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A comparative study of different references for EEG spectral mapping: the issue of the neutral reference and the use of the infinity reference

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Abstract

Based on EEG data recorded from 11 subjects with eyes open and the left mastoid (M) reference, three data sets were generated by re-referencing to the conventional linked mastoids (L), average (A) and the new 'infinity' (I) reference provided by the reference electrode standardization technique (REST, Yao 2001 *Physiol. Meas.* **22** 693–711). The EEG power in the alpha frequency band with the four different references was calculated and compared with respect to the total energy and spatial *amplitude weight centre* (AWC) coordinates, to compare the effects of different references on power mapping in the frequency domain. Compared with the I reference, the AWCs of the EEG with the M reference show significant shifts to the right, frontal and superficial positions, the L reference significant shifts to frontal and superficial positions, and the A reference shifts the AWC significantly to a deeper position. Furthermore, the power maps of the M and L references have larger total power than the I reference, while that of the A reference has the smallest total power. These results confirm that different choices of reference electrodes result in systematic changes in the distribution of EEG frequency power, and in order to reduce the effect of such systematic shifts on the explanation of EEG mappings, a common reference is necessary for EEG research. We recommend the I reference for objective use in cross-laboratory studies and clinical practices, as it is far from all the other electrodes and can act as a neutral reference.

Keywords: neutral reference, mastoid, average, infinity, mapping, power, EEG, alpha

(Some figures in this article are in colour only in the electronic version)

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1. Introduction

The choice of EEG reference electrode is a critical issue for many studies (Hagemann *et al* 2001, Mima and Hallett 1999). Both the evoked potential (EP) and the spontaneous potential (EEG) of neural activities are currently read in terms of components thought to reflect distinct neural generators (Desmedt *et al* 1990, Chen *et al* 2002, Niedermeyer and Lopes da Silva 1999). Each component can be defined by characteristics such as polarity, scalp region, spectra, range of latencies and amplitudes. Ideally, the reference electrode should not affect these characteristics, which require the reference to behave neutrally. However, it is well known that only the difference between the two potentials referenced at a neutral point can be measured, so it is indispensable to set a reference in human scalp recordings (Geselowitz 1998). The cephalic electrode, such as the *vertex* (Cz) (Bruder *et al* 1997, Lehmann *et al* 1998, Hesse *et al* 2004), the tip of the *nose* (Andrew and Pfurtscheller 1996, Klimesch *et al* 1996, Essl and Rappelsberger 1998), *uni-mastoid or ear* (Basar *et al* 1998, Thatcher *et al* 2001), *linked mastoids or ear* (Gevins and Smith 2000, Croft *et al* 2002, Newton *et al* 2003), *neck ring* (Katznelson 1981), Oz (Merlet *et al* 1998), and *average* (Offner 1950, Nunez *et al* 2001, Rodriguez *et al* 2004) reference, etc, have been used. Each may yield some effects on the recordings, so different reference sites have been recommended for studies of different potentials (Wolpaw and Wood 1982, Desmedt *et al* 1990, Dien 1998).

Since neural electrical activation is a spatio-temporal process, a reference also affects both spatial and temporal aspects. The two important aspects of the choice of reference electrode on the spatial aspect of the EEG are: (1) for noiseless scalp potentials the reference does not affect the inverse localization of neural active sources (Geselowitz 1998, Pascual-Marqui and Lehmann 1993); (2) the effect of a reference on the shape of a temporal EEG potential map is to add or subtract a constant value at all locations, like raising or lowering the water level in a landscape, without changing the overall shape (Geselowitz 1998). These two points show that the effect of reference on spatial aspect is not a crucial, but a phenomena change, and so, if our concern is the spatial aspect, we do not need to pay specific attention to the reference problem.

