av. of 10 mm	4 studies; Av. of 4-8 mm	————
ACTUAL HEAD	1 study; Av. of 20 mm	1 study; Av. of 10 mm †	1 study; 10 mm vs. 8 mm

head model used in the inverse solution is always a perfect sphere (for the EEG usually with spherical layers representing scalp, skull, etc.) This use of the spherical model is important in understanding the results of these experiments. We note that the location of the dipole electrodes in these experiments are always accurately known, otherwise there is no "true source location". Thus, we do not list those studies of localization accuracy where there is no independent and clear knowledge of source location such as with X-rays. An example of this type is the report of Yamamoto, Williamson et al. (1988), where an actual neural source in the human brain is used, but there is no proof of its location or, in fact, if it is a single source.

There are three levels of work described here to measure localization accuracy for MEG and EEG. At the simplest level, localization experiments were performed in a saline sphere as an approximation to the human head. In this case we would expect accurate localization (perhaps 2-3 mm error) because the spherical model in the inverse solution is an exact fit to the saline sphere, hence there are no modelling errors; this leaves only noise and placement errors, which can be made arbitrarily small in a controlled experiment of this type. At the next higher level of realism, experiments were performed in a saline-filled skull as an approximation to the human head. In this case we would expect more localization error because the spherical model used in the inverse solution is no longer an exact fit (at this time the spherical model is the best yet available). Finally, at the most realistic level, experiments were performed in an live human head. Here we would expect a further increase in localization error because noise and placement error cannot be as carefully controlled as in saline laboratory model. Table II is a summary of the following review, and may be followed along with the review.

We first consider the experimental studies of EEG localization alone. These were performed by two groups (Henderson et al. 1975; Smith et al. 1985a and Smith et al. 1985b). Henderson et al. measured localization accuracy using a dipole in several artificial heads; they used both a saline sphere, then a skull filled with saline, surrounded by a simulated "scalp". In both of these they obtained an average accuracy of localization of about 10 mm. In the sphere they should have obtained better accuracy with the techniques available to them, because there need not have been any significant source of error; however, their experimental problems are not clear.

Smith et al. measured EEG localization accuracy in the actual, living human head. The dipoles were depth electrodes implanted in epilepsy patients for the purpose of seizure monitoring; the electrode locations were known from X-rays. The neural signal was simulated by a repeated current pulse of rectangular shape. This pulse shape, unfortunately, nearly always produces an artifact in the resulting EEG signals; this is a spike at either or both the leading and the trailing edge of the EEG pulse, due to capacity coupling of the high frequencies. Unless handled carefully, this artifact produces a localization error because it results in a false EEG signal amplitude. With this artifact present, they obtained an average error of localization of about 20 mm, in a total of 24 dipoles in 12 patients, where some of this error was certainly due to the spike artifact.

Many localization accuracy experiments have been made of MEG alone. In nearly all of these an artificial head of some sort was used. One group (Barth et al. 1986) measured localization accuracy in both a saline sphere

