Using EMSE and EGI for Source Analysis Display and Illustration
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Introduction

The purpose of this paper is to provide a manual for doing cortical source analysis with scalp-recorded electroencephalogram (EEG) and event-related-potentials (ERP). The manual done in this paper is a result of experiences using the "EMSE Suite" (Source Signal Imaging, Inc) with the EGI 128-channel sensor net (Electrical Geodesics, Inc). The system that has been developed can be used to produce electrode placement files that map the EGI electrodes for an individual MRI. These placement files may then be used to coordinate EEG / ERP recordings with the MRI files for location of cortical areas acting as electrical current sources for the observed EEG. This system is useful for working with individual participants and may be used for multi-participant studies.

Background

The purpose of this document is to detail the analysis of ERP data with component and source analysis. The electroencephalogram (EEG) consists of a varying electrical potential recorded on the scalp. The source of the EEG potential are thought to be changes in post-synaptic electrical potentials occurring during cortical activity. The EEG may be measured with electrodes placed on the scalp, and provide changing electrical potential with reference to a specific location. The EEG may synchronized to specific environmental, internal, or physical events. Such potential changes related to a specific event are termed "event related potentials" (ERP). The ERP is hypothesized to be a function of the cognitive or physiological activity surrounding the event. Techniques have been used to quantify the ERP by averaging over many trials in order to increase the signal of the electrical potential related to the event over the noise inherent in EEG activity. The averaged ERP thus has changes in electrical potential specifically related to the event of interest. An alternative approach to averaging EEG to obtain the ERP is to use filtering techniques. Quantitative techniques exist to relate the recording on the scalp to electrical current sources in the cortex. This document details an approach to that analysis.

A central tenet of cognitive psychophysiology's use of EEG is that event-related changes occur in EEG and may be extracted with numerical techniques. The typical approach is to assume that the event-related changes in EEG, "event-related-potential" (ERP), are small relative to the ongoing EEG activity. Thus, the ERP cannot be seen on a single trial because it is hidden by irrelevant EEG activity (signal-to-noise is low). However, the ERP activity is consistent across multiple events whereas irrelevant EEG activity is random. Thus, averaging the EEG time-locked to multiple events will increase the signal-to-noise ratio leading to averaged ERP data,

and typical time-locked and spatially distributed ERP components. The averaged ERP often is segmented into "ERP components". A commonly accepted view of ERP components is that they are defined by scalp topography, temporal morphology, and relation to experimental variables (Donchin, Ritter, & McCallum, 1978; Fabiani, Gratton, & Coles, 2000; Spencer et al., 1999).

"Cognitive psychophysiology" becomes "cognitive neuroscience" when the purpose of using EEG or ERP is to infer the activity of brain areas related to the experimental manipulations or cognitive processes. Such activity may be measured by doing "cortical source analysis". (Scherg, 1990; Scherg, 1992; Scherg & Picton, 1991; Huizenga & Molenaar, 1994). Cortical source analysis uses quantitative methods to infer electrical current sources in the brain that generate the observed EEG activity on the scalp. These sources are termed "equivalent current dipoles" (ECD). The ECDs are believed to be caused by combined neural activity acting in parallel (and topographically aligned) so that their combined activity transmits current that may be recorded on the scalp. Cortical source analysis hypothesizes a (a set of) dipole (s) located in the cortex representing a current source generated by a large number of neurons located in a discretely bounded area. The "forward solution" (Scherg, Picton, 1991) may be calculated that represents the electrical current that would occur on the scalp from a dipole with specified location and magnitude vectors. The forward solution current topography is compared with the current measured with scalp electrodes, and the dipole location / magnitude adjusted to achieve a best fit between the hypothesized and actual current.

Using EEG and ERP as measures of brain activity is a relatively recent development in cognitive psychophysiology and cognitive neuroscience. Studies with studies 20 EEG electrodes (Richards, 2000) or 40 EEG electrodes (Richards, 2001) were recorded. Using this amount of electrodes limits the ability to infer the brain sources of the scalp-recorded electrical activity. Two recent developments have improved the resolution of EEG/ERP recording for cognitive psychology and cognitive neuroscience (Swick, Kutas, & Neville, 1994; Gevins & Cutillo, 1995; Gevins, Leong, Smith & Le Du, 1995). First, high-density EEG/ERP recording has partially solved the problem of spatial localization by recording at higher densities than the International 10-20 system. One such recording configuration is the "geodesic net" developed by Don Tucker (Electrical Geodesics Inc; Tucker, 1993; Tucker, Liotti, Potts, Russell, & Posner, 1994). These nets have 128-electrode configurations and provide interelectrode distances of 35 to 40 mm for adults and 20 to 25 mm for infants (Tucker, 1993). Second, better quantitative techniques allow the quantitative estimation of source dipoles. Scalp current-density topographical mapping (Nunez, 1990; Perrin, Bertrand, & Pernier, 1987; Perrin, Pernier, Bertrand, & Echallier, 1989; Srinivasan, Nunez, Tucker, Silberstein, & Cadusch, 1996) allows the visualization of current densities on the scalp and localizes the source currents for the potential changes recorded with EEG (or ERP). This allows better spatial resolution of local cortical sources reflected on the scalp topography. Techniques using dipole modeling (e.g., "brain electrical source analysis"; Scherg, 1990; Scherg, 1992; Scherg & Picton, 1991; Huizenga & Molenaar, 1994) have been improved over early versions. These hypothesize specific locations for neural generators (cortical dipoles, source potentials) of the recorded scalp potentials, and compare the scalp distributions generated by the hypothesized cortical current source with actual potentials recorded in the experiments. These algorithms are now more sophisticated, do not suffer the indeterminacy of the 10-20 system, and are widely available in computer programs.

The Source Signal Imaging, Inc has developed programs for doing ECD modeling from scalp-recorded EEG and ERP. The EMSE Suite program has a "Source Estimator" module that reads in EEG or ERP data and does plots, topographical maps, and ECD analysis. The "MR Viewer" reads in MRI files and allows the ECDs from the Source Estimator to be displayed on scalp, cortex, or MRI slices. The main purpose of this paper is to present techniques for using EMSE programs with 128-channel EEG recording to do topographical mapping, ECD analysis, and for illustration of ECDs on MRIs for individual or groups.

(Note: An alternative system for doing this is the "BESA" system (BESA 2001, and Brain Voyager). I have used both and find the BESA program a little more sophisticated than the EMSE program concerning the ECD analysis. However, I have found the EMSE program to be much more transparent in its file use and in its topography system. Since I do a lot of my programs in C++ for analysis, warping heads to different spaces, I decided to go with the EMSE program.)

EEG Recording

The electroencephalogram (EEG) was recorded with the EGI (Electrical Geodesics Incorporated, Eugene, OR) 128 channel EEG recording system (Tucker, 1993; Tucker, Liotti, Potts, Russell, & Posner, 1994). The "Geodesic Sensor Net" consists of 128 Ag-AgCl electrodes mounted in a geodesic configuration with elastic connections. A sponge is located in the pedestal and the entire net was soaked in a saline-based electrolytic solution to wet the sponges. The net has pedestals marked with the vertex, ears, and nasion locations. The net's anatomically-marked locations were used to position the sensor net and the elasticity of the connections between pedestals positioned the other electrodes in a fixed set of positions on the scalp. The electrode positions cover the scalp relatively evenly with interelectrode distances of 35 to 40 mm. The EEG scalp sites are not those traditionally used such as the 19 electrodes of the "International 10-20" system (Jasper, 1958; Pivik, Broughton, Coppola, Davidson, Fox, & Nuwer, 1993) but a rough correspondence can be made (Luu & Ferree, 2000; Srinivasan, Tucker, & Murias, 1998). The electrode recordings were adjusted to record with impedances below 100 kΩ. The EEG signal was referenced to the vertex and was amplified with the EGI "NetAmps" that consist of high-impedance amplifiers and a PowerPC-based computer system. The EGI "NetStation" computer program was used to control zero and gain calibrations for each participant, impedance calibration, A/D sampling, and EEG data storage. The sampling rate of the EEG was 250 Hz (4 ms samples) with band-pass filters set at 0.1 to 100 Hz, with 20K amplification. The vertex-referenced EEG was algebraically recomputed to an average reference.

The choice of 100 kΩ as the maximum impedance value was based on the high input impedance of the EGI amplifiers. These amplifiers have an input impedance of about 200 MΩ. compared with traditional EEG amplifier impedances of about 10 MΩ. Given the recommendation of interelectrode impedances being at least 1% of amplifier input impedance (e.g., 10 kΩ for 10 MΩ amplifier; Picton et al., 2000), 100 kΩ is appropriate for this amplifier. Ferree, Luu, Russell, and Tucker (2001) estimate that for this amplifier system a 50 kΩ preparation would lead to a maximum 0.025% signal loss, and therefore the current levels should lead to no more than a 0.050% signal loss. Ferree et al. (2001) found no discernible signal loss with electrode preparations at about 40 kΩ.

Recording is also done with infant participants. The 128-channel net for infants consists of 124 electrodes mounted in a geodesic configuration with elastic connections. There are three net sizes of 38 to 41 cm, 41 to 43 cm, and 43 to 45 cm, that will fit infants from 8 to 26 weeks of age (Richards & Hunter, 1997; Richards, 2000; Richards, 2001). The 124 scalp electrodes have an average interelectrode distance of 21 mm, well below the recommendation that a maximum of 30 mm be used for high-density recordings to resolve focal electrical potential changes and sharp field gradients, and provide an adequate average reference (Srinivasan, Tucker & Murias, 1998). An additional 4 connections are available in the electrode connector for electrodes at the outer canthii and below the two eyes. These four electrodes are placed with electrodes using adhesive electrode collars. The use of these four electrodes allows the elimination of the geodesic components over the infant's face, such as is used in the adult versions of the sensor net. The placement of the sensor net results in electrode impedances of about 10 to 50 kΩ.

MRI Recording

These are details of the MRI recording that we do. We use a local health care provider, "Palmetto Imaging" (Columbia, SC). These scans are done in a GE 0.5 T system and so their resolution is not as great as it could be. It is sufficient for doing EEG / ERP based ECD analysis. The total time in the scanner is about 25 minutes and we have done this with children as young as age 8 with no difficulties. This protocol is supervised by Jeffrey Schatz. See Appendix A for full details.

1—An initial rapid, fast-spin echo saggital sequence to get the head orientation (12 slices, TE=25, TR=300, 5 mm slices with 2 mm gap).

2—An SPGR sequence (i.e., incoherent gradient echo- rf spoiled) to look at anatomy and for co-registration with EEG / ERP or TMS. Primarily T1 weighted but some T2 information is present so that there is better gray matter / white matter contrast (60 slices, 45 degree flip angle, TE=12, TR=50, 3 mm contiguous slices).

3—A fast spin echo T2-weighted axial sequence to view any pathology (29 slices, TE=102, TR=6000, 5 mm slices with 0.5 mm gap).

4—An intermediate weighted axial sequence, which in some cases will give a better view of pathology than the T2-weighted sequence (19 slices, TE=23, TR=2500, 5 mm slices with 2.0 mm gap).

5—Description of how the images from the MRI are transformed into the VMI files of the EMSE system.

The result of the MRI recording is a volumetric MRI set (*.vmi files). This set has the individual slices from the MRI incorporated into a single file that represents the MRI. The resulting MRI set can represent MRI slices in the saggital, axial, or coronal planes across the entire skull. In our system these come from the T1-weighted sequence and represent 3 mm slices.

