

## EE 791 EEG-4 Recording Strategies in EEG

Although EEG recording has become much easier due to the PC for most data acquisitions and processing, the fundamentals have not changed. A high gain amplifier/filter combination is required for each because of the very low amplitude (10's of  $\mu\text{V}$ ) which should be AC-coupled and have very high input impedance ( $>20\text{ M}\Omega$ ). One has to choose the number of required channels, the location of the measuring and reference electrodes, and the location of the ground. Originally the EEG were simply stored as paper records and visual inspections and measurements the only methods of processing. Later with the advent of the minicomputer (late 1960's) data were simultaneously recorded through a A/D laboratory interface and subsequent processing done through specially written programs written in assembler or Fortran (still no graphical displays other than the chart recorder). With the introduction of the faster PC and friendlier operating systems, modern EEG systems run under Windows and graphical displays (30 sec/page) and signal processing easily accomplished.

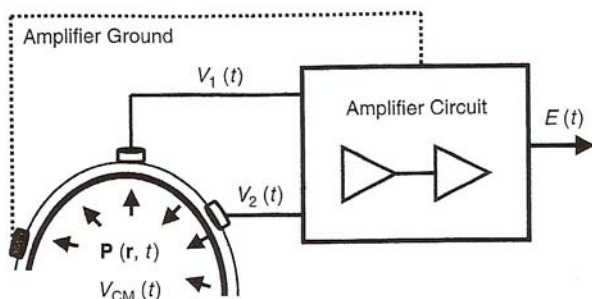


Figure 7-2 Brain mesosources  $\mathbf{P}(\mathbf{r}, t)$  generate scalp potential differences  $V_2(t) - V_1(t)$ . The potentials at scalp locations 1 and 2 are  $V_1(t) + V_{CM}(t)$  and  $V_2(t) + V_{CM}(t)$ , respectively, where the common-mode potential  $V_{CM}(t)$  is typically due mostly to capacitive coupling with power line fields. The amplifier circuit may contain several amplifier stages plus external circuit elements. The EEG system is designed to reject the common-mode potential  $V_{CM}(t)$  and amplify the potential difference between pairs of scalp locations such that the output voltage is proportional to scalp potential differences, that is,  $E(t) \cong A[V_2(t) - V_1(t)]$ , where  $A$  is the total system gain. The amplifier system makes no distinction between recording electrodes and the so-called EEG "reference electrode." By contrast, the (internal) ground electrode placed on the scalp, nose, or neck provides a reference voltage to the amplifier to prevent amplifier drift and to facilitate better common mode rejection.

In Fig 7-2 brain mesosources  $\mathbf{P}(\mathbf{r}, t)$  (current dipole moments per unit volume) and biological artifacts generate scalp potential differences  $V_2(t) - V_1(t)$ . Environmental electric and magnetic fields also generate scalp potentials  $V_{CM}(t)$  which are the same over the entire scalp surface (common mode signals) provided the subject is sufficiently far from strong EM sources (typically  $> 1.5\text{ m}$ ). Some biological sources distant from both electrodes will also present as common mode signals to both electrodes, e.g. ECG. The output  $E(t)$  can be considered as  $E(t) \cong A[V_2(t) - V_1(t)]$  if the amplifier is considered to have infinite common mode rejection ratio CMRR. The amplifier doesn't differentiate between the two measuring electrodes and records signals from both,

whereas the ground electrode references the electronic ground to the scalp potential to prevent amplifier drift and improve the CMRR. A more accurate equation for  $E(t)$  is:

$$E(t) = \left(1 - \frac{Z_1 + Z_2}{2Z_{IN}}\right)[V_2(t) - V_1(t)] + \left(\frac{Z_1 - Z_2}{Z_{IN}}\right)V_{CM}(t) + \vartheta\left(\frac{1}{Z_{IN}^2}\right)$$

Where  $Z_1$  and  $Z_2$  are the electrode impedances and  $Z_{IN}$  is assumed to be much greater than either  $Z_1$  or  $Z_2$ . The second term is a contribution of the common mode signal proportional to the difference between the two electrode impedances. This implies That the electrode impedances should be kept as low as possible ( $\leq 5\text{ K}\Omega$ ). Low electrode impedances also reduce recorded noise due to cable motion artifact and magnetically coupled 60 Hz noise.