The effect of a reference on the temporal aspect of the EEG data is due to the fact that a temporally non-neutral (active) reference may introduce an unknown component to the potential on all other electrodes. Such an unknown component added to the EEG time course will change the temporal waveform, hence the frequency domain power of the EEG (Lehmann 1988, Maurer 1989, Geselowitz 1998, Yao 2001). To solve this problem, great effort has been put in to finding a relative non-active point on the body surface, and arguments on this topic have existed for a long time (Geselowitz 1998, Dien 1998, Desmedt *et al* 1990, Wolpaw and Wood 1982, Maurer 1989, Pascual-Marqui and Lehmann 1993, Hagemann *et al* 2001). However, it is impossible to find a neutral reference on the scalp or body; there is no single location where the potential can be considered to be neutral (Geselowitz 1998) because the neural electric activities are distributed spatio-temporal dynamic processes.

For the four references concerned in this work, the left mastoid (M) reference is a commonly used on-line reference, since it provides a place for robust attachment of an electrode with low impedance. The analysis of data thus recorded assumes that the mastoid is relatively inactive, however this has been persuasively shown to be false (Lehtonen and Koivikko 1971, Hagemann *et al* 2001). The validity of the linked mastoids (L) reference also depends on the assumption of little or no activity on the mastoids or an assumption of anti-symmetry of the neural electric activities of the left and right hemisphere. The commonly recommended average (A) reference (Offner 1950) assumes that the mean of all recording channels is approximately neutral. However, this approximation is valid only with accurate spatial sampling of the scalp fields, which requires a sufficient electrode density and full coverage of the head's surface. If this requirement is not fulfilled, an average reference effect will exist and bias the scalp recordings (Dien 1998). Provided by the reference electrode standardization technique (REST), the new infinity (I) reference is a mathematical method that approximately transforms the EEG recordings with a scalp point reference to recordings with a reference at infinity (Yao 2001). As a point at infinity is far from all the possible neural electric sources, it may be considered as a neutral reference. We have previously performed validation simulation studies with assumed neural sources in a concentric three sphere head model that included the effects of the electrode number, volume conductor model and noise effects (Yao 2001). The results showed that the I reference is very effective in recovering the potential referenced at infinity for sources located at the superficial cortical region and the I reference could be especially important in recovering the temporal waveform and frequency domain power information of EEG recordings.

Frequency based quantitative EEG power mapping has shown to be a useful tool for investigating brain regional mechanisms underlying various normal and disordered brain states (Knotta *et al* 2001, Lehmann 1988). For example, in the study of AD/HD (attention-deficit/hyperactivity disorder), the calculation of absolute and relative power estimates were considered as the most commonly used form of EEG analysis (Barry *et al* 2003). The relevant effect of the reference is mainly on the EEG waveform and its frequency spectra (Maurer 1989), therefore it is particularly relevant for frequency power mapping. In this work, the power maps of the M, L, A and I references are compared.

2. Material and methods

2.1. Sample and EEG recordings

Eleven healthy right-handed adult male volunteers (age: 18–30 years) were recruited from university staff and students. The study was approved by the Local Ethics Committee and was in accordance with the Helsinki Declaration. Informed consent was obtained from each subject prior to the study. Experiments were performed in a quiet, air-conditioned (20–21 °C) laboratory with soft natural light. Subjects were requested to sit in a comfortable chair and relax. The EEG was recorded using Ag/AgCl electrodes from 128 scalp electrodes (including two EOG channels) with a left mastoid reference (M). Electrodes were applied to the scalp using a carefully positioned nylon cap in accordance with the 10–5 extension of the International 10–20 electrode system (Oostenveld and Praamstra 2001). The vertical and horizontal eye movements (EOG) were recorded from a bipolar lead placed next to the orbit. The data was sampled at 512 Hz. Scalp electrode impedances were below 10 k. Two to three minutes of spontaneous EEG was recorded while the subject had his eyes open. Muscle, EOG and movement artefacts were visually identified during off-line editing; epochs containing an artefact were excluded from further analysis. The data sets were separated into epochs of 2 s each, and 60 artefact free epochs were chosen for analysis per subject; a band-pass filter from 0.5 to 100 Hz and a 50 Hz notch filter were applied to the data.