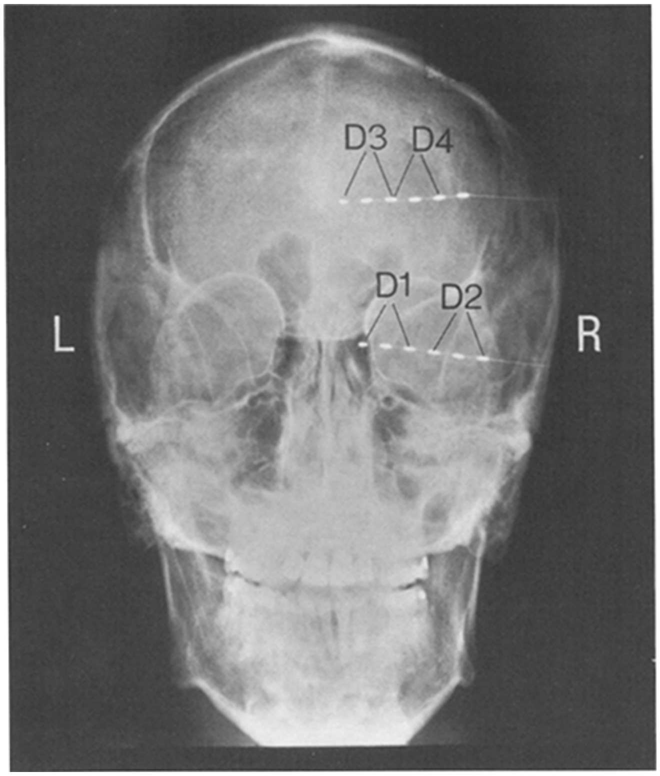

Figure 1. X-ray of one of the three patients in the MIT-Beth Israel study showing a typical example of depth electrodes in the brain. Six electrodes can be seen on each of the two catheters. D1, D2, D3, and D4 are the four dipoles, where each is due to the pair of electrodes indicated.

and in the head of an human cadaver, where the brain tissue was removed and replaced with conductive salt jelly (effectively a saline skull). They obtained an average error of 1.5 mm in the sphere and 3.2 mm in the cadaver head. At about the same time another group (Weinberg et al. 1986) similarly measured the MEG localization accuracy in a human skull filled with a saline medium. After refining the use of a spherical model to take into account the non-sphericity of the skull, they obtained an average error of 3.5 mm. A third group (Janday and Swithenby 1987) measured MEG localization accuracy in both conducting-gel filled spheres, and partial spheres combined with human skulls. They attempted several forms of data analysis and, although the localization errors are not clearly stated, appear to have found an average error of localization of about 2 mm for the spheres, and perhaps 10 mm for the spheres-plus-skull. Yet another group (Hansen et al. 1988) also measured localization accuracy in saline-filled sphere and obtained an average error of about 2 mm. Finally, a fifth group (Yamamoto et al. 1988) measured MEG localization accuracy in a sphere filled with saline, and in a model skull filled with saline. They found a localization accuracy of better than 3 mm in each. In summary, these measurements, all in artificial heads, show an MEG localization error of 2 or 3 mm in a spherical conductor, and an average error in the range of 4-8 mm, for a skull-shaped conductor where the "brain region" is always homogeneous. Presumably the larger error with the skulls is due to the use of the spherical model in the inverse solution which, as noted above, is not a perfect fit to the skull shape.

This brings us to about 1988. We first describe the status in the MEG community at this time, concerning MEG localization. On the one hand, the claim had become widespread that the MEG was capable of a localization accuracy of several mm, therefore by implication was much better than EEG localization, reported to be 20 mm (from Smith et al.) A typical example is the claim "For cortical sources...MEG has much better spatial resolution than EEG, 1 to 2 mm under favorable conditions" (Hari and Lounasmaa 1989). On the other hand, theory indicated that MEG localization should not be much better than that of the EEG (as summarized above). Further, the above claim was not based on any direct experimental comparison of MEG vs. EEG, but mostly on the artificial-head MEG measurements vs. the real-head EEG measurements of Smith et al. This controversy was of importance because expensive MEG systems were being purchased in part due to the MEG localization claim. It was also important because the thrust of much MEG activity was moving in the direction of localization, thereby detracting from other uses of the MEG. Because of its importance, our MIT group had formed a collaboration with the epilepsy group at Beth Israel Hospital in Boston in order to experimentally test the claim of superior MEG localization.

The test was made of MEG vs. EEG localization in the same living head (Cohen et al. 1990), and so far is the only experiment of this kind. The source was a dipole of accurately known location, again due to depth electrodes already implanted in epileptic patients for seizure monitoring, as shown in Figure 1. The dipole current was now a sine wave with rounded ends (instead of a rectangular pulse) in order to minimize high frequencies and the resulting spike artifact in the EEG (as in Smith et al.). MEGs and EEGs from this source were measured at sixteen locations over the head. Then, using a spherical head model, an inverse solution was performed on the MEG and EEG data separately to determine the apparent source of each. This location was compared with the known location (from X-rays), to determine the localization accuracy.