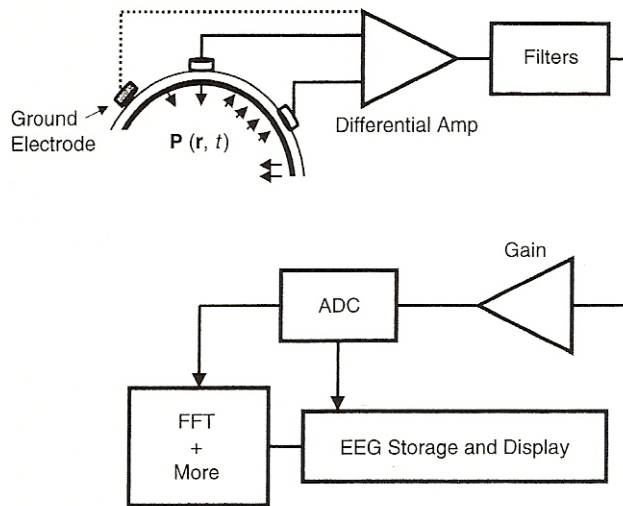


Figure 7-3 The major components of a typical EEG recording system. Electrodes record scalp signals due to brain current sources (arrows) that are passed through differential amplifiers sensitive to potential differences between electrode pairs and insensitive to the (generally much larger) spatially constant potentials over the scalp (common modes). Modern EEG systems record simultaneously from about 32 to 131 scalp locations. Analog filters low pass the input signal, typically removing substantial EEG power above about 50 to 100 Hz. High-pass analog EEG filters typically remove substantial power below about 0.5 Hz, depending on application and filter roll-off characteristics. A notch filter may or may not be used to remove power line frequencies (60 Hz in the US). The scalp potential difference signal is substantially boosted by amplifier gains. In modern EEG systems, the analog signals are sampled and numbers assigned to each part of the waveforms (ADC, analog to digital conversion). This step requires measuring ADC output produced by a calibration signal. EEG waveforms may then be displayed on a paper chart or computer screen and stored for additional processing, typically starting with application of fast Fourier transforms (FFT) to each data channel. Adapted from Cadwell and Villarreal (1999) and Fisch (1999).

Figure 7-3 shows the essential components of a modern EEG system where a PC can acquire, process, analyze, display and store the multi-channel EEG signals. Good instrumentation and recording protocols limit the amount of noise and artifact in the EEG signal. However, biological artifact such as eye-blinks, ECG, eye movement, face and

scalp EMG, etc have to be recognized automatically by special software or by visual inspection, and either removed mathematically or that segment of EEG rejected. A simple automatic detector is a level detector that rejects any EEG signal whose amplitude exceeds a preset limit. In most clinical or research studies the subject is seated semi-reclined in a comfortable chair in a darkened room with eyes closed but not dozing off. This avoids eye-blinks and motion artifact. The number of channels for the 10-20 system is 19 with a single (or at most two) reference electrode and a ground electrode placed anywhere on the scalp or neck. Sampling rates range from 200 Hz to 1 kHz with most machines having a maximum of 500 Hz. Filtering is set to have a bandpass of .3 – 70 Hz in modern machines to account for gamma1 and gamma2 EEG. A 60 Hz notch filter in North America can be included to remove any leftover power line signal. It is recommended that the high pass section have a high order filter to remove baseline drift. Although the signal should be low-pass filtered to avoid aliasing if it is greater than ½ the sampling, severe low pass filtering such as 30 Hz is to be avoided. EMG artifact will still exist at 15 – 30 Hz and is visually similar to beta activity. Leaving the filter setting at 70 Hz will allow one to more easily recognize EMG artifact.

Although the EEG has been recorded using a particular electrode as reference, the reference can be changed by processing post collection to any other recorded electrode (one that may have less signal). If the N channels have been recorded with reference channel  $V_r$  such that

$$V_n - V_r; \quad n = 1, N$$

We can choose another reference channel  $V_y$  using the transformation:

$$V_n - V_y \equiv (V_n - V_r) - (V_y - V_r)$$

There is no such thing as a monopolar recording, all electrodes, with the exception of the ground, can and do record signals and the choice of reference is difficult because we do not know the locations of contributing sources in the brain. The most common choices for reference are opposite ear or mastoid, linked ears or mastoids and the common average.