2.2. Re-reference recordings

In our recordings, with the left mastoid as the reference, we actually have recordings of 124 channels with 123 potential differences. Hence we have

$$V_{\text{measured}}(t) = \begin{pmatrix} v_1(t) \\ \cdot \\ \cdot \\ v_{123}(t) \\ 0 \end{pmatrix}, \tag{1}$$

where $v_1(t)$ up to $v_{123}(t)$ are the recordings of each electrode referenced to left mastoid. So we have channel 123 being the right mastoid sensor, and channel 124 being the left mastoid sensor. To show the similarity between the different re-referencing methods, we will write each of them (including the originally measured left mastoid) as a set of linear equations. This reveals that any type of re-referencing can be achieved by multiplying the recorded data with a single (and usually sparse) matrix. We will omit the index t for time from now on to improve readability.

2.2.1. Mastoid (M) reference recordings V_m.

$$V_m = K V_{\text{measured}}. \tag{2}$$

Here V_m is actually the same as V_{measured}, and the transfer matrix K is an identity matrix with size N by N with $N = 124$, which is the number of total channels.

2.2.2. Linked mastoids (L) reference recordings.

Recordings with linked mastoids as the reference are defined as V_l (Dien 1998, Hagemann *et al* 2001)

$$V_l = L V_m, \tag{3}$$

where

$$L = \begin{bmatrix} 1\,0\ldots 0 & -0.5 & 0 \\ 0\,1\,0\ldots 0 & -0.5 & 0 \\ \ldots & & \\ 0\ldots 1 & -0.5 & 0 \\ 0\ldots 0 & +0.5 & 0 \\ 0\ldots 0 & -0.5 & 0 \end{bmatrix}. \tag{4}$$

The size of the transfer matrix L is also N by N.

2.2.3. Average (A) reference recordings.

Recordings referenced to the mean of all recording channels at each time point are obtained by

$$V_a = A V_m, \tag{5}$$

where

$$A = K - \begin{bmatrix} 1/N \ldots 1/N \\ \ldots \\ 1/N \ldots 1/N \end{bmatrix}. \tag{6}$$

2.2.4. Infinity (I) reference recordings. Based on high-density multi-channel recordings, an approximate neutral potential recording can be realized through off-line re-reference processing provided by the reference electrode standardization technique (REST) (Yao 2001). REST is based on the theoretical relation between the scalp recordings with a body reference and neural source model with source strength S (Helmholtz 1853, Geselowitz 1998, Pascual-Marqui and Lehmann 1993). For an infinity neutral reference, we have

$$V = GS, \tag{7}$$

where the transfer matrix G depends on the head model, source configuration and electrode montage, and has a reference at infinity. The scalp noise is not included in this model and is assumed to be zero. Meanwhile, for the left mastoid (M) referenced recordings V_m, we have

$$V_m = G_m S. \tag{8}$$

Based on the Moore–Penrose generalized inverse, a minimum norm solution (MNS), which is a valuable method whenever no reliable *a priori* information about source generators is available (Hauk 2004), we have

$$S = G_m^+ V_m. \tag{9}$$

The symbol $(^*)^+$ denotes the generalized inverse. From equation (7) to equation (8), the transfer matrix G was replaced by G_m (i.e. a forward model assuming a reference in the model at the left mastoid). From equations (7) and (8) we see that the source (S) is the same, which reflects the fact that the reference does not affect the localization of neural active sources in the case of noise free scalp potentials (Geselowitz 1998, Pascual-Marqui and Lehmann 1993). Thus we may use the inverse shown in equation (9) to reconstruct the potential V in equation (7) referenced at infinity as V_i

$$V_i = G(G_m^+ V_m) = U V_m, \tag{10}$$

where

$$U = G G_m^+. \tag{11}$$

U is the final transfer matrix which is determined by the lead-field matrixes G_m and G. Based on equations (7)–(11), we do not need to know the actual source S because what we really need are the matrixes G and G_m. As the potential produced by any sources can be equivalently produced by a source distribution which encloses the actual sources inside the distribution (Helmholtz 1853), we may assume an equivalent source distribution (ESD) on the cortical surface that encloses all the possible neural electric sources inside, and assume that S in equations (7) and (8) is the ESD instead of the actual neural electric sources. Thus the matrixes G and G_m are determined by the head model, electrode montage and the spatial geometric information of the assumed equivalent source distribution model (Yao 2001). The ESD may be a closed radial dipole layer or a charge layer (Yao 2000, Yao and He 2003).