Interlude about EMSE and EGI interface

First, this discussion will focus on a single individual who gets the MRI and has had some type of EEG recording. There are two types of files that need to be created to interface the two systems: electrode placement files and fiducial measurement files. One aspect of the EMSE program is the necessity of creating "electrode placement" files ("*.elp", or ELP) that have the three-dimensional coordinates of the electrode placements. The data in our lab is recorded with the "Electrical Geodesics Inc" (EGI) 128-channel sensor net, amplifiers, and recording system. In order to use the EMSE Source Estimator program to do ECD analysis or topographical maps, an ELP file has to be created. This file has one electrode listed for every EEG / ERP channel that will be entered into the Source Estimator program. The electrode locations must be related to the individual's scalp measurements. At some point information from the individual has to be entered into the MR Viewer (e.g., displays of ECDs obtained from MR Viewer). This requires a set of fiducial measurements for that individual. This will translate the dimensions of the ECD found in the Source Estimator with the dimensions of the MRI (vmi file) in the MR Viewer. This translation is called "co-registration" and demands a set of fiducial measurements to make the two spaces overlap.

The fiducial points in the MRI and the ELP file are the nasion, right pre-auricular point, and left pre-auricular point. These points are located in the MR Viewer program and may be permanently stored in the VMI file. The co-registration in the MR Viewer uses these three points (and can use other points) in the VMI file and three points representing these locations in an ELP file. The actual measurements in the VMI and ELP file may differ, i.e., be in a different coordinate frame. The co-registration allows locations stored in the ELP-based reference system to be displayed in the MR Viewer VMI-based reference system.

One technique (that I do not use) is to use a module of the EMSE Suite called the "Locator". This module along with a spatial receiver / transmitter system could be used to locate the actual locations in 3-D space of the fiducial locations for an individual and locate the actual scalp locations of the electrodes. This process is intensely tedious. Each individual electrode has to be located with the transmitter device (electrode pushed aside, located transmitter device, push transmit button). It is possible to do this with a cooperative adult participant. However, with younger children this would be impractical. Additionally, the primary application for this method for me is infant participants. This procedure could not be done with infants.

So, I have followed a theoretical-computational route for this. A brief description of this procedure will be given in this section, followed by much greater detail in the following section. Additionally, Appendix 1 details these points step-by-step. 1) Several points are identified in mm coordinates from the VMI file in the MR Viewer. These points are placed in an ELP file that I will refer to as the participant-MRI-based fiducial file (or simply the participant's fiducial file). These measures are in mm coordinates for that participant. 2) The second step is to generate a scalp wireframe for this participant. This is done in the MR Viewer program with a wizard-based procedure and is very easy to do. However, the wireframe must be saved in a coordinate system. Thus, the VMI and ELP-fiducial file must be co-registered. This step results in a scalp wireframe for that individual that represents scalp coordinates in the mm coordinates of that participant. 3) The fiducial points from the participant are read by a C++ program that generates a theoretically-

derived electrode placement file for the EGI net. This program uses uses the nasion, inion, right and left mastoid, right and left pre-auricular points, and vertex points measured in the MR Viewer. These points and their anatomical representation (Luu & Ferree, 2000; Srinivasan, Tucker, & Murias, 1998) are then used along with the circular-spherical-geodesic structure of the net to generate a vector along which lines represent the theoretically-generated location of the electrode. The location on this vector is then compared with the scalp wireframe derived from that individual's MRI, and the nearest point on the wireframe is saved and defines the electrode location. This location is then stored in an ELP file. The resulting ELP file represents, therefore, the theoretically derived computed geodesic location on the actual scalp of that individual. 4) A second fiducial file also is created at this point. This file is an ELP file that has fiducials that are in the Talairach coordinate system (Talairach & Tournoux, 1988). This is done by taking cortex measurements on the VMI file in the MR Viewer, translating these cortex measurements on this individual, so that they match the dimensions of the Talairach cortex found in the Talairach manual. This fiducial file is used in later analyses do a co-registration between the VMI-based coordinate system and the Talairach-ELP coordinate system, to display ECD files that are in the Talairach coordinate system. This is extremely useful for taking ECDs from different participants, translating the ECDs into the Talairach system, and then displaying them on a single MRI. It also is useful for localizing anatomical locations on an MRI with Talairach information and for coordinating ECDs from participants that have not had a MRI.

The MR Viewer program is used to create skull "wireframe" coordinate files. The wireframe files consist of small triangles with coordinates located on the skull (or other anatomical location) that define the boundaries of the skull. The wireframe is done in the MR Viewer program for the skull. The wireframe coordinates must be saved in the fiducials file space. This is done by co-registering the fiducials file with the volumetric files, and then saving the wireframe in the fiducial file coordinate system. At a minimum, a wireframe file must be made for the scalp in the MR Viewer. It would be beneficial to create outer- and inner-skull wireframe for use with realistic head shape models for cortical source analysis. Also, cortex wireframes may be created for cortical source analysis (cortical activity display) or for Visualizer displays of electrical activity on the cortex. The Visualizer program (and EMSE) also may used a "head shape" file. This head shape file is calculated from the wireframe in a computer program, or may be actual measurements made with a 3-d measurement system. The wireframe file OR head shape file is used in the EMSE, MR Viewer, or Visualizer, so the head shape file is redundant to the scalp wireframe file.

At this point there are several files:
*.vmi: represents the volumetric representation of the MRI and contains the three fiducial points;
*.wfr & *.hsp: represents the scalp wireframe based upon the individual's MRI;
*Fiducials.elp: fiducial points (nasion, pre-auricular) and the other points for that individual
*Talairach fiducials.elp: fiducial points and other points in Talairach coordinate system
*.elp: represents the theoretically-derived computed geodesic location on the individual's scalp.

The fiducial files, head shape and wireframe files, and electrode placement files, are used in the EMSE EEG / ERP analysis program. The electrode placement files are used for the electrode locations. These electrode locations are used for topographical maps, source analysis, and 3-d Visualizer presentations. The head shape and wireframe files may be used in the Visualizer

program for showing electrical activity on the scalp, skull, or brain. The wireframe files (scalp, outer skull, inner skull) may be used in equivalent current dipole analysis with realistic head shape models. These realistic models get away from the spherical calculations to calculations based on actual head shape.

Head and scalp measurements from structural MRI

The structural MRI recording for a participant may be used to find head and scalp measurements. These measurements may be used in the EMSE (or BESA) computer programs for doing topographical mapping of the EEG or ERP, equivalent current dipole analysis, other source analysis, and presentation of electrical potential changes in 3-D images. The measurements made on the MRI are necessary for correct placement of electrical activity on scalp, skull, or brain locations.

There are several locations that may be identified in the MRI using the MR Viewer computer program. These are given with a brief explanation of their importance and the description of their identification. In each case, the volumetric display of the MR Viewer is used to identify the locations on the MR. The saggital, coronal, and axial coordinates of the MR Viewer are recorded in an Excel file that computes a "fiducials" file for later use in the system. The order of the identifying these locations is somewhat arbitrary, but the following order is useful in the identification process. Note that left and right skull locations are reversed in the MR viewer.

AC and PC: Anterior commisure (AC) and posterior commisure (PC). The anterior commisure is a band of fibers running laterally connecting the two hemispheres inferior-posterior to the genu of the corpus collosum anterior to thalamus, and appears to be in the third ventricle. The posterior commisure is a similar band of fibers posterior to the thalamus, anterior to the splenum of the corpus collosum, and appearing in the third ventricle near the third-fourth ventricle canal. The AC and PC are important because these two neural landmarks are used in the Talairach system to mark the coordinates of the cortex. The AC-PC line forms the axial plane of the Talairach system, with the vertical AC line being the axis for the axial dimension. The AC is located in the MR viewer by identifying on the saggital view a likely candidate anterior of the ventricle and inferior to the corpus collusum. This candidate is confirmed on the coronal and axial views as a fiber band running between the two hemispheres. The PC is located similarly. The figure on page 5 of the Talairach manual is helpful in finding these. The AC-PC line marks the anterior-posterior axis (coronal) of the coordinate system.

LPA and RPA: The left and right preauricular points are the next step in the identification. The preauricular points are the bone immediately anterior to the ear canal, and middle (superior-posterior) of the canal. These points mark the saggital (left-right) plane for the coordinate system. These are also used as "fiducial points" in the EMSE system for co-registering disparate coordinate systems. These points are lower than the AC-PC line. The ear opening is found on the axial view and the center of this opening is determined. The coronal view is then used to get the height of the point and the axial view is used for the anterior-posterior coordinate. The place where the vertical plane defined by the left and right preauricular locations transects the AC-PC line is the origin of the saggital, coronal, and axial coordinates.

Nasion: The nasion is the bone immediately above the eye sockets in the skull midline. The nasion is the third fiducial point in the EMSE system. The nasion is superior to the LPA-RPA plane and inferior to the AC-PC line. It is not on the same plane as these (as assumed by EGI and EMSE) but between the two. The axial view of the MR Viewer is used to find the center between the two eyes. The saggital view is then used to find the top portion of the skull. Then, return to the axial view at this point to determine the spatial coordinates.

RM and LM: The right and left mastoids are defined as the bone immediately posterior to the ear opening. The right and left mastoids are on the same axial plane as the LPA and RPA. The right and left mastoids are important for identification because external measurements are made from these points and each has an electrode placed on it with the EGI sensor net. When the LPA and RPA are identified, similar measurements should be made behind the ear opening for the mastoids.

Inion: The inion is the base bone of the skull at the occipital location. The inion is used only for the external measurements. It is generally (always?) at the same level as the LPA, RPA, RM, and LM.

Miscellaneous scalp and cortex locations: Several locations are identified on the AC-PC line (or AC-PC/LPA-RPA transection). These locations are used to determine the radii of the skull and for proportional calculations for coordinating EMSE spherical coordinates, MRI coordinates, and Talairach coordinates. On the axial view at the AC-PC level: scalp at front and rear of skull on AC-PC line, cortex at front and rear on AC-PC line, cortex on left and right on AC-PC plane at the largest width. On the saggital view on the AC-PC plane, find the cortex on top with the tallest height and the vertex—scalp on midline at its tallest point.

Eye electrode locations: The electrode locations for , 17, 125, 126, 127, and 128 must be location. These electrode locations are not on the concentric sets of electrodes in the EGI sensor nets and must be individually measured. , 17 is midway between the eyes. On the axial plane the middle of the skull is determined. Warp the point to the saggital view, find the middle height, and warp back to the axial view. Pick the middle point. On this same axial plane electrode 125 is the skull location immediately posterior to the right eye socket (left side of MR) and electrode 128 is the skull location immediately posterior to the left eye socket. On this same axial plane, warp to the saggital view in the middle of the right eye socket. Electrode 126 is located immediately below the bone of the eye socket. Warp to this height, go to the axial plane at this height, locate the center of the left eye socket, warp the saggital view, and identify the location of Electrode 127 on the saggital view.

Participant MRI-based fiducial file (*Fiducials.elp)

The locations identified on the volumetric view of the MR Viewer are used to create a "fiducials" file for this individual. The fiducials file is constructed as an "electrode placement file" in the EMSE system. This file contains the three "fiducials" used by the EMSE and MR viewer programs to co-register different coordinate systems. Additionally, it contains the measurements made on the MRI in the MR viewer. Each of the measurements is an "electrode". An Excel file is available in which the MR Viewer coordinates are placed and calculations are

made of the "electrodes" in a format for the EMSE system electrode placement files. Additionally, the external head measurements and the spherical coordinates of the EMSE Equivalent Current Dipole sphere are in this file.