### **The Quest for an Ideal Reference**

Figure 7-4 shows the visual evoked potential VEP recorded over the right occipital area ( $O_2$  in the 10-20 system) with the reference mathematically shifted to other electrodes. Figure 7-4a shows the recordings for references within 2.7 cm of the vertex electrode  $C_z$ . The amplitude is reduced for references on either side of the midline. When reference positions are located on the forehead, the middle positive peak in the signal is accentuated with the signal modified in the 100 to 350 ms post stimulus interval. When the reference is chosen in the left mastoid area (1) and 3 cm apart over the temporal lobe (2 and 3) the first 100 ms positive peak is lost and no discernible peak occurs until 200 ms. Unfortunately there is no location that can guarantee distance from all brain sources. Large areas of the cortex may be synchronously or near synchronously active resulting in large dipole dimensions or generator size (< 10 cm) and this could be recorded by an electrode at a considerable distance.

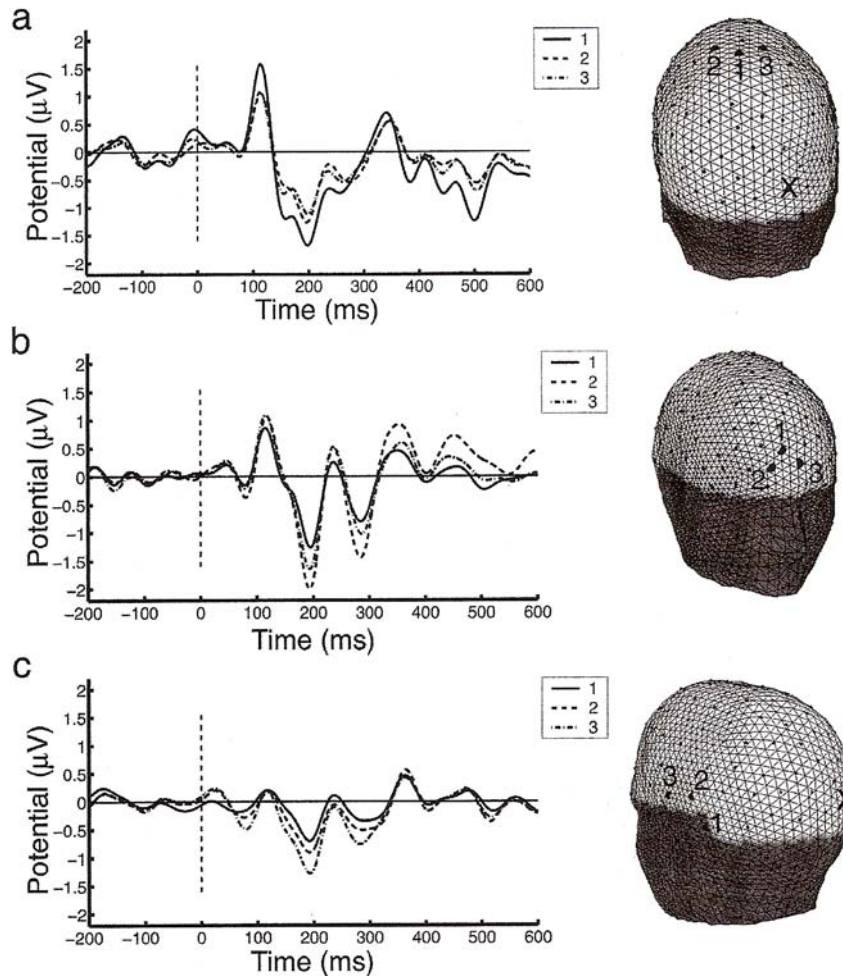


Figure 7-4 Example traces of a visual evoked potential (VEP) obtained in a 22-year-old male using different references. The visual stimulus was a circular Glass pattern formed by superimposing a rotated random dot pattern on itself (Murias 2004). The EEG data were sampled at 1000 Hz with a hardware high-pass filter at 0.1 Hz and low-pass filter at 100 Hz. The traces of EEG were then low-pass filtered at 30 Hz using a 10th order Butterworth filter, and averaged over 100 repetitions of the stimulus. The VEP was recorded at a channel over right occipital cortex (X or  $O_2$ ) with respect to a vertex reference. The reference was shifted by subtracting the potential recorded at the new reference location (with respect to the vertex) from the potential at the occipital channel (with respect to the vertex) as in (7.1). The head plots locate the recording electrode (X) and three reference sites (1-3) for each plot. (a) Three near-vertex references (one recorded and two transformed). (b) Three frontal references (transformed from vertex recording). (c) Three left mastoid references (transformed from vertex recording).