Before measuring the patients, the entire system was calibrated with an artificial head, which was again a saline-filled sphere. Exactly the same equipment and methods were used as subsequently in the patients, except that the EEG electrodes were here silver wires pasted to the inside of the sphere. The purpose was to make sure that the system accuracy was good enough to test the hypothesis being investigated. After much testing and "tuning", it was found that every EEG and MEG measurement could be made with an accuracy of less than 3 mm. We were then ready for the human measurements. These were made of four dipoles in each of three patients. The results are summarized in Table III. Because most dipoles were oriented quite radially to the skull, their MEG signals were suppressed and showed poor signal/noise; this is because the MEG signal from a radial dipole in a perfect sphere is always zero (Baule and McFee 1965). After discounting these noisy data (7 of the 12 dipoles) the average MEG error of localization, in the remaining 5 dipoles, was found to be 8 mm. The average EEG error (for 12 dipoles, all of low noise) was found to be 10 mm. This was a factor of two better than the 20 mm result of Smith, et al., presumably because we had no spike artifact. Also, the EEG recordings were of generally higher fidelity. This result suggests that the MEG offers no great advantage over the EEG in the specific task of localizing a dipole source.

Table III. Results of MEG vs. EEG localization experiment (Cohen et al., 1990). D1, D2, D3, and D4 are the four dipoles in each patient. MEG data in brackets were discarded because the low signal/noise may have degraded the localization accuracy. Sup=superior; convex=convexity; rad=radial; tang=tangential; S/N=signal/noise.

	Dipole	Approx. location	Approx. angle	MEG S/N	MEG error (mm)	EEG error (mm)
Patient 1	D1	Cingulate gyrus	rad.	11	13	15
	D2	Middle frontal gyrus	rad.	10	7	12
	D3	Parasag. sup. frontal gyrus	tang.	44	7	1
	D4	Convex. sup. frontal gyrus	tang.	38	4	10
Patient 2	D1	Amygdala	rad.	3	no solution	17
	D2	Middle temporal gyrus	rad.	3	[24]	12
	D3	Supplementary motor area	rad.	6	[12]	10
	D4	Superior frontal gyrus	rad.	8	9	7
Patient 3	D1	Amygdala	rad.	5	[28]	7
	D2	Middle temporal gyrus	rad.	4	[40]	15
	D3	Supplementary motor area	rad.	5	[17]	9
	D4	Superior frontal gryus	rad.	5	[7]	8
Average error, omitting magnetic data in brackets where the singal/noise is poor					8	10

There has been some debate and criticism of this MEG-EEG study, mostly because of the fact that a single-channel MEG detector was used here instead of the multi-channel systems now available. The main point of the criticism is that, had we used a up-to-date multi-channel MEG system (for example, the 37 channel commercial system now available) our MEG error would have been considerably less, hence the MEG error of localization perhaps would have dropped to less than 5 mm and therefore would have been two or three times better than that of the EEG. Our response to this criticism has been the following. Our single-channel system performed well enough with the spherical head to yield a localization accuracy of better than 3 mm; therefore, how could this single-channel suddenly turn much worse in the patient measurements? Stated otherwise, if the single-channel worked well with the sphere, then it should work equally well with the patient. Further, the 8 mm localization error found in the MEG is readily ascribed to the use of the spherical model in the inverse solution. As implied throughout this report, this is the model which everyone uses, simply because no better model is available at this time. That is, the use of the spherical model, because no other is available, is enough to account for the 8 mm error. Finally, in the very complex matter of how detector errors become reflected in localization errors, there is no guarantee that the use of a 37-channel system would not actually have made matters worse, that is producing even a larger MEG error. For example, it could be, because the detection coils are all tied together on a spherical surface, that an error in "aiming" becomes much worse in this case than in a single-channel system, where such errors tend to cancel out because each "aim" is different. We can only add that this MEG-EEG experimental comparison was done in a careful way, involving more than two years of work, and should be considered accordingly by the MEG and the EEG community.