The coordinate space for the fiducials file could be any coordinate space. A typical coordinate space is based on the LPA, RPA, and nasion measures. i.e., a significant "zero" axis is goes through these locations on the scalp. However, particularly for later coordination with the Talairach space, the fiducials I use are actually based on the AC-PC axis. That is, the zero point for the saggital plane is a point located midway between the AC and PC locations. The intersection axis (coronal plane) is based on a line drawn from the LPA to the RPA. However, since the RPA and LPA are not (usually) in the axial plane of the AC-PC line, then the line between the AC and PC is above the RPA-LPA line, and the zero point for the system is where a perpendicular line from the RPA-LPA line would intersect the AC-PC plane. This provides two benefits. First, since the AC-PC line defines the axis of the entire system, the system may be easily transformed from the individual's MRI measurements to a Talairach space without geometric manipulations (simple linear transformation). This is because the Talairach space also is based upon the AC-PC line and similar RPA-LPA line. Second, the EMSE Source Estimator program calculates a sphere for the ECD analysis. This sphere is a best-fitting sphere based on the electrode locations in the ELP file, and it is centered at the 0, 0, 0 location for the ELP electrodes. It is not centered by a coordinate system based on the fiducials intersections. Since the electrode locations in the ELP file, and the coordinate space in the fiducials file, are based on the AC-PC line, the ECD locations in the EMSE Source Estimator program are in AC-PC coordinate space. It is therefore a simple linear transformation from the ECDs generated in the EMSE program to ECDs in the Talairach coordinate space (also based on AC-PC space) and does not involve geometric transformations.

The fiducials file is used in several places in the EMSE system. First, this file may be used as the fiducials file to co-register different coordinate systems. In the MR Viewer, the fiducials file may be co-registered with the volumetric files. This will place "electrode" marks on the MR Viewer volumetric views. These electrode marks should occur at the appropriate anatomical landmarks measured on the skull or brain. This fiducial file co-registration is used when dipoles or other source coordinates are plotted onto the volumetric views in the MR viewer. The fiducials file also is used to create an electrode placement file for the EGI sensor net.

External head measurements are made for the participants who have the MR. These measurements also are made for every participant in the EEG lab. These head measurements help to create electrode placement files for individuals and relate individual EEG /ERP to the MRs. The external measurements are: nasion-inion diameter, mastoid-mastoid diameter, mastoid-nasion-mastoid circumference, mastoid-inion-mastoid circumference, nasion-vertex-inion circumference, mastoid-vertex-mastoid circumference (or LPA-vertex-LPA circumference). The external head measurements are stored in the fiducials file. They are in a location below where the EMSE programs reads data.

The external head shape parameters may be calculated from the wireframe coordinates. The external head shape parameters are nasion-inion diameter, right to left mastoid diameter, mastoid-nasion-mastoid circumference, mastoid-inion-mastoid circumference, nasion-vertex-

inion circumference, and mastoid-vertex-mastoid circumference. The fiducials file contains the locations of the nasion, inion, vertex, and mastoids. Each of these anatomical locations exists in the wireframe. The diameter measurements are directly calculated from the fiducial measurements. The circumference measurements may be computed by drawing a circle from the known locations (e.g., left mastoid to nasion to right mastoid), finding the closest point on the wireframe to the points on the circle, and doing a numerical integration to find the circumference on this circle. These calculations match very closely with the measurements made with external measurement devices.

Talairach-based fiducial file (*Talairach Fiducials.elp)

The prior section discussed the creation of a fiducials file based on a spatial framework defined by the MR Viewer program and the participant MR. An alternative spatial framework, or spatial coordinate system, is a space based on an anatomical dissection of a human brain done by Talairach (Talairach & Tournoux, 1988). This coordinate system is based on a coordinate space whose origin is the anterior commisure, with the axial plane defined by a line running through the anterior and posterior commisures, and the coronal and saggital planes defined as perpendicular to the AC-PC line. Talairach (Talairach & Tournoux, 1988) present this spatial framework with the anatomical dissection of a human brain and the identification of Brodmann areas and cortical areas for this brain. The "Talairach framework" or "Talairach space" consists of this origin and a brain with a specific coronal, saggital, and axial radii. The Talairach space has at least three functions. First, it may be used as an atlas to identify the cortical areas via the figures in the stereotaxic atlas. Second, the Talairach coordinates are being used in the research literature interested in neuroimaging and cortical source analysis. Third, the Talairach coordinate system provides a standard system for collating sources across disparate head sizes.

The fiducial files in the MRI framework may be translated into the Talairach framework. From the known radii for the MRI framework and the radii found in the Talairach atlas, a proportional translation may be made from the fiducial file created on the participant MRI into a fiducial file created with the Talairach dimensions. This Talairach fiducial file will have the anatomical landmarks proportionally to where they should appear in the Talairach atlas. This file is therefore the Talairach fiducials for that specific participant's MR. Thus, if one has Talairach coordinates from any individual they may be mapped (as dipoles, sources, electrodes) onto this participant's MRI in the MR viewer by coordinating the volumetric set with a source set defined by the Talairach fiducials for that participant. That is, the Talairach fiducials are co-registered with the MRI from the individual, and then Talairach-based dipoles or sources may be plotted together on the same volumetric views even if the dipoles or sources are from different individuals.

These fiducial files have been done as a dipole file. A "Talairach Fiducials.ecd" file was created that has the Talairach coordinates for parts of the cortex, such as: frontal pole of cortex, point of the AC-PC line at the corpus callosum, point at the AC, PC, half-way between PC and rear, and rear of cortex. Around these points other places are found, such as the top of the cortex, right and left of cortex, and bottom of cortex or outer lateral-inferior portion of temporal cortex. These fiducials can then be used as fiducials to register the Talairach space with individual participant MRI space.

Talairach anatomical locations on a participant's MRI

One use of the Talairach fiducial file is that coordinates of specific locations may be found in the Talairach atlas and plotted on the MRI of a specific individual. This is done in the following manner. The Talairach fiducial file for that individual's MRI is co-registered with the VMI for that individual. This then allows the loading of dipole files (*.ECD) in which the dipoles are located in Talairach coordinates. The dipole locations may come from known anatomical locations in journal articles or like sources. These locations are then entered manually into an ECD file and then loaded in the co-registered MR Viewer. The locations then appear as dipoles in the coordinates that the Talairach map would designate for that individual's MRI. Tres cool!!

I currently use a technique that can map the MRIs for an individual participant onto the Talairach coordinate system. First, fiducial points are located in the MRI of an individual. These consist points on the coronal axis (AC-PC line) of the front and rear of the cortex, the anterior-most point of the corpus collusum (CC), the AC, PC, and a point midway between the PC and rear of the cortex. At the CC point, the dimensions of the cortex (top, right, left, bottom) are found, and at the other points, the top, right, left, and most inferior-lateral portions of the temporal cortex are located. These same fiducial markers were found for the Talairach coordinate system. Any point in the Talairach coordinate system may be mapped into the MRI system by defining the spherical coordinates (phi, theta, radius) of the Talairach point, finding the closest Talairach fiducial, getting a ratio of the radii of the corresponding MRI fiducial to the Talairach fiducial, multiplying the ratio times the radius of the Talairach coordinate, and then translating this coordinate into the participant MRI. Of course, this also can be done in the reverse manner (translate MRI coordinate into Talairach system). One interesting application of this technique is to take a set of coordinates in the Talairach system that define a Brodman area, or anatomical structure, translate the coordinates into a participant MRI, and then use the three-dimensional wireframe of that participant to identify "source volumes" for realistic cortical source analyses. The principle of this translation from/to Talairach to/from MRI space may be applied to two MRIs.

Talairach daemon database and participant's MRI

In addition to this, there are several computer programs that will receive entries in X (coronal), Y (saggital), and Z (axial) dimensions and give the Talairach space for these dimensions. One of these programs is the "Talairach Daemon" (Research Imaging Center, University of Texas Health Sciences Center at San Antonio (Fox & Uecker, 2005; Lancaster, Summerln, Rainey, Freitas, & Fox, 1997; Lancaster, Woldorff, Parsons, Liotti, Freitas, Rainey, Kochunov, Nickerson, Mikiten, Fox, Freitas, Rainey, Kochunov, Nickerson, Mikiten, & Fox, 2000).

"The Talariach Daemon is a data base and data retrieval system returning anatomical labels (traditional, feature-based terms) when queried with a Talairach coordinate. The entire brain has been anatomically labeled using a five-level, volume-based, terminological hierarchy. Level One ("hemisphere") has six components: left and right cerebrum; left and right cerebellum; left and right brainstem. Level Two ("lobe") divides each hemisphere into lobes or lobe equivalents. In cerebrum and cerebellum, lobes are as traditionally defined. In brainstem, three lobe-equivalents

are defined: midbrain, pons and medulla. In both cerebrum and cerebellum, brain areas lying deep to traditionally defined lobes are termed sub-lobar. Level Three ("gyrus") divides each lobe into gyri or gyral equivalents. Nuclear groups, such as thalamus or striatum, are gyral equivalents. Level Four of the hierarchy is tissue type. Each gyrus or gyral equivalent is segmented into grey matter, white matter and CSF. Level Five of the hierarchy is cell population. Cerebral cortex is labeled by Brodmann area. Nuclear groups are labeled by subnuclei. Cytoarchitectonic labels for cerebellar cortex and tract labels for white matter are being developed but are not yet available.

The Talairach Daemon's labels are stored as a volume array (1 mm isometric voxels) spanning the extent of the brain in Talairach 1988 atlas. This corresponds to approximately 500,000 voxels. Each voxel in this array contains a pointer to voxel-specific brain information. This information is called a relation record and is managed as a linked list. A relation record can store any information that is recorded using Talairach coordinates. To eliminate the need for storing duplicate information in relation records, each record contains pointers to the information rather than the information. This scheme offers the potential for extremely high speed access to information within the relation records." http://www.loni.ucla.edu/ICBM/ICBM_Daemon.html

I generated coronal, saggital, axial coordinates that covered the entire database, saggital = -70 to 70, coronal =-102 to 65, axial -42 to 67; 206560 observations at 1 mm area. I then submitted these coordinates with the Talairach Daemon Client to the TD server and generated theTalairach Daemon's labels for nnnnn points covering the entire brain in 1 mm voxels. This information is stored in a SAS dataset and a txt file for input to other programs. The data can then be used in conjunction with other programs to translate a MRI coordinate into the Talairach system and look up the lobe, gyrus, Brodmann area, corresponding to that MRI coordinate. (First, it may be used as an atlas to identify the cortical areas via the figures in the stereotaxic atlas. Second, the Talairach coordinates are being used in the research literature interested in neuroimaging and cortical source analysis. Third, the Talairach coordinate system provides a standard system for collating sources across disparate head sizes.)

One other use of this database is to generate wireframe files or MRI volumes based on the Talairach system translated into a MRI space. For example, one can find all the points belonging to a specific gyrus (anterior cingulate cortex) or Brodmann area (BA 19), translate those points from the Talairach coordinate into the MRI coordinate, and then identify all the tetrahedra in a FEM wireframe that correspond to the specified area. These tetrahedra can then be stored in a separate wireframe file and used as a source volume in realistic cortical source analysis. Or, similar identifications of areas can be made, translated into the MRI space, and then Analyze files may be created as "overlay" files for the MRI. These can then be displayed as overlays of the MRI volume (e.g., using MRICro).