Can a scientist use a reference on another part of the body that is far away from all brain sources, however large? Nearly all current flow related to brain sources remains in the head with very little exiting through the narrowing at the neck. This has to be true because very little ECG is measured on the scalp despite the heart being a much larger generator with the ECG 100 times the EEG (property of reciprocity). In Fig 7-5 below the reference has been moved to the wrist which may add 5  $K\Omega$  to the path ( I doubt this since the bulk of electrode impedance is the electrode/electrolyte/skin interface with



additional body impedance no more than 500  $\Omega$ ). This is much smaller anyway than the amplifier input impedance and has no effect other than a pathway mismatch. Locating it somewhere else on the body can add muscle, nerve or movement artifact creating additional problems.

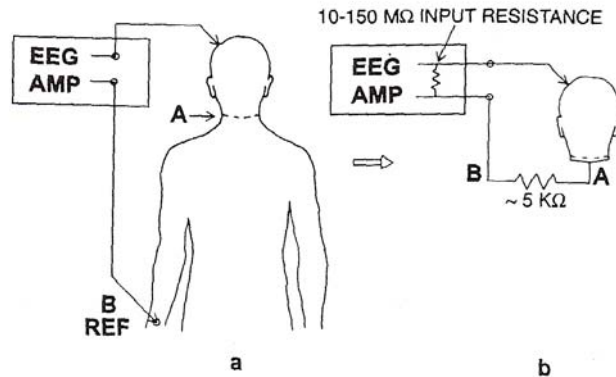


Figure 7-5 This figure addresses the general question—Can a “distant” reference for scalp EEG be found? (a) The physically distant reference at the hand (B) is electrically equivalent to a reference at the neck (A) with respect to sources in the head. The hand reference can be expected to pick up more EKG and other artifact. (b) The circuit equivalent to (a), but ignoring non-brain sources. Reproduced with permission from Katznelson (1981).

In summary there are no true references distant from brain sources. A test would be if an epileptic focus occurred in the right temporal lobe, locating the reference on the left side should keep it distant from the localized epileptic focus. If moving the reference around on the left side doesn’t change the recorded signal, it truly is a remote reference. Unfortunately the VEP results of Fig 7-4 show otherwise.

### Bipolar Recordings

These recordings are made with both electrodes near each other (1 – 3 cm), resulting in much greater recording specificity since most of the distant brain sources present as common mode signals. Clinicians can make use of bipolar recordings to examine clearly more localized sources. Locating the two electrodes across isopotential lines on the scalp gives maximum signal and along the same isopotential line gives zero potential. Figure 7-7 shows the results of recording the VEP from one central electrode while the other is located along a circle with radius 2.7 cm. The solid line gives the average of all recorded potentials. Although the signal structure is different than Fig 7-4, the peaks still occur at the same times post stimulus. Figure 7-7b shows that the VEP source is very close to the central electrode while a and c show the source more distant. Figure 7-7a shows that recording on the central line with bipolar electrodes will subtract the two VEP occipital signals, while 7-7c shows that the more parietal recording site is further away from the occipital VEP site.