Finally, at the time of this writing, a report has just appeared of an experiment similar to ours, but measuring only the MEG (Balish et al. 1991). Again, epileptic patients were measured who had received intracranial electrodes for epilepsy monitoring. However, where depth electrodes were used in our patients, subdural electrode strips were used in the patients of this new study, which necessitated craniotomies. As a result of the scalp surgical disturbance, simultaneous EEG's could not be measured. A 7-channel MEG system was used, placed over the scalp a number of times to yield 50 or more MEG locations. An MEG localization accuracy of about 10 mm was obtained if only dipoles showing low noise were used as in our experiment (and about 17 mm for all dipoles). Therefore, this result confirms the MEG result in our MEG-EEG experiment.

Conclusions

Both in theory and experiment, it is seen that the MEG offers no significant advantage over the EEG in the specific task of localizing a dipole source. Because almost all focal sources in the brain can be represented by a dipole when viewed from the surface of the head, this conclusion applies to all focal sources in the head, due to both spontaneous and evoked neural activity. In spontaneous activity, this particularly applies to some types of epileptic spikes; in evoked activity, this refers to the early components such as N20-P30 of the somatosensory evoked response.

Although it had been implied that the main use of the MEG is its very superior localizing ability compared with the EEG, even without this ability the MEG remains very useful. For example, from the theoretical point of view it was seen that the MEG handles source modelling errors differently than does the EEG. Thus, in using a single dipole to approximate actual extended (non-focal) and multi-focal sources, the error of localization for this dipole would be different for MEG and EEG. Which is more accurate would depend on the nature of the actual source being approximated; MEG would be better for one type of source, and EEG for another. In addition, differences in MEG and EEG localizations (the distance between each apparent source) may be useful in characterizing extended and multi-focal sources.

However, the main use of the MEG, in our opinion, is the suppression of its signal produced by a source which is oriented radially to the skull. This suppression is a feature unique to the MEG. As mentioned, the suppression is due to the fact that a radial dipole in a perfect sphere produces no external magnetic field (Baule and McFee 1965). In the actual head therefore, because it is an imperfect sphere, the external field is suppressed instead of being zero. The suppression factor was experimentally found to be six in the rabbit head (Melcher and Cohen 1988), and was seen again to be about six in the human head as an auxiliary result in the MEG-EEG experiment (Cohen et al. 1990). This is a significant degree of suppression, and the MEG could stand as a useful tool in this regard alone. Thus, the MEG is sensitive mainly to tangential sources, while the EEG is known to be sensitive to both radial and tangential sources, although somewhat more to radial sources. We here suggest that this use of the MEG be called "source angularization", in analogy with the established term "source localization". Although the MEG has not yet been used this way clinically, it has already been successfully applied in choosing between competing source models of an evoked response in the normal human brain (Wood et al. 1985); this is illustrated in Figure 2. The evoked source in this case was relatively focal, and cer-

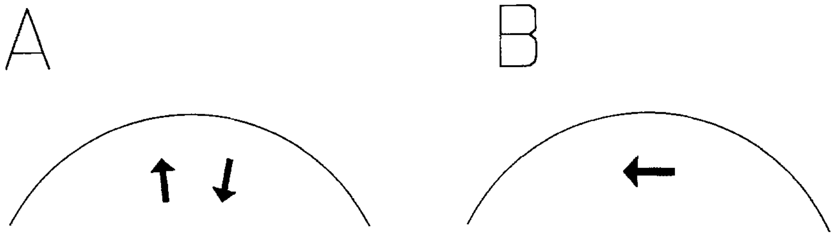

Figure 2. A and B were two competing source models for the evoked somatosensory N20-P30 EEG signal, producing similar EEG spatial patterns over the scalp. However, by using the MEG, it was shown that B was the correct model. This is because the radial dipoles in A would produce no MEG signal, while B would produce a characteristic pattern in the MEG, which was indeed seen.

tainly the MEG will show further usefulness in characterizing more extended sources, say those located across fissures or those which are more widespread yet.

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