Creation of single-subject electrode placement files: Individual with MRI

The correct use of the cortical source analysis would be to have structural MRI recordings on a participant in order to accurately use information from that participant for electrode placements on the anatomical locations of the skull, and to relate the placements on the skull to underlying cortical areas. Such electrode placement files perform the functions of landmarks for cortical

areas. This need is obviated somewhat for college-age participants for whom there is a reasonable assumption of a regular relation between skull landmarks and underlying cortical areas. However, for differences across individuals, particularly when concerns about the individual subjects are concerned, the use of participant structural MRI recordings is paramount. The creation of electrode placement files for individuals with a structural MRI recording will be detailed in this section. This function is implemented in the "Head Shape" computer program.

The creation of an electrode placement file for a participant with structural MRI recordings follows the fiducial file measurements and the known construction of the EGI sensor net. The fiducial file measurements made on the individual contain skull landmarks, including, nasion, inion, vertex, pre-auricular points, mastoid, front-rear and left-right scalp locations for the AC-PC line, and eye measurements. The EGI sensor net has several of these locations over which specific electrodes are assumed to lie: nasion-17, right-mastoid-101, left-mastoid-57, vertex-ref, the eye locations (125, 126, 127, 128). Thus, the registration of the MRI fiducials on these electrode positions is unambiguous.

The EGI sensor net is organized in concentric sets of electrodes and locations of the sensor net electrodes may be referenced to the known electrode locations. There are eight concentric sets of electrodes (seven full and one partial circle), the nasion-17 and the eye electrodes. I assume that the eight concentric sets are equally divided. Since the mastoid locations are on the seventh set, the distance from the vertex to each of the concentric sets may be calculated. The distribution of the electrodes around a single set may be calculated by knowing the midline locations, the number of electrodes, and assuming an equal distribution around the circle. Thus, the EGI sensor net electrodes may be placed on spherical locations by virtue of the "geodesic" organization of the electrodes in the sensor net.

Given the spherical locations of the electrodes on the sensor net, an electrode placement file may be generated by finding the closest location from the electrode locations on the sphere to the head shape generated for the individual. This is accomplished by moving a line from the origin of the sphere to (and through) the coordinates of the electrodes. The point in the head shape file created for this individual that is closest to this line is considered to be the electrode location for this individual. This electrode location is given in the framework of the fiducials from the MRI and thus may be co-registered with the MRI, individual scalp/skull/brain wireframes, and the fiducials file. The electrode placement file may therefore be used in the EMSE program for topographical maps, equivalent current dipole analysis, realistic head model analyses, and Visualizer presentations.

One discussion point from earlier: the coordinate system of the electrode placement files and the locations of the electrodes are in the coordinate frame of the AC-PC axis. This comes about as follows. First, the fiducials files are created from measurements taken from the VMI in the MR Viewer program. The measurements are placed into an Excel file and transformed so that they are in the AC-PC coordinate space. Second, during the process when the scalp wireframe is created and saved, it is saved in the co-registered spatial coordinate system. Since the fiducials file and the VMI file are co-registered, the saved scalp wireframe is in the coordinate system of the fiducials file—the AC-PC axis. Third, since the points for the ELP file are picked from this scalp wireframe, the resulting ELP file is created in the AC-PC axis coordinate system. This has

a direct benefit for the EMSE Source Estimator program. The EMSE Source Estimator program calculates a sphere for the ECD analysis. This sphere is a best-fitting sphere based on the electrode locations in the ELP file, and it is centered at the 0, 0, 0 location for the ELP electrodes. It is not centered by a coordinate system based on the fiducials intersections. Since the electrode locations in the ELP file, and the coordinate space in the fiducials file, are based on the AC-PC line, the ECD locations in the EMSE Source Estimator program are in AC-PC coordinate space. It is therefore a simple linear transformation from the ECDs generated in the EMSE program to ECDs in the Talairach coordinate space (also based on AC-PC space) and does not involve geometric transformations.

Creation of single-subject electrode placement files: Individual without MRI

The correct use of the cortical source analysis would be to have structural MRI recordings on a participant in order to accurately use information from that participant for electrode placements on the anatomical locations of the skull, and to relate the placements on the skull to underlying cortical areas. This need is obviated somewhat for college-age participants for whom there is a reasonable assumption of a regular relation between skull landmarks and underlying cortical areas. There may be times when MRI recordings on individual participants is not possible. For example, it would be impractical to do so in large-scale studies. In such studies where normal college-age participants is used it is very likely that nothing would be gained by individual MRIs. There also may be participant concerns that prohibit individual MRI recordings. This would be true for recording on special populations (normal infants, preschool children) or for whom the recording protocol would create experimenter-initiated human subjects' risks (recording of ADHD children in experimental research without direct benefit to the individual). An alternative strategy is to use MRIs from typical individuals. The creation of electrode placement files for individuals without a structural MRI recording will be examined in this section. This is implemented in the "Head Shape" computer program.

The creation of electrode placement files for individuals without a structural MRI recording is based upon individuals with MRI recordings. It is assumed that basic head shape idiosyncratic details will not affect the electrode placement file locations. So, head measurements are taken from the individual like those taken from the participants that had the MRI recording. The distance between the current individual and the individuals with the MRI recordings is computed. The MR-individual with the smallest distance to the current participant is chosen as the template for this individual. This procedure depends on having an adequate selection of MRI recordings for participants with particular sets of head sizes. Given the large changes in head size over age (infancy through adolescence) this procedure should have an adequate selection of MRI recordings for each age that is tested.

The actual electrode placement files for each individual are "warped" to fit the measurements of that participant. The relative proportion of this participant's measurements from front-rear, left-right, and midline-vertex are compared to those of the participant whose MRI was chosen. The electrode placement file for this individual is based on the electrode placement file of the MR-individual with a linear adjustment by the proportion difference between these two participants. In addition to the warped electrode placement file, a fiducials file is created that also is changed from the MR-individual by the proportion difference with the current participant. The warped

electrode placement file and the warped fiducials file constitute a sufficient set of measurements to do EMSE analyses (topographical maps, equivalent current dipole). These files also are used in the transformation of EMSE equivalent current dipoles to Talairach coordinate space.

The warped electrode placement files and the warped fiducial files are used in several situations. First, dipole or source analysis based on individual participants should use an electrode placement file for that individual. The warped electrode placement file suffices for this. This allows the calculation of topographical maps, equivalent current dipole and source analysis, and electrode plotting to be done relative to that participants head size and shape. Second, it is possible that dipole coordinates or source coordinates generated in EMSE with the warped electrode placement file may be used with the MR viewer. In this case, the volumetric set would be co-registered with the warped fiducials set for this participant (using the MRI on which the warped fiducials was based). Then, dipoles or sources could be plotted on this MR. Third, the dipole coordinates in an "ECD" file from EMSE may be transformed into the Talairach coordinate framework. In that case, the Talairach fiducial file for that MRI would be used in the co-registration, and the transformed dipole coordinates or source coordinates could be loaded and plotted in the MR Viewer. Finally, the translation of the dipoles or sources into Talairach coordinates may be the "dependent variables" for that individual. These coordinates may be combined (means, dispersion) across individuals from differing head sizes or shapes.

Special note on the dipole coordinates in the EMSE computer program.

The equivalent current dipole analysis of the EMSE computer program may be used in conjunction with the fiducial files to calculate locations that may be displayed on the MRI volumetric displays. The dipole coordinates in the EMSE program are in spherical coordinates representing the best-fitting sphere in the electrode placement files space. This sphere does not map unequivocally onto the MRI program, i.e., cannot be coregistered on the MRI volumetric space. Two transformations are possible. First, the dipole coordinates in the EMSE program may be mapped into the coordinate system of the MRI fiducials file. The saggital, coronal, and axial coordinates of the dipole in the EMSE program may be calculated as a proportion of the maximal sphere proportions for that individual. These proportional coordinates may be standardized against the known front, rear, left, right, and top brain sizes of the MRI recording upon which the electrode placement file is made. The resulting coordinates may be mapped onto the MRI volumetric space when the volumetric space and the fiducials file are co-registered in the MR Viewer program. Second, the dipole coordinates of the EMSE program may be mapped into the Talairach coordinate system. The proportional measurements in the spherical system of the EMSE program may be transformed by the known dimensions of the Talairach system. The resulting Talairach coordinates therefore may be mapped on the MR, examined in the Talairach figures, and be used as a standard system to compare across individuals. A computer program implements these two transformations and also determines the figure numbers for the saggital, coronal, and axial maps in the Talairach book for these coordinates.

The equivalent current dipole analysis (and source analyses) in the EMSE Source Estimator computer program calculate a reverse-solution source dipole for a potential / current map. The program must use an electrode placement file in order to show the location of the electrical activity. The program calculates a "best-fitting" sphere to fit into the electrode coordinates. This

sphere does not map unequivocally upon the anatomical landmarks of the system. This best fitting sphere is not deterministically related to the x, y, z coordinates, and it is definitely not based upon a coordinate system defined by lines drawn between the three fiducials. However, since the coordinate system of the ELP files is based on the AC-PC line, the origin of the sphere is a close approximation of the origin of the system (where LPA-RPA plane transects AC-PC line). The resulting sphere is used to calculate dipole coordinates (saggital, coronal, axial location, and saggital, coronal, axial projection). These coordinates are based in the system of the sphere and do not map directly on the MR viewer.

Two empirical tests were done to confirm this impression. The cardinal points on the upper hemisphere were calculated. These included front and rear, right and left, vertex, and a line on the sphere from rear to vertex to front. These points were then saved in a ECD file. The fiducial file from the electrode placement file was then co-registered with the volumetric file for that participant. The points in the ECD file plotted as a sphere in the MR viewer and not on the cardinal points of the cortex. This shows that the spherical system in the EMSE equivalent current dipole model translates as a sphere in the MR Viewer and does not warp to fit the coordinate system of the cortex in the volumetric files of the MR viewer.

A second empirical test was done to test the cardinal points of the EMSE equivalent current dipole module. Electrical recording simulated files were created that had a series of zeros, except for a circle of ones around specific electrodes. These electrodes were: inion, nasion, vertex, F4, C4, P4, O2, and line running from Oz to Cz along the median, and electrodes along the median below Oz. The equivalent current dipoles for these totally positive electrical activity should be located on the surface of the cortex nearest the electrode center. The translation from the potential map to the dipole map was unambiguous. That is, the vertex electrode activation was accompanied by a dipole at the vertex. F4, C4, P4, and O2 were located in the appropriate place. The line of activations from vertex to Oz to below the AC-PC line followed the sphere in the appropriate places. This confirms that the vertical origin in the spherical system of EMSE matches the vertical origin defined by the electrode placement files and the fiducial files, i.e., the AC-PC line.

So, a transformation of the coordinates of the dipoles in the EMSE system must assume the dipole coordinates from that system are proportionally based on the sphere size. The sphere size may be obtained simply by examining the spherical coordinates where the sphere intersects the axes in the EMSE plot. This sphere size is saved in the fiducials file for use with a computer program. The proportional distance of the dipole coordinates to the saggital, coronal, and axial radii can be translated into the radii of the MRI for the individual. The saggital, coronal, and axial coordinates of the dipole in the EMSE program may be calculated as a proportion of the maximal sphere proportions for that individual. These proportional coordinates may be standardized against the known front, rear, left, right, and top brain sizes of the MRI recording upon which the electrode placement file is made. The resulting coordinates may be mapped onto the MRI volumetric space when the volumetric space and the fiducials file are co-registered in the MR Viewer program. A test of this transformation (using both of the above empirical tests) placed the dipoles on the MR viewer in the expected cardinal locations of the cortex in the volumetric space.