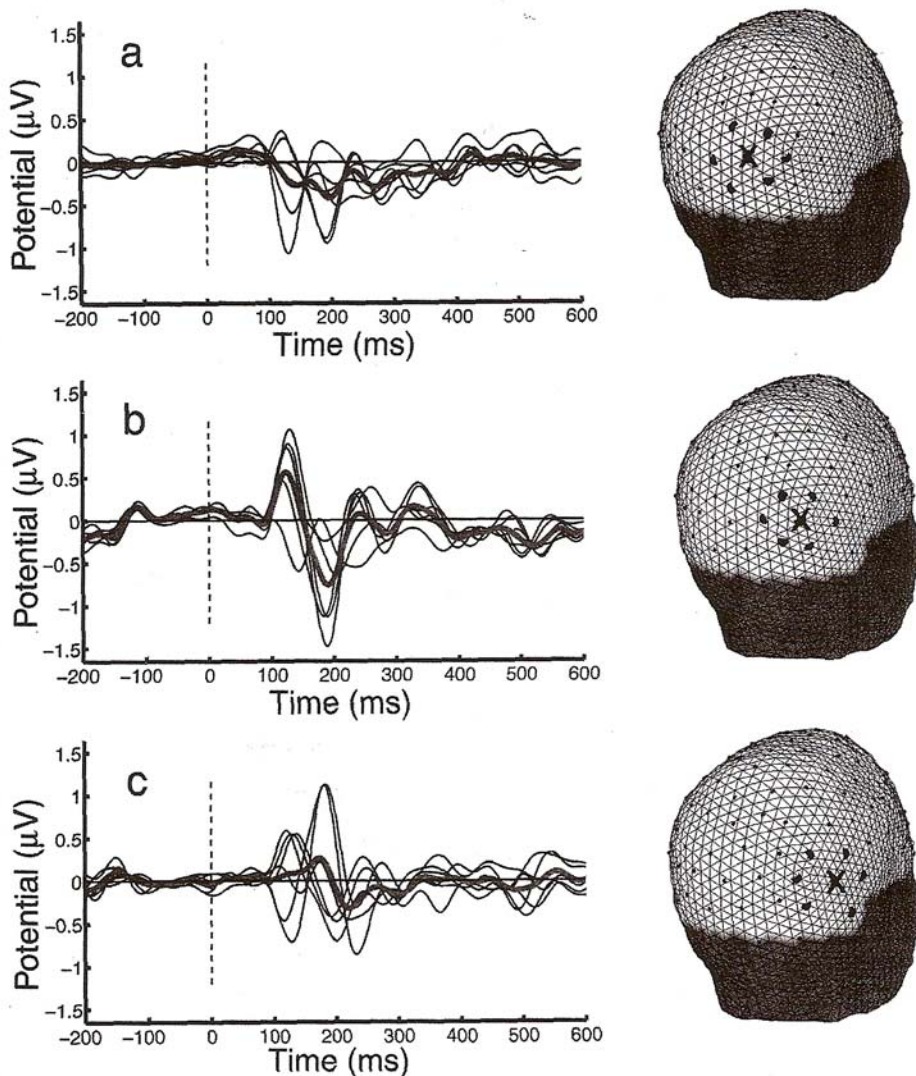


Figure 7-7 Example bipolar potentials for a visual evoked potential (VEP). The details of the recording are given in the caption of fig. 7-3. Bipolar potentials are calculated by taking the difference between the potential recorded at the central electrode (with reference at the vertex) and the potential at each of six surrounding electrodes (with reference at the vertex). The separation distance between electrode pairs is 2.7 cm. Each plot (a-c) corresponds to the center electrode X in a different location in the right posterior area. The six black lines in each plot correspond to each bipolar evoked potential. The thick gray lines are the average of the six bipolar evoked potentials in each plot (a-c).

### Linked-Ears or Linked-Mastoid Reference

This is a common recording protocol and one used by many researchers. Nunez and Srinivasan in their book attack it heavily but I think with spurious scientific basis. A typical recording layout is shown in Fig 7-8 with the reference potential in b recorded with just the electrode potentials  $R_1$  and  $R_2$  while in c a large series resistance  $R$  has been added to avoid “shorting out” the two hemispheres. The connection can be physical or the link made mathematically using the following equation where  $V$  is the channel signal and the two reference potentials are considered equal:

$$(V - V_1) - \frac{V_1 - V_2}{2} \equiv V - \frac{V_1 + V_2}{2}$$

They equate mastoid and ear which is reasonable since no currents from brain sources would flow in the ear meaning that the potential in the earlobe is the same as at the ear attachment site. However, they argue that current from the left hemisphere would flow through the electrodes and wires to the right hemisphere if the two hemispheric potentials were different, thus “shorting out” the two hemispheres. This doesn’t make sense to me since current would flow much more easily inside the cranium through volume conduction ( total impedance < 100Ω) than through the skin/electrode impedances of the two reference electrodes (total > 10 kΩ).