In REST, the head model is a three-concentric-sphere model, the normalized radii of the three concentric spheres are 0.87 (inner radius of the skull), 0.92 (outer radius of the skull) and 1.0 (radius of the scalp), and the conductivities are 1.0 (brain and scalp) and $0.0125 = 1/80$ (skull). The solution for the surface potential of the three-concentric-sphere model can be found in the literature (Rush and Driscoll 1969, Yao 2000). The assumed equivalent source distribution model is assumed to be a discrete equivalent dipole layer on a closed surface formed by a spherical cap surface with radius $r = 0.869$ above a transverse plane at $z = -0.076$. A discrete approximation of the closed surface was further assumed, consisting of 2600 radial dipoles on the spherical cap surface and 400 dipoles on the transverse plane perpendicular to that plane (Yao 2001). The electrode montage is the 10–5 extension of the

International 10–20 electrode system (Oostenveld and Praamstra 2001) with 124 electrodes involved in the calculation (the EOGH and EOGV were excluded). Our previous simulation studies (Yao 2001) showed that the more accurate the head model in REST, the better the potential V reconstruction, and the results also showed that even though the known three-concentric sphere model was replaced in REST by a single sphere model, the effect of the reference still could be reduced a lot. Further details of the REST algorithm can be found in Yao (2001).

In summary, the four re-referenced data sets from the original M reference recordings $v_{\text{measured}}(t)$ are obtained by the related transfer matrixes K, L, A and U, respectively.

2.3. Spectra power and amplitude weight centre (AWC) calculation

For each subject the artefact free data was analysed by the FFT to get the power of each channel in the frequency domain in two alpha frequency bands: Alpha1 (7.5–9.5 Hz) and Alpha2 (10–12 Hz). The total power over all channels for each frequency band was calculated by summation over all the channels. Furthermore, in order to identify the possible systematic effects of the references on the spatial distribution of power, the amplitude weight centre (AWC) of each was also calculated for each subject for use in a later statistic test. The AWC was defined as

$$Xc(j) = \frac{\sum_{i=1}^{N} x_i A_i(j)}{\sum_{i=1}^{N} A_i(j)}, \qquad Yc(j) = \frac{\sum_{i=1}^{N} y_i A_i(j)}{\sum_{i=1}^{N} A_i(j)}, \qquad Zc(j) = \frac{\sum_{i=1}^{N} z_i A_i(j)}{\sum_{i=1}^{N} A_i(j)}, \tag{12}$$

where $A_i(j)$ is the square root of the power of the frequency band j at electrode i. $(Xc(j), Yc(j), Zc(j))$ are the coordinates of the AWC. (x_i, y_i, z_i) are the coordinates of electrode $i (i = 1, \ldots, N)$, and $N = 124$ is the total number of electrodes. The shift in the AWC can be displayed in the three orthogonal directions. A similar parameter was used in a study of alpha blocking (Rijke and Visser 1989).

In the calculation, the coordinates of the electrodes are distributed on a sphere according to the 10–5 extension of the International 10–20 electrode system (Oostenveld and Praamstra 2001). The head surface is described here as a sphere of radius 10 cm, so that the AWC results can be compared to the dimensions of a real head. The Cartesian coordinate system was defined with the centre of the sphere as the origin, and the x-axis towards the right ear, the y-axis towards the nasion and the z-axis towards the vertex.