In addition to a transformation of the dipole coordinates (spherical system) into the volumetric coordinates (MR Viewer), the coordinates may be transformed into the Talairach spatial coordinate framework. The proportional measurements in the spherical system of the EMSE program may be transformed by the known dimensions of the Talairach system. The resulting Talairach coordinates therefore may be mapped on the MR, examined in the Talairach figures, and be used as a standard system to compare across individuals. A computer program implements these two transformations and also determines the figure numbers for the saggital, coronal, and axial maps in the Talairach book for these coordinates.

Segmenting the structures in the head

Another topic of great importance for the use of the EMSE program is the segmentation of the structures of the head. A major goal of this work is to use the known locations of head structures of individual participants and develop realistic head models for cortical source analysis. This is particularly important for infant participants with head topographies that are qualitatively different than that of children and adults. The segmenting process is used to identify structures inside the head that would have differing conductivity values for cortical source generation to the cortex. The segmenting is done using a combination of procedures in the Source Signal computer program, MR Viewer.

The current from a source inside the cortex must pass through several media before generating current and potential changes on the scalp. These structures include: gray matter, white matter, CSF including ventricles and subskull space, skull, scalp, orbits, nasal cavity. These structures have differing conductivity values. In order to trace current value from a cortical source to the scalp, one must know the location of each structure to correctly assign current flow through structures of differing impedance, or resistance. The concern is with electrodes recording potential and current changes, so the structures of interest are generally located above about 10% below the nasium-mastoid-inion circumference.

The Source Signal computer program, MR Viewer, is used for the segmentation and to generate wireframe models of the head structures. The segmentation is done with a combination of "wizards" and of grow / arithmetic techniques. The segmentation process results in a number of "region" (*.rgn) files that represent the head structures. These region files are then used in the wireframe of MR Viewer to create wireframes of the structures. The wireframes may be of single structures, and a single wireframe representing the entire head, may be constructed. Note that the goal of segmentation for the MR Viewer program is to create structures for use in the EMSE computer program. In general, the specific aspects of head structures are unimportant for the EMSE program and so several modifications are done to the proposed EMSE procedure.

A general conceptual overview will be given of the segmenting process. The process is outlined in detail in Appendix C, D, and the latest, E. The first steps in the analysis involve the use of the segmentation wizards. The "Head to Cortex" results in three region files: a) CSF and Other Structures consisting of the ventricles, subarachnoid space CSF, and outside of head; b) white-matter-expanded, which is the white matter of the brain; c) a region from the "Brain Extraction" of the entire brain. The "Inner Skull Segmentation" uses the white-matter-expanded and results in an Inner Skull region, which consists of all matter inside the cortex. The "Outer Skull

Segmentation" includes, I think, all matter inside of the skull. However, we have found this wizard is imperfect in identifying the proposed area. The EMSE computer program uses the "Scalp" generated by the mesh wizard, the "Inner Skull" and "Outer Skull" generated in the segmentation steps, for its realistic head model. Finally, the "Cleanup" wizard cleans the outside of the head and may result in a region that includes only the outside of the head.

The next steps involve the growth and logical operations from the segmentation editor. The first step is to create a cortex and gray matter regions. The cortex segment is created by a logical operation involving the "Inner Skull", and "not and" the CSF. This removes the ventricles from the inner skull, leaving the cortex. The gray matter is created by a logical operation involving the cortex region and "not and" the white-matter-expanded. This removes the white matter from the cortex and leaves the gray matter. The second step is to create the skull. This is done by loading the "Outer Skull" region and eroding it until it does not touch the skull. Then, the skull area is "grown" from an area that excludes the outer skull. It is very likely that this step will require hand editing. A third step is to create the eye orbits and nasal cavity. These are done by loading other structures (i.e., brain), creating bounding regions around these areas, and using the grow function. Fourth, it is possible that the "Cleanup" procedure created an area that excluded most of the interior. However, if not, a "Outside of Head" may be created now. This is done by loading enough of the created regions to block interior assignment of pixels, including skull, orbits, nasal cavity, outer skull. These regions are excluded, and the outside of the head is grown. Fifth, the scalp is merely the location between the outside of the head and the skull. The CSF and Other matter region is used by excluding skull and outside of head, creating the CSF. ALSO, it is possible to create the "sub-arachnoid" CSF by using the CSF "not and" the inner skull, and a "Ventricle CSF" by using the CSF and the inner skull.

One important note about the scalp created in the mesh wizard and the scalp created in our steps. The scalp created in the mesh wizard is essentially the outside of the head. It is useful in creating the electrode positions because the electrodes should be lying on the outside of the head. However, it is not a wireframe that represents the scalp depth. The scalp region created in the steps just outlined is a region containing all of the scalp and may be used in a wireframe for the scalp modeling.

Wireframes of head structures

The final step in the entire process is to create wireframes of the structures. For use with the EMSE program, a wireframe of the scalp already exists. One may create wireframe models of the "Outer Skull" and "Inner Skull" that may be used for some display purposes. The EMSE program purports to use these for realistic head modeling but the results are questionable. Single wireframes of each structure may be created. These wireframes are very useful for display purposes. For example, wireframe models may be created of the brain, or cortex, or gray matter, and dipoles or electrical activity may be displayed on these wireframes. One may also use the regions and wireframes to present displays of the skull cut at horizontal locations with the cortex appearing outside.

One wireframe that is (will be) used in the realistic head models is a wireframe containing all of the head structures. This is created by loading the scalp, skull, CSF, orbits, nasal cavity, gray

matter, and white matter. Each region is assigned a "property" such as skin, bone, CSF…, which assigns a conductivity value to the region. The wireframe is then created with all structures. The resulting wireframe contains the coordinates of the wireframe and the conductivity values for each interior region. This wireframe is used, will be used, in realistic head model cortical source analysis.

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Table 1: Anatomical areas identified in the "Talairach Daemon Database" for which ECD files can be created to show Talairach anatomical locations on individual participant MRIs. These may be done in a single file for areas that are physically connected across the hemisphers (e.g., caudate, thalamus, corpus collosum) but should be done in separate left- and right- hemisphere files for areas that are bilaterally represented (e.g., superior occipital lobe).

Angular Gyrus Bdmn a. 39
Angular Gyrus Bdmn a. 40
Anterior Cingula *
Anterior Cingula Bdmn a. 10
Anterior Cingula Bdmn a. 24
Anterior Cingula Bdmn a. 25
Anterior Cingula Bdmn a. 32
Anterior Cingula Bdmn a. 33
Anterior Cingula Bdmn a. 42
Anterior Cingula Bdmn a. 9
Caudate Caudate Body
Caudate Caudate Head
Caudate Caudate Tail
Cingulate Gyrus Bdmn a. 23
Cingulate Gyrus Bdmn a. 24
Cingulate Gyrus Bdmn a. 31
Cingulate Gyrus Bdmn a. 32
Cingulate Gyrus Bdmn a. 9
Claustrum *
Cuneus *
Cuneus Bdmn a. 17
Cuneus Bdmn a. 18
Cuneus Bdmn a. 19
Cuneus Bdmn a. 23
Cuneus Bdmn a. 30
Cuneus Bdmn a. 7
Extra-Nuclear Bdmn a. 13
Extra-Nuclear Optic Tract
Fourth Ventricle *
Fusiform Gyrus Bdmn a. 18
Fusiform Gyrus Bdmn a. 19
Fusiform Gyrus Bdmn a. 20
Fusiform Gyrus Bdmn a. 36
Fusiform Gyrus Bdmn a. 37
Inf. Frontal *
Inf. Frontal Bdmn a. 10
Inf. Frontal Bdmn a. 11
Inf. Frontal Bdmn a. 13
Inf. Frontal Bdmn a. 25
Inf. Frontal Bdmn a. 44

Inf. Frontal Bdmn a. 45
Inf. Frontal Bdmn a. 46
Inf. Frontal Bdmn a. 47
Inf. Frontal Bdmn a. 6
Inf. Frontal Bdmn a. 9
Inf. Occipit Bdmn a. 17
Inf. Occipit Bdmn a. 18
Inf. Occipit Bdmn a. 19
Inf. Parieta Bdmn a. 2
Inf. Parieta Bdmn a. 39
Inf. Parieta Bdmn a. 40
Inf. Parieta Bdmn a. 7
Inf. Tempora *
Inf. Tempora Bdmn a. 19
Inf. Tempora Bdmn a. 20
Inf. Tempora Bdmn a. 21
Inf. Tempora Bdmn a. 37
Insula *
Insula Bdmn a. 13
Insula Bdmn a. 22
Insula Bdmn a. 29
Insula Bdmn a. 40
Insula Bdmn a. 41
Insula Bdmn a. 47
Lateral Ventricl *
Lentiform Nucleu *
Lentiform Nucleu Lateral Globus P
Lentiform Nucleu Med. Globus Pa
Lentiform Nucleu Putamen
Lingual Gyrus *
Lingual Gyrus Bdmn a. 17
Lingual Gyrus Bdmn a. 18
Lingual Gyrus Bdmn a. 19
Med. Frontal G *
Med. Frontal G Bdmn a. 10
Med. Frontal G Bdmn a. 11
Med. Frontal G Bdmn a. 25
Med. Frontal G Bdmn a. 32

Med. Frontal G Bdmn a. 6
Med. Frontal G Bdmn a. 8
Med. Frontal G Bdmn a. 9
Mid. Frontal G *
Mid. Frontal G Bdmn a. 10
Mid. Frontal G Bdmn a. 11
Mid. Frontal G Bdmn a. 46
Mid. Frontal G Bdmn a. 47
Mid. Frontal G Bdmn a. 6
Mid. Frontal G Bdmn a. 8
Mid. Frontal G Bdmn a. 9
Mid. Occipital *
Mid. Occipital Bdmn a. 18
Mid. Occipital Bdmn a. 19
Mid. Occipital Bdmn a. 37
Mid. Temporal *
Mid. Temporal Bdmn a. 19
Mid. Temporal Bdmn a. 20
Mid. Temporal Bdmn a. 21
Mid. Temporal Bdmn a. 22
Mid. Temporal Bdmn a. 37
Mid. Temporal Bdmn a. 38
Mid. Temporal Bdmn a. 39
Orbital Gyrus Bdmn a. 11
Orbital Gyrus Bdmn a. 47
Paracentral Lobu Bdmn a. 3
Paracentral Lobu Bdmn a. 31
Paracentral Lobu Bdmn a. 4
Paracentral Lobu Bdmn a. 5
Paracentral Lobu Bdmn a. 6
Parahippocampal *
Parahippocampal Amygdala
Parahippocampal Bdmn a. 19
Parahippocampal Bdmn a. 20
Parahippocampal Bdmn a. 27
Parahippocampal Bdmn a. 28
Parahippocampal Bdmn a. 30
Parahippocampal Bdmn a. 34
Parahippocampal Bdmn a. 35
Parahippocampal Bdmn a. 36