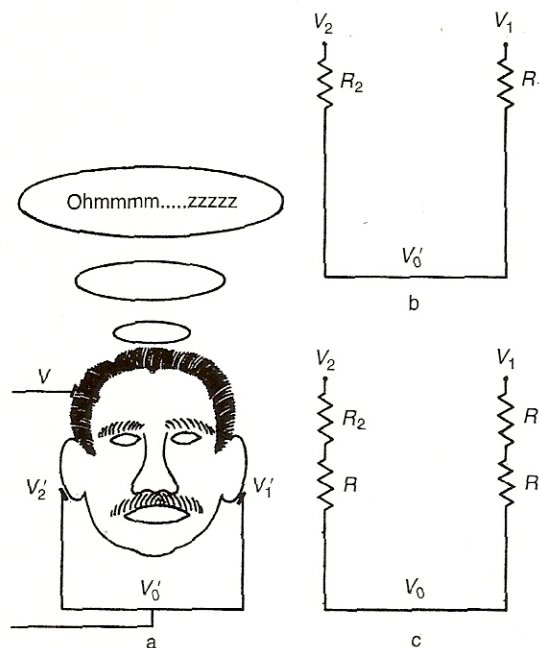


Figure 7-8 Schematic of the physically linked-ear or linked-mastoid reference. (a) The physically linked ear reference imposes a new boundary condition forcing the two sites to essentially the same potential, thereby generally changing the potential distribution over the head. The magnitude of this effect depends on the source distribution and the contact resistances  $R_1$  and  $R_2$ . (b) The link between electrodes has a resistance that is equal to the combined resistance of the two ear contacts,  $R_1 + R_2$ . (c) The problem of current flowing in the wire can be minimized by adding a large series resistance  $R$ , but this may result in a substantial rise in noise level depending on the imbalance between this linked-reference and the contact resistances of the recording electrodes (Ferree et al. 2001). This implies that as the effective resistance of the linked-reference varies during an experiment, the corresponding noise level also varies.

Another difficulty these authors see is that  $R_1$  in general is not precisely equal to  $R_2$  resulting in the potential  $V_{12}$  not being the average of the two ear or mastoid potentials as shown by:

$$V_{12} = \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2}$$

In general these two resistances may differ by 20% reinforcing their claim somewhat But in my estimation having a weighted sum of two potentials on opposite sides of the head will more likely result in a lower value than just having a single electrode as reference.

### The Average Reference

If one considers that all currents (and subsequent potentials) in the head should add to zero since little seems to leave by way of the neck, the surface potential integral at any instant of time over the scalp should be zero. This does not account for the underside of the brain but is a reasonable approximation. If one represents a channel signal by  $V_n$  where  $n = 1, 2, \dots, N$ , the total number of channels:

$$V_n = \Phi(\mathbf{r}_n) - \Phi(\mathbf{r}_R)$$

Where  $\mathbf{r}_n$  is the position of the  $n$ th electrode and  $\mathbf{r}_R$  is the reference electrode site, although  $\Phi_R$  is assumed the reference potential at “infinity”. The average of these potentials at any instant of time can be written as

$$\frac{1}{N} \sum_{n=1}^N V_n = -\Phi(\mathbf{r}_R) + \frac{1}{N} \sum_{n=1}^N \Phi(\mathbf{r}_n)$$

Rearranging the terms gives:

$$\Phi(\mathbf{r}_R) = \frac{1}{N} \sum_{n=1}^N \Phi(\mathbf{r}_n) - \frac{1}{N} \sum_{n=1}^N V_n$$

The first term should vanish if  $N$  is large enough and the electrodes are suitably placed to cover the surface potential integral. Subtracting this common average reference potential from each channel will result in a true reference free EEG signal. This is theoretically very attractive but doesn't really work for the 10-20 system because of insufficient channels. For spontaneous EEG it should work reasonably for the 10-20 system because the signal amplitudes for all channels are similar. However, in my experience for evoked potentials using a limited electrode set it doesn't work at all because the sum will be dominated by the channels having the evoked potentials. In this case the evoked potential is already obtained by synchronous averaging, resulting in channels having no evoked potential being close to zero. The right hand term in the above equation would have an averaged (divided by  $N$ ) evoked potential which would then be subtracted from every channel resulting in apparent cross-talk.