3. Results

3.1. Power mappings

The average power maps over the 11 subjects in Alpha1 (7.5–9.5 Hz) and Alpha2 (10–12 Hz) bands are shown in figure 1. From figure 1 some systematic changes can be found from one reference to the other. As the I reference at infinity is far from all the other electrodes, we chose it as the standard for comparison. For the M reference (left mastoid), the activities on the maps were shifted to the right when compared with the I reference. For the L reference, in contrast to the M reference, a good balance between the left and right was shown. However, when compared with the I reference, the activities on the maps of both L and M references showed a little forward shift. The power for the A reference was generally smaller than that of the other references.

In summary, these power maps demonstrated distinct differences in both power values and distributions among the four references.

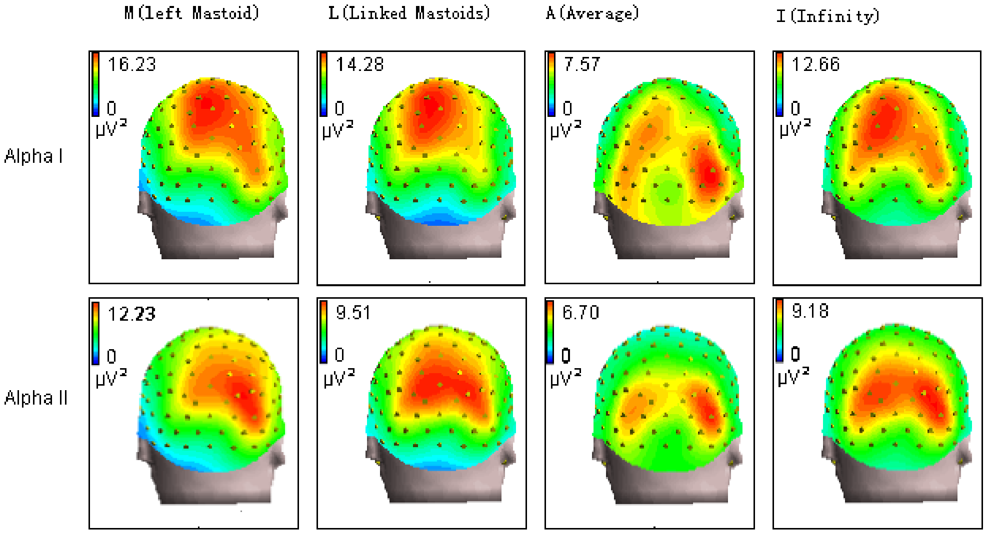

Figure 1. Power maps of the EEG recordings with different references. The frequency bands are Alpha1 (7.5–9.5 Hz) and Alpha2 (10–12 Hz). The power is analysed by FFT with 2 s epochs free of artefacts.

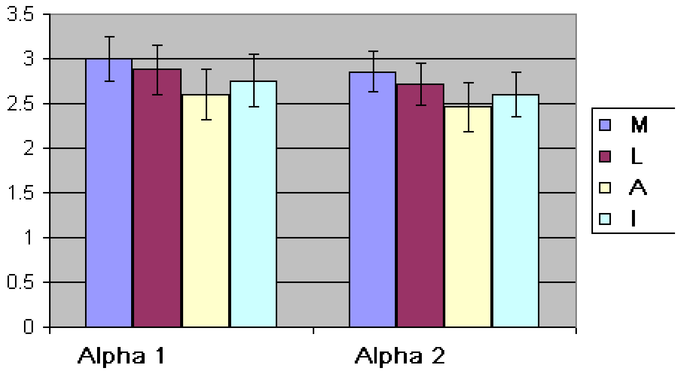

Figure 2. Log_{10} (total power) of the EEG with different references. Alpha1 (7.5–9.5 Hz), Alpha2 (10–12 Hz) averaged over 11 subjects. The vertical axis is the $\log_{10}$ of total power over all channels. The vertical bars indicate the standard deviation. Where the four references are M (left mastoid), L (linked mastoids), A (average) and I (infinity).

3.2. Differences of power values

The values of total power in $\log_{10}$ over all channels are shown in figure 2. This figure shows that the total power of the recordings with the M reference is the largest, followed by the L and I references, and that the A reference is the smallest.

In order to make sure that the difference is not due to chance, a one-way repeated-measures ANOVA was conducted on the $\log_{10}$ transformed total power values (Szava *et al* 1994) of the 11 subjects. The results demonstrated the differences that between the four references are significant (Alpha1: $F = 109.49$, $P < 0.001$; Alpha2: $F = 78.05$, $P < 0.001$), and the pair-wise multiple comparison procedures (Tukey Test) gave $P < 0.001$ for all cases except that for Alpha2, between L and I, which gave $P = 0.001$. Therefore we conclude that the reference

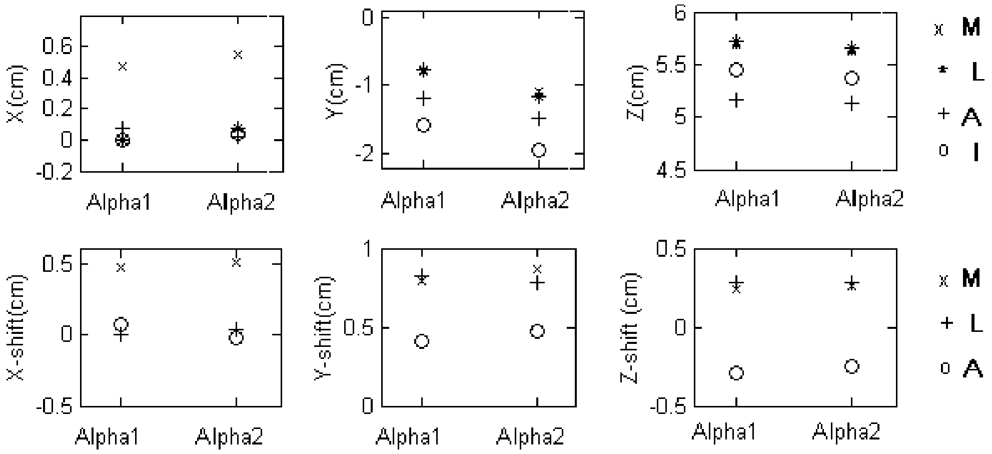

Figure 3. Coordinates of, and shifts in, the amplitude weight centre (AWC) of power maps at the two frequency bands. The Cartesian coordinate system was defined with the centre of the sphere as the origin, and the x-axis towards the right ear, the y-axis towards the nasion and the z-axis towards the vertex. Upper row: coordinates of the AWCs of power maps. Lower row: coordinate differences of the AWCs, comparing reference M (left mastoid), L (linked mastoids), A (average) with I (infinity).

has a significant effect on the power values, and any explanations of physiological processes based on power difference should take this fact into account.

3.3. Systematic shifts of AWCs

The coordinates of the AWC are shown in figure 3, where the upper row shows the actual Cartesian coordinates of the AWCs and the lower row shows the coordinate differences between M, L, A and I. The results of the statistic tests over the 11 subjects show that, for the x-axis values of the AWCs, the M reference has a significant ($p < 0.001$) difference along the x-axis of the AWCs to the other three references, and that the differences among the other three references are not significant. For the y-axis and z-axis values of the AWCs, only the difference between M and L is not significant; all the other differences are significant ($p < 0.001$ or $p < 0.05$). When comparing the AWCs of M, L and A with the I reference for the Alpha1 band (figure 3 (lower row)), the M reference (left mastoid) shows significant ($p < 0.001$) right ($+x$), frontal ($+y$) and superficial ($+z$) shifts (x: 0.5 ± 0.2; y: 0.8 ± 0.2; z: 0.24 ± 0.07 (cm)). The L reference shows an AWC with an identical location from left to right, but significant ($p < 0.001$) frontal and superficial shifts (x: 0.00 ± 0.09; y: 0.8 ± 0.2; z: 0.28 ± 0.08(cm)). In contrast, the A reference resulted in a significant shift to the bottom (x: 0.0 ± 0.2; y: 0.4 ± 0.4; z: -0.3 ± 0.1). For the Alpha2 band, the results are similar.

4. Discussions

4.1. The effects of the M and L references

The above phenomena of the M and L references are clearly related to the spatial positions of the mastoids. The mastoids are at the lower rear of the ears within our model coordinates of $(x, y, z) = (-8.0, -5.5, -2.4)$ cm and $(x, y, z) = (8.0, -5.5, -2.4)$ cm, where the minus y (-5.5 cm) means that these two points are closer to the occipital region than to the frontal region. Thus they may have a bigger effect on the potential of the electrodes in the occipital region than on the frontal electrodes. This results in a shift in the EEG power maps to the anterior region compared to the average and infinite references. The maximum shift of the AWC to the anterior is $y = 0.8 \pm 0.2$ cm at the Alpha2 band. Similarly, the negative shift along the z-axis (-2.4 cm) means that they have a larger effect in the relative lower region, resulting in an AWC shift to a more superficial location. The maximum shift of the AWC to the vertex is $z = 0.28 \pm 0.08$ (cm) at the Alpha1 band.

The amplitude amplifying effect of the both mastoid references (figure 2) can be reasonably explained if we assume the generators of the alpha are mainly located in the parieto-occipital area (Michel *et al* 1992). For such a generator, the inverse alpha polarity at the mastoids compared to the parietal and occipital sensors amplifies the power in the posterior regions.

4.2. The effect of the A reference

If our electrode montage is a dense and full coverage of the head's surface, the A reference will be a neutral reference, while the actual upper hemisphere sampling will definitely change the amplitude weight centre. Due to the average reference effect, the potential amplitudes are smaller for electrodes located in the centre of the electrode array than for those located on the edge, the weight centre will be lower than the actual case (z: -0.3 ± 0.1 cm). Meanwhile, due to the lack of facial sensors, the A reference also shows a frontal shift (y: 0.4 ± 0.4 cm).

4.3. The I reference

The I reference is theoretically far from all the electrodes thus it is a neutral reference. In theory, if we have full and homogenous coverage of the head, the I reference will be the same as the A reference. Different from the other three references, the effectiveness of the I reference depends on the assumed volume model, sensor and source configuration as well as the choice of the inverse method of the source configuration. However, our simulations have shown that even though there are some errors in the head model and scalp potential, REST may still reduce the effect of the reference to a great degree (Yao 2001).

4.4. The I reference and other reference-free techniques

After the discussions shown above about the I reference and the other three popular references, the relations between the I reference and other available reference-free techniques should be considered, for example the scalp Laplacian (SL) (Hjorth 1975) emphasizes shallow and localized sources because the differential calculation acts as a spatial high-pass filter, and the high-spatial-frequency components on the scalp surface of shallow and localized sources are more abundant than those of deep or smooth distributed sources. In fact, the Laplacian is different from the electric potential in physics; it is approximately proportional to the flux of the entrant current flowing from the scalp into the skull. Therefore a reference-free potential or a reference-effect reduced potential like that given by the I reference, in practice, is important on its own, no matter whether or not the SL can be precisely deduced from the potential or be directly measured (Nunez *et al* 1994, Geselowitz and Ferrara 1999).

Another reference-free technique is the magneto-encephalogram (MEG). Both the EEG and the MEG are due to neural electric current sources; however, they are different in the response of the sources in practice. The MEG collected by a coil detector with its axis normal to the scalp surface is usually a recording of the vertical component of the whole magnetic flux vector. As noted, the MEG does not detect a radial source, but only a tangential source, while the EEG sees both the radial source and tangential source, and so a combination of EEG and MEG is encouraged in solving the inverse problem (Cohen and Cuffin 1987).

Another reference-free quantity is the cortical potential reconstructed by