Parahippocampal Bdmn a. 37	Sub-Gyral Bdmn a. 13	Sup. Tempora Bdmn a. 22
Parahippocampal Hippocampus	Sub-Gyral Bdmn a. 19	Sup. Tempora Bdmn a. 29
Postcentral Gyru Bdmn a. 1	Sub-Gyral Bdmn a. 20	Sup. Tempora Bdmn a. 38
Postcentral Gyru Bdmn a. 2	Sub-Gyral Bdmn a. 21	Sup. Tempora Bdmn a. 39
Postcentral Gyru Bdmn a. 3	Sub-Gyral Bdmn a. 37	Sup. Tempora Bdmn a. 41
Postcentral Gyru Bdmn a. 4	Sub-Gyral Bdmn a. 38	Sup. Tempora Bdmn a. 42
Postcentral Gyru Bdmn a. 40	Sub-Gyral Bdmn a. 39	Supramarginal Gy Bdmn a. 39
Postcentral Gyru Bdmn a. 43	Sub-Gyral Bdmn a. 40	Supramarginal Gy Bdmn a. 40
Postcentral Gyru Bdmn a. 5	Sub-Gyral Bdmn a. 46	Thalamus *
Postcentral Gyru Bdmn a. 7	Sub-Gyral Bdmn a. 6	Thalamus Anterior Nucleus
Posterior Cingul Bdmn a. 18	Sub-Gyral Bdmn a. 7	Thalamus Lateral Dorsal N
Posterior Cingul Bdmn a. 23	Sub-Gyral Bdmn a. 8	Thalamus Lateral Posterio
Posterior Cingul Bdmn a. 29	Sub-Gyral Hippocampus	Thalamus Mammillary Body
Posterior Cingul Bdmn a. 30	Subcallosal Gyru Bdmn a. 25	Thalamus Med. Dorsal Nu
Posterior Cingul Bdmn a. 31	Subcallosal Gyru Bdmn a. 34	Thalamus Med. Geniculum
Precentral Gyrus Bdmn a. 13	Subcallosal Gyru Bdmn a. 47	Thalamus Midline Nucleus
Precentral Gyrus Bdmn a. 3	Sup. Frontal *	Thalamus Pulvinar
Precentral Gyrus Bdmn a. 4	Sup. Frontal Bdmn a. 10	Thalamus Ventral Anterior
Precentral Gyrus Bdmn a. 43	Sup. Frontal Bdmn a. 11	Thalamus Ventral Lateral
Precentral Gyrus Bdmn a. 44	Sup. Frontal Bdmn a. 6	Thalamus Ventral Posterio
Precentral Gyrus Bdmn a. 6	Sup. Frontal Bdmn a. 8	Third Ventricle *
Precentral Gyrus Bdmn a. 9	Sup. Frontal Bdmn a. 9	Transverse Tempo Bdmn a. 41
Precuneus Bdmn a. 19	Sup. Occipit Bdmn a. 19	Transverse Tempo Bdmn a. 42
Precuneus Bdmn a. 23	Sup. Occipit Bdmn a. 39	Uncus Amygdala
Precuneus Bdmn a. 31	Sup. Parieta Bdmn a. 5	Uncus Bdmn a. 20
Precuneus Bdmn a. 39	Sup. Parieta Bdmn a. 7	Uncus Bdmn a. 28
Precuneus Bdmn a. 7	Sup. Tempora *	Uncus Bdmn a. 34
Rectal Gyrus Bdmn a. 11	Sup. Tempora Bdmn a. 13	Uncus Bdmn a. 36
Sub-Gyral *	Sup. Tempora Bdmn a. 21	Uncus Bdmn a. 38

Table 2. List of participant numbers and ages of MRIs currently done.

A list of the participants and BD and other characteristics can be found at:

\\jerlab\laboratory data\magneticresonanceimage\Anatomical MRI Participant Description.xls

A list of the progress for segmentation can be found at:

\\jerlab\laboratory data\magneticresonanceimage\Segmenting for Each Participant.xls

Table 3. EMSE and MR Viewer files relevant to this work

Volumetric imaging (*.vmi):The VMI files contain the saggital images from the MRI and may be viewed in the MR Viewer in the saggital, axial, and coronal planes. The VMI files have an intrinsic measure of mm based on the actual size of the MRI. The VMI files also contain registration points (fiducials), nasion, left- and right-mastoid. The registration points are used in conjunction with probe files to co-register two measurement systems.

Registration (*.reg): The REG files contain a co-registration between a probe file and the VMI file. When wireframe files are created, the measurements are done in the probe-file measurement system via the REG files. The REG files also are used when plotting dipoles on the MRI; the dipole files are in the measurement system of the probe file used to create the REG file.

Wireframe (*.wfr; *.3fr): The WFR files contain locations on the MRI and "wireframes" of MRI entities (scalp, skull, cortex, CSF). A wireframe consist of the actual locations on the MRI and a series indices to geometric (triangles, quadrangles) figures for the actual locations. The wireframe may be used in external programs to plot the MRI entities or in boundary element modeling for cortical source analysis based on realistic head models. The wireframes are created in the coordinate system of a registration file / probe file coordinate system. The 3fr additionally contains information about the type of entity and its conductivity useful for "finite element modeling" or "boundary element modeling".

Probe (*.elp): The ELP files contain registration points (fiducials) and electrode locations ("electrode placement files", ELP). The registration points are the nasion, left- and right-mastoids. These points are used with the VMI files to co-register the probe and VMI files. The electrode placements are used in EMSE for EEG, ERP, and source modeling. In my system there are ELP files based on the participant's measurements (Participant MRI-Based Fiducial Files) and ELP files based on the Talairach system oriented towards a participant (Talairach-based Fiducial Files). Thus, REG files may be created for the specific individual to create wireframes or plot dipoles for that individual, or be created for the Talairach-based coordinate system for wireframes or dipoles in Talairach space.

Dipole (*.ECD): The ECD files contain equivalent current dipole locations. These files are typically generated in the EMSE program when doing ecd analyses. The files should be in the same coordinate system as the REG file. This is actually a problem when doing the ecd analyses in EMSE, since EMSE creates them in the "best-fitting sphere" (see text). These coordinates also may be created from other programs—i.e., a set of "Talairach locations" was generated from a database of measurements that can be used to map specific locations.

Region (*.rgn): The RGN files contain information about specific entities in the MRI file. These entities are defined by the user through the "Segment" dialog or through wizards. Such entities typically are the cortex, outer and inner skull, skull, scalp, and CSF. The RGN files are created with MRI-type algorithms based on MRI grayscale values (wizard, expansion, dilation, erode, fill, grow, paint). The RGN files are used to create wireframe files, and the resulting wireframes have the entity in the coordinate system of the registration file. The wireframes may be used for plotting and display in the EMSE program.

Table 4: List of segmented regions and wireframes created in MR Viewer

Segments created by MR Viewer Wizards
Brain: All areas of the MRI representing the brain, including subcortical and cerrebellum
Inner skull: Consists of the everything inside the cortex and bounded by the cortex
Outer skull: Consists of everything presumably inside the skull. Poorly done
White-matter expanded: Consists of the white matter of the brain

Segments created by MR Viewer manual creation
Skull: skull of the head, including bones below the brain not useful for source analysis
Cortex: Cortex, consisting of "Inner Skull" excluding ventricles of CSF
Gray matter: Consists of the gray matter. Found by using cortex and excluding white matter
Eye sockets: The portion of the MRI where the eyes are located
Nasal cavity: The portion of the MRI where the nasal cavity is located
Outside of head: Segment is a preliminary step in the analysis, not used in source analysis
Scalp: Area from outside of head to skull. Note: This region and wireframes based upon this
   region differ from the scalp wireframe created by the wizard. The wizard wireframe is the
   outside of the scalp and does not include the depth of the scalp. This region includes the
   scalp from the outside of the head to the skull
CSF: The CSF region includes all portions inside the head that have CSF
Subarachnoid space: The CSF region excluding the inner skull
Ventricles: The CSF region inside of the inner skull

Wireframes important for EMSE
Scalp: This wireframes comes from the scalp wizard, not from the segmenting process
Inner skull: Consists of the everything inside the cortex and bounded by the cortex
Outer skull: Consists of everything presumably inside the skull. Poorly done

Other interesting wireframes, primarily for display
The following wireframes may be interesting for display purposes:
Brain: All areas of the MRI representing the brain, including subcortical and cerrebellum
Cortex: Cortex, consisting of "Inner Skull" excluding ventricles of CSF
Gray matter: Consists of the gray matter. Found by using cortex and excluding white matter
White-matter expanded: Consists of the white matter of the brain
CSF: The CSF region includes all portions inside the head that have CSF
Subarachnoid space: The CSF region excluding the inner skull
Ventricles: The CSF region inside of the inner skull

Wireframe used for realistic head models and cortical source analysis
Head wireframe. Includes segments for: scalp, skull, eyes, nasal cavity, CSF, white matter, and
gray matter.

Appendix A: MRI procedures for downloading files from Palmetto Imaging

Getting the MRI files from Palmetto Imaging:
1. We can pick up the tape within about 30 minutes after the scan is completed. Palmetto Imaging saves the MRI files to a digital (DDS) tape for us as well as their own tape back-up system, in case we were to lose our copy.
2. Bring the tape back to the HDERP lab for downloading.

Getting files off of the tape:

1. Turn on tape drive attached to experimental control computer in EEG control room.
2. Boot the computer.
3. Enter Windows ME
4. From the Start menu, select Programs – Application – NovaXchange
5. If the tape is a standard acquisition (our standard protocol), load the "proc123" file. (if you have modified scan protocol, you will need to set up the download via "copy tape to disk" menu; see Jeff for more instructions)
6. Select "Rewind"; wait for message on screen that tape is rewound.
7. Click on "Run"; wait patiently.
8. If the program gives you an error message or otherwise crashes, eject the tape and turn off the tape drive and the computer. Return to step 1.
9. If step 7 goes without an error, you will have 123 files on the C: drive in the folder "schatztemp". The first file (file001) is header information and has no MR data in it. Files 2-15 (file002 – file015) are typically the first sequence (T1 axial localizer, 14 slices that do not contain dorsal parts of the brain), files 16-75 are the second sequence (T1 thin-slice sagittal scan in 60 slices); files 76-104 are the third sequence (T2 axial scan in 29 slices), and files 105-123 are the last sequence (Proton Density weighted scan in 19 slices).

Reading the files with MRIcro:

(Continuing from above as if you are on the same computer)
1. From the Start menu select Programs – MRIcro
2. From the Import menu select "Convert dicom…."
3. Change the number of images to the appropriate number of images for the sequence you wish to view. (usually either 60 or 29)
4. Click on "select"
5. Select the first image from the sequence you wish to view (usually either file002 or file054).
6. Name the header file with whatever designation you want for the MRI file name.
7. Under the file menu, select "Open analyze format…"
8. Select the image file you just created. Image files will end with .img.
9. Under the file menu, select "save as…[clip/etc.]".
10. Using the dialog box in the lower left-hand corner, you may want to modify the image. For example, for later use in Analyze you would indicate the file is a "sagittal-right" or "sagittal-left", because Analyze assumes all files are axial in orientation. See below for conversion to format for the MR viewer program used with EMSE.

Converting files with MRIcro to use with MR Viewer program

1. Continuing from above, change the settings in the "save as" dialog box to 8-bit integer file type and select "flip left/right". Then "save as [Intel] (little-endian)" file type. You will be asked to rename the file, although the default will add an "x" to the beginning of the file name, which is usually acceptable.
2. Move the new file to the server to use with MR Viewer program.

Creating volumetric file from MR Viewer

1. From the server, open the MR Viewer program.
2. From file menu select New – volume referenced set – volumetric set
3. Click on the "Setup" page
4. Select "lumped" for file type and set slice numbering from 1 to 60 (if using T1 sagittal sequence), set offset at 0.
5. Click on the "Read" page.
6. Click on MRI type.
7. Select "RawByte" as MRI type, select specify offset (set offset value to 0), make sure nothing is checked in the "Read Raw Image" section.
8. From the "Read" page, make sure that the "Autobuild" command is deselected (not checked).
9. Click on "Files" and open the "*.img" file that you moved over to the server.
10. Within the new dialog box, for the standard T1 sequence, select the sagittal viewpoint, and check "reverse vertically". Accept these settings.
11. From the main "Read" page, select "Build".
12. Your volumetric set should appear in all 3 planes.
13. From the "Navigate" dialog box, click on "Save". Save the file so that you can recall it in the future without rebuilding the file.

Appendix B: Creating fiducial and electrode space with EMSE and computer programs

Create the subject fiducial file:
The subject fiducial file consists of fiducials and specific locations in the MRI: These are
recorded in an Excel file that calculates values based on the AC-PC line
Anterior commisure: The band of fibers connecting two hemispheres, anterior to thalamus
Posterior commisure: Band of fibers connection two hemispheres, posterior to thalamus
LPA and RPA: Left and right preauricular points, bone immediately anterior to ear canal
Nasion: Bone immediately above the eye sockets in the skull midline.
Fiducial points: The fiducial points are the nasion, RPA, and LPA
Right and left mastoid: The bone immediately posterior to the ear canal, at same axial level as
  LPA and RPA
Inion: The base bone of the skull in the occipital location.
Scalp at front and rear: Points on scalp at front and rear of head, on AC-PC axial slice
Cortex at front and rear: Points on cortex at front and rear of cortex, on AC-PC axial slice
Cortex on left and right: Points on left and right of cortex, on AC-PC axial slice.
Cortex on top: On the sattigal slice of the AC-PC plane, point on cortex on AC-PC plane
Scalp at midline: Scalp on highest point on the AC-PC plane
Eye electrode locations: The electrode locations for 17, 125, 126, 127 and 128.

The Excel file is saved into a text file, called S#### Fiducials.elp

Create a scalp wireframe:
The scalp wireframe is created in the MR Viewer programs
Load the *.vmi file containing the MRI for the participant.
Locate the nasion, LPA, and RPA on the MRI for co-registration. These should be identified on
  the MRI and should be identical to the measurements placed in the subject fiducials file.
Do the co-registration step. For this step, choose a weighting of 1, 1, 1, for the three fiducials,
  and no other points used in the co-registration. Do the registration and save the registration file.
Use the Mesh wizard for creating the scalp. Choose 20 as value of the … for the mesh. This
  wireframe should be saved, and the registration is needed to identify the dimensions of the
  space in which it is saved.

Create a subject-based electrode file:
A C++ computer program reads the fiducial file and creates an electrode placement file and other
entities. The program needs, S#### Fiducials.elp, S####.wfr, the scalp wireframe generated by
the MR Viewer scalp wizard, S#### Head measurements and S#### Subject information files.

Appendix C: Segmenting and Wireframes of head structures; With help from Greg Sasine.
July, 2003. This does not really work. See appendix D.

MR Viewer Wizards

Initial set up
       Open the volumetric (.vmi) file containing the participants MR Scan
       Open the registration (.reg) file containing fiducial points
       Use the '+' microscope button to enlarge the 3 views

Preparing the segmentation wizard
       Click on Edit, segmentation to Open the segmentation box
           In the box, Click on Region Control
           This will allow you to save your progress and monitor the wizard
       Click on wizards, segmentation to Open the segmentation wizard

Chose the head to cortex segmentation wizard
       Click next until the CSF segmentation begins (5 times)
       Save CSF once it appears, you will not be able to save it later
           To save the CSF click on it in the segmentation box, region tools to highlight it
           Click Properties, change the name to CSF and Other Material
           Click save
       Click next
       Uncheck the proceed with tiling box in the center
       Click finish
       Save white matter expanded
       Do this step once with the "Brain Extraction" and once without. Save the extracted
        brain to "Brain".

Cortex to inner skull segmentation wizard
       Wizards, segmentation, cortex to inner skull
       Click next, uncheck tiling box, click finish
       Save inner skull.

Inner skull to outer skull segmentation wizard
       Wizards, segmentation, inner skull to outer skull
       Click next until finished (uncheck tiling box if necessary)
     Save outer skull

Cleanup wizard
       Region Tools, Exclude outer skull, Remove all other segments, Apply
       Wizards, segmentation, clean outside of head
       Click next (4 times)
       Save cleanup before finish, or it will disappear
       Click finish
       Remove all segments from region control except cleanup

The cleanup may include areas inside head and may require manual editing
Alternatively, in a final step we may create an outside of head

Creating the Skull
Load the outer skull
Check the outer skull region across the head to make sure skull is not included
If skull is included, do the "Erode" with a value of about 10 until not touching skull
Click exclude (in region control), Apply
Grow Skull
Add region, name it skull, specify type as bone
Segmentation box, grow region
Specify range 60-250
Specify starting point in skull
Click grow
It is probably that manual editing is necessary.
The thickness and shape of the skull should be determined by the scan itself.
This manual edit is to cleanup the skull by filling in breaks and removing
nonsense areas. Save the skull often, using backups, to prevent starting over.

Segmentation Box, Visual Edit, chose action unset, start edit
Use the box and line tools (or others if you prefer) to select the areas to be
unset (removing the color)
Unset all areas outside the skull
Save cleanup often, using backups to prevent starting over.
Segmentation box, Visual Edit, choose action set, start edit
Follow the same procedures to add lines or fill in skull areas

Creating the Cortex
Region tools, Add, Cortex
Load Inner Skull, Click Yes to overwrite current region
Load "CSF and other materials," Click No
Region Tools, Arithmetic
Cortex 'and' Inverse* CSF (click the inverse box next to CSF) = Cortex
To inverse the CSF click the inverse box next to it in the arithmetic box. This
operation will be used frequently to build the realistic head model.
Save cortex
Remove all segments from region control

Creating the Gray Matter
Add Gray Matter, specify type as gray matter
Load Cortex, Click Yes
Load White matter expanded, click no
Arithmetic
Gray Matter 'and' inverse* White Matter Expanded = Gray Matter
Save Gray Matter

Creating the eye sockets, then the nasal cavity
       Load skull, exclude; load brain, exclude
       Add Right eye
       Bounding Box, Set box loosely around eye
       Grow region, range 1-255. Using the 1 will exclude cleanup area outside of head
       Repeat stepso create left eye
       Add, Eyes, specify type as eyes
       Arithmetic, right eye or left eye = eyes
       Save eyes
       Add, nasal cavity, specify type as air
       Bounding Box, Set box loosely around nasal cavity
       Grow region, range 1-255
       Save nasal cavity

Creating outside of head
       If the cleanup procedure did not result in a good outside of head, follow these steps
       Load enough structures to eliminate the inside of head. These include:
        Skull, eyes, nasal cavity, brain. Exclude each of these
       Add "Outside of head"
       Grow starting from the outside, using "0 to 0" as the values. The "0" values were set in
        the clean phase

Creating the Scalp Region
       Remove all segments from the region tools
       Load outside head
       Load, and exclude: cortex, inner skull, outer skull, skull, eyes, nasal cavity
       Region control, region tools
       Expand the outside head, by value 2, until reaches skull
       Properties, Rename outside head expanded
       Save
       Remove all segments
       Add scalp, specify type as skin
       Load outside head expanded, Click Yes
       Load outside head, Click no
       Arithmetic
       Scalp and inverse* outside head = scalp
       Save scalp

CSF and other CSF entities
       Add CSF, specify type as CSF
       Load 'CSF and other materials' Click yes
       Load the following for each Click no: cortex, eyes, nasal, outside head, skull, scalp
       Arithmetic
        CSF and inverse* cortex = CSF
        CSF and inverse* eyes = CSF
        CSF and inverse* nasal = CSF

CSF and inverse* outside head = CSF
CSF and inverse* skull = CSF
CSF and inverse* scalp = CSF
Save CSF
Add "Ventricles" and set type as CSF
Load "CSF" Click yes
Load Inner skull, click no
Arithmetic. Ventricles and Inner Skull = Ventricles
Save ventricles
Add "Subarachnoid space" and set type as CSF
Load CSF click yes
Inner skull should already be loaded
Arithmetic. Subarachnoid space and inverse inner skull = subarachnoid space.

At this point, segments have been created for all interesting parts. Including, scalp, skull, brain, cortex, gray matter, white matter, eyes, nasal cavity, CSF, including sub-arachnoid CSF and ventricles. Use the mesh function to create meshes for any interesting mesh products. However, there is one grand mesh file that should be created.

Load scalp, skull, CSF, eyes, nasal cavity, gray matter, white matter. For each, check the properties, which should be skin, bone, CSF, eyes, air, gray matter, and white matter, respectively. Use the 3fr mesh function and create a mesh. Select all regions for creating the mesh. Select a value of … for the … to create a finely tuned mesh.

Appendix D: Segmenting and Wireframes of head structures
Revised, July 2003. Did this on first two infant participants. It is possible that Appendix D will not work on infants, or poor MRIs.

MR Viewer Wizards

Initial set up
    Open the volumetric (.vmi) file containing the participants MR Scan
    Open the registration (.reg) file containing fiducial points
    Use the '+' microscope button to enlarge the 3 views

Preparing the segmentation wizard
    Click on Edit, segmentation to Open the segmentation box
        In the box, Click on Region Control
        This will allow you to save your progress and monitor the wizard
    Click on wizards, segmentation to Open the segmentation wizard

Cleanup wizard
    Wizards, segmentation, clean outside of head
    Click next (4 times)
    Save cleanup before finish, or it will disappear
    Click finish
    Remove all segments from region control except cleanup
      The cleanup may include areas inside head and may require manual editing
      Alternatively, in a final step we may create an outside of head
    Save S#### Cleanup.
    Save the VMI file, with cleaned up outer head
    Save "S#### Outside Head" as inverse-cleanup

Creating the eye sockets, then the nasal cavity
    Add Right eye
    Bounding Box, Set box loosely around eye
    Grow region, range 1-255. Using the 1 will exclude cleanup area outside of head
    Repeat steps create left eye
    Then, do visual edit of eyes to remove extraneous material
    Add, Eyes, specify type as eyes
    Arithmetic, right eye or left eye = eyes
    Save eyes
    Add, nasal cavity, specify type as air
    Bounding Box, Set box loosely around nasal cavity
    Grow region, range 1-255
    OR, just do this with visual edit. The nasal cavity is easy to see
    Save nasal cavity

Creating the Skull
      Grow Skull
            Add region, name it skull, specify type as bone
            Segmentation box, grow region
            Specify range 60-250
            Specify starting point in skull
            Click grow
            It is probably that manual editing is necessary.
              The thickness and shape of the skull should be determined by the scan itself.
              This manual edit is to cleanup the skull by filling in breaks and removing
              nonsense areas. Save the skull often, using backups, to prevent starting over.
              A lot of manual editing here will help
      After the manual editing add the Eyes and Nasal Cavity to skull
      Go around the eyes and make sure the eye bone sockets are visually edited.
      After all editing, remove Eyes and Nasal cavity
        Skull AND not Eyes = Skull; Skull and not Nasal Cavity=Skull
        OR, may have to do Nasal Cavity and not Skull = Nasal Cavity

            Segmentation Box, Visual Edit, chose action unset, start edit
              Use the box and line tools (or others if you prefer) to select the areas to be
                unset (removing the color)
              Unset all areas outside the skull
              Save cleanup often, using backups to prevent starting over.
            Segmentation box, Visual Edit, choose action set, start edit
              Follow the same procedures to add lines or fill in skull areas

Creating the Scalp Region
      Remove all segments from the region tools
      Load outside head
      Load, and exclude: skull, eyes, nasal cavity
      Region control, region tools
      Expand the outside head, by value 2, until reaches skull
      Properties, Rename outside head expanded
      Save
      Remove all segments
      Add scalp, specify type as skin
      Load outside head expanded, Click Yes
      Load outside head, Click no
      Arithmetic
      Scalp and inverse* outside head = scalp
      Save scalp
      Do visual editing to clean up inside and outside scalp
      If holes, use Dilate/Fill with a very large number—fills holes only

Make the inner skull
       Load scalp, skull, eyes, nasal cavity—exclude
       Grow out from inner to get inner brain area—inner skull
       Save S#### Inner Skull
       Do Dilate/Fill with large number to fill holes

Make the outer skull
       Load skull, inner skull
       Skull OR inner skull = outer skull
       Load scalp, no
       Outer Skull and inverse-Scalp = Outer Skull (elim scalp)
       Save S#### Outer Skull

Eliminate the exterior segments of the brain
       Load the inner skull.
       Make sure it covers all the brain parts
       Use the Segment function—erases all image except inner skull
       Save as S#### Brain.vmi

Run the head to cortex segmentation wizard
       Click next until the CSF segmentation begins (5 times)
       Save CSF once it appears, you will not be able to save it later
              To save the CSF click on it in the segmentation box, region tools to highlight it
              Click Properties, change the name to CSF and Other Material
              Click save
       Click next
       Save white matter expanded
       Save white matter
       Uncheck the proceed with tiling box in the center
       Click finish
       Do this step once with the "Brain Extraction" and once without. Save the extracted
        brain to "Brain". The BET at the end is the brain. S#### Brain

Creating the Cortex
       Region tools, Add, Cortex
       Load brain, or white matter expanded, Click Yes to overwrite current region
       Load "CSF and other materials," Click No
       Region Tools, Arithmetic
        Cortex 'and' Inverse* CSF (click the inverse box next to CSF) = Cortex
        To inverse the CSF click the inverse box next to it in the arithmetic box. This
         operation will be used frequently to build the realistic head model.
       Save cortex
       Remove all segments from region control

Creating the Gray Matter
       Add Gray Matter, specify type as gray matter
       Load Cortex, Click Yes
       Load White matter, click no
       Arithmetic
       Gray Matter 'and' inverse* White Matter = Gray Matter
       Save Gray Matter

CSF and other CSF entities
       Add CSF, specify type as CSF
       Load 'CSF and other materials' Click yes
       Load the following for each Click no: cortex, eyes, nasal, outside head, skull, scalp
       Arithmetic
        CSF and inverse* cortex = CSF
        CSF and inverse* eyes = CSF
        CSF and inverse* nasal = CSF
        CSF and inverse* outside head = CSF
        CSF and inverse* skull = CSF
        CSF and inverse* scalp = CSF
       Save CSF
       Add "Ventricles" and set type as CSF
       Load "CSF" Click yes
       Load Brain, click no
       Arithmetic. Ventricles and Brain = Ventricles
       Save ventricles
       Add "Subarachnoid space" and set type as CSF
       Load CSF click yes
       Brain should already be loaded
       Arithmetic. Subarachnoid space and inverse Brain = subarachnoid space.

Creating outside of head
       If the cleanup procedure did not result in a good outside of head, follow these steps
       Load enough structures to eliminate the inside of head. These include:
        Skull, eyes, nasal cavity, brain. Exclude each of these
       Add "Outside of head"
       Grow starting from the outside, using "0 to 0" as the values. The "0" values were set in
        the clean phase

Create the cortex (use white matter expanded, or brain), inner skull, outer skull, and scalp wireframes. These are used in the EMSE realistic head model.

At this point, segments have been created for all interesting parts. Including, scalp, skull, brain, cortex, gray matter, white matter, eyes, nasal cavity, CSF, including sub-arachnoid CSF and ventricles. Use the mesh function to create meshes for any interesting mesh products. However, there is one grand mesh file that should be created.

Load scalp, skull, CSF, eyes, nasal cavity, gray matter, white matter. For each, check the properties, which should be skin, bone, CSF, eyes, air, gray matter, and white matter, respectively. Use the 3fr mesh function and create a mesh. Select all regions for creating the mesh. Select a value of … for the … to create a finely tuned mesh.

Appendix E: Segmenting and Wireframes of head structures with MR 5.1
Revised, August, 2005, to do on Experiment 50 participants. #### is participant subject number.
Any time a wireframe is done, use "20" as mesh order.

MR Viewer Wizards

Initial set up
        Open the workspace
        Open the volumetric (.vmi) file containing the participants MR Scan
        Raise the brightness and adjust the contrast until you can clearly see the brain.
        Zoom in and turn on the crosshairs and warp to point
        Edit/Segmentation, Region control tab. Move to side for later
        Wizards/Segmentation/Next
        Box around all views (0-255 in each dimension probably works)
        Go through Wizard, BUT:
          When the red wireframe is created, check it outlines brain with axial navigator
           Check the white matter step for correct WM. If not, back, redo with small init. Value
           Check the gray matter step for correct GM and WM.
        At "Proceed with Tiling"
           Save 5 regions listed (WM, WM Expanded, GM, CSF, and _BET_)
           Use S####<>nameofregion for each of the regions.
        At end of tiling, save to S#### White Matter Expanded.
        Quit the MRViewer program for next step

Wizard/Cortex to Inner Skull. Use the White Matter Expanded region, will create Inner Skull
region (save) and Inner Skull wireframe
Wizard/Inner Skull to Outer Skull. User Inner Skull region, save Outer Skull rgn wfr.

Cleanup wizard
        Wizards, segmentation, head surface
        Click next, choose Fill Inside Holes, Segment Outside of Head (cleans up VMI)
        Save cleanup before finish, or it will disappear
        Click finish
        Save S#### Cleanup.
        Save the VMI file, with cleaned up outer head
        Save "S#### Outside Head" as inverse-cleanup

Creating the eye sockets, then the nasal cavity
        Add Right eye
        Bounding Box, Set box loosely around eye
        Grow region, range 1-255. Using the 1 will exclude cleanup area outside of head
        Repeat steps create left eye
        Then, do visual edit of eyes to remove extraneous material
        Add, Eyes, specify type as eyes
        Arithmetic, right eye or left eye = eyes
        Save eyes

Add Right Eye Socket
Use Visual Edit to draw socket around the eye
Ditto for Left Eye Socket
Add, nasal cavity, specify type as air
Bounding Box, Set box loosely around nasal cavity
Grow region, range 1-255
OR, just do this with visual edit. The nasal cavity is easy to see
Save nasal cavity

Creating the Skull
Grow Skull
Add region, name it skull, specify type as bone
Segmentation box, grow region
Specify range 60-250
Specify starting point in skull
Click grow
It is probably that manual editing is necessary.
  The thickness and shape of the skull should be determined by the scan itself.
  This manual edit is to cleanup the skull by filling in breaks and removing
  nonsense areas. Save the skull often, using backups, to prevent starting over.
  A lot of manual editing here will help
It might be the case that the scalp can be created first, and the skull expanded outward,
  Or expand inner skull or brain until it hits skull, or fill skull then expand, etc
After the manual editing add the Eyes and Nasal Cavity to skull
Go around the eyes and make sure the eye bone sockets are visually edited.
After all editing, remove Eyes and Nasal cavity
  Skull AND not Eyes = Skull; Skull and not Nasal Cavity=Skull
  OR, may have to do Nasal Cavity and not Skull = Nasal Cavity

Segmentation Box, Visual Edit, chose action unset, start edit
  Use the box and line tools (or others if you prefer) to select the areas to be
    unset (removing the color)
  Unset all areas outside the skull
  Save cleanup often, using backups to prevent starting over.
Segmentation box, Visual Edit, choose action set, start edit
  Follow the same procedures to add lines or fill in skull areas

Creating the Scalp Region
Remove all segments from the region tools
Load outside head
Load, and exclude: skull, eyes, nasal cavity
Region control, region tools
Expand the outside head, by value 2, until reaches skull
Properties, Rename outside head expanded
Save
Remove all segments

Add scalp, specify type as skin
Load outside head expanded, Click Yes
Load outside head, Click no
Arithmetic
Scalp and inverse* outside head = scalp
Save scalp
Do visual editing to clean up inside and outside scalp
If holes, use Dilate/Fill with a very large number—fills holes only

An alternative to creating the skull and scalp, is to create the scalp first
Remove all segments from the region tools
Load outside head
Add scalp, load outside head from rgn into scalp, properties skin
Region control, region tools
Expand the scalp by value 1, two or three times
Arithmetic is scalp and invert-outside-head is scalp
Load all other entities (WM, GM, eyes, nasal) and do invert-and arithmetic

Make the inner skull
Load scalp, skull, eyes, nasal cavity—exclude
Grow out from inner to get inner brain area—inner skull
Save S#### Inner Skull
Do Dilate/Fill with large number to fill holes

Make the outer skull
Load skull, inner skull
Skull OR inner skull = outer skull
Load scalp, no
Outer Skull and inverse-Scalp = Outer Skull (elim scalp)
Save S#### Outer Skull

Eliminate the exterior segments of the brain
Load the inner skull.
Make sure it covers all the brain parts
Use the Segment function—erases all image except inner skull
Save as S#### Brain.vmi

CSF and other CSF entities
Add CSF, specify type as CSF; load Whole Head into CSF rgn
Load the following for each Click no: cortex, eyes, nasal, outside head, skull, scalp
  (actually, load all entities that make up the whole head model)
Arithmetic
  CSF and inverse* cortex = CSF
  CSF and inverse* eyes = CSF
  CSF and inverse* nasal = CSF
  CSF and inverse* outside head = CSF

CSF and inverse* skull = CSF
CSF and inverse* scalp = CSF
Save CSF
Add "Ventricles" and set type as CSF
Load "CSF" Click yes
Load Brain, click no
Arithmetic. Ventricles and Brain = Ventricles
Save ventricles
Add "Subarachnoid space" and set type as CSF
Load CSF click yes
Brain should already be loaded
Arithmetic. Subarachnoid space and inverse Brain = subarachnoid space.

Creating outside of head
If the cleanup procedure did not result in a good outside of head, follow these steps
Load enough structures to eliminate the inside of head. These include:
Skull, eyes, nasal cavity, brain. Exclude each of these
Add "Outside of head"
Grow starting from the outside, using "0 to 0" as the values. The "0" values were set in the clean phase

At this point, segments have been created for all interesting parts. Including, scalp, skull, brain, cortex, gray matter, white matter, eyes, nasal cavity, CSF, including sub-arachnoid CSF and ventricles. Use the mesh function to create meshes for any interesting mesh products. However, there is one grand mesh file that should be created.

Load scalp, skull, CSF, eyes, nasal cavity, gray matter, white matter, and all parts of the segments created earlier. For each, check the properties, which should be skin, bone, CSF, eyes, air, gray matter, and white matter, respectively. Use the FEM mesh function and create a mesh. Select all regions for creating the mesh. Select a value of … for the … to create a finely tuned mesh.

Make several source volume meshes: gray matter; gray-white matter; brain; whole head, GM-WM-CSF; GM-WM-CSF-Eyes.