In Figure 7-9, two dipole sources have been modeled, one radial at a depth of a superficial gyrus located near the right mastoid and one tangential at the sulcus level across the midline. Using a 4-sphere head model and a forward solution the authors have obtained the surface potential lines for a 110 electrode array spaced an average of 2.7 cm apart. As can be seen, relocating the reference site from b (vertex), c (left mastoid), d (right mastoid), e (linked mastoids) and f (common average) does distort the equipotential lines with results much as expected.

### Spatial Sampling of EEG

In a time series it is well known that the sampling rate must be greater than twice the highest frequency component in the signal for proper representation of the signal in the



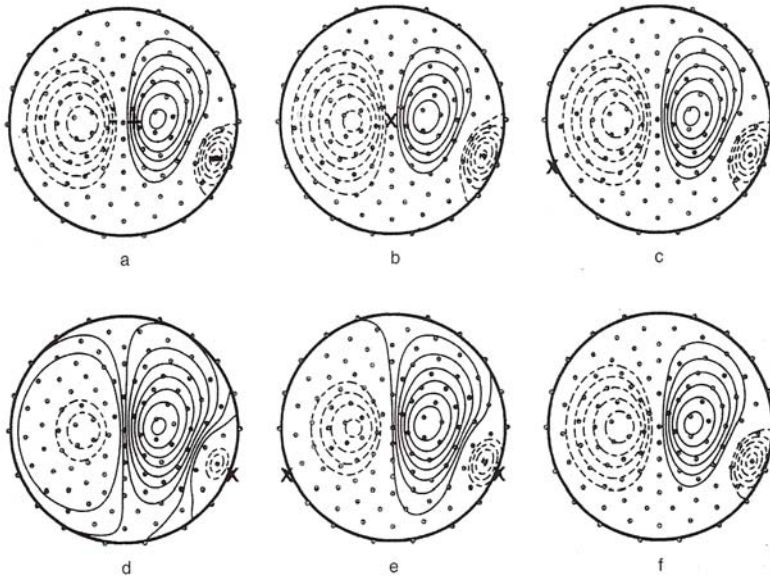


Figure 7-9 Potential maps on the surface of the 4-sphere head model due to two dipole sources – one radial at lower right and one tangential in the center. The tangential source is located 3.2 cm below the scalp; it has twice the strength of the radial dipole located 1.4 cm below the scalp. The four concentric spheres model parameters are given in fig. 6-5. Potentials were calculated at 111 surface sites, with nearest-neighbour separation of about 2.7 cm and subtending an angle of 109 degrees from vertex. The simulated electrode positions are indicated by small gray circles. Topographic maps of the potential distribution were obtained from a spline interpolation as discussed in chapter 8. (a) Potential map with respect to infinity. (b) Potential map with reference indicated by an X located at the vertex. (c) Potential map with reference X at the left mastoid. (d) Potential map with reference to a right mastoid electrode. (e) Potential map with respect to the mathematically linked (averaged) mastoids. (f) Average reference potential map obtained by first calculating the potentials at 110 electrode sites with respect to the vertex and then calculating the average reference using (7.10) with the first sum set to zero.

sampled time domain (Nyquist criterion). If a signal is under-sampled, the missing frequency components cannot be recovered due to aliasing (the frequency spectrum folds over itself at  $\frac{1}{2}$  the sampling rate or folding frequency). The Nyquist criterion for discrete sampling applies to spatial sampling as well as temporal sampling. The potential field on the scalp exists as a continuous (in space) field and is composed of spatial frequencies much like harmonics in a time signal. We cannot low pass filter to avoid aliasing as we do in time based sampling so if our electrode spacing isn't small enough we cannot represent higher spatial frequencies and they will appear as aliased lower spatial frequencies, thereby distorting the spatial maps. Figure 7-10 shows the effects of signals with higher harmonics represented by fields measured ideally and by 110 (2.7 cm spacing) electrodes and 36 (5.8 cm spacing similar to 10-20) electrodes. In this figure as the spatial frequencies increase as shown by higher harmonic numbers, the 36 electrode set results in aliasing already at  $n=5$  as shown by smoother isopotentials with the 110 electrode set showing aliasing at  $n=9$ .

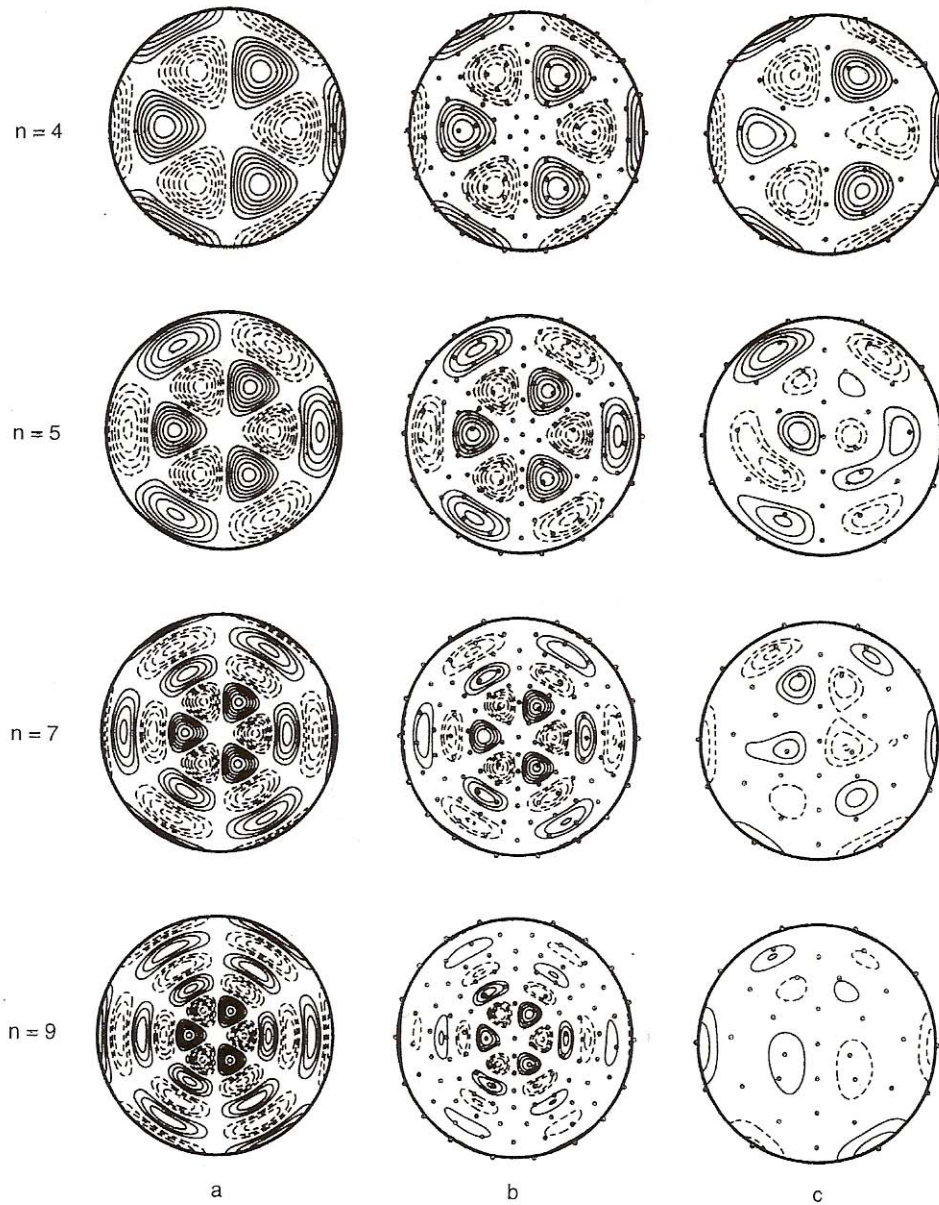


Figure 7-10 Spatial sampling of spherical harmonics. Each row corresponds to a different spherical harmonic of degree  $n = 4, 5, 7,$  and  $9$  with order fixed at  $m = -3$ . These functions are plotted on a sphere as viewed from the north pole with latitude angle (measured from the pole) in the range  $0^\circ < \theta < 109^\circ$ . The spatial patterns contain progressively higher spatial frequencies as the degree  $n$  increases down the plot. (a) The *gold standard*, that is, the functions are plotted with infinite or perfect sampling. (b) The map obtained by sampling each spherical harmonic with 111 electrodes (2.7 cm spacing) and spline-interpolation. (c) The map obtained by sampling each spherical harmonic with 36 electrodes (5.8 cm spacing) and spline interpolation. Small gray circles indicate the electrode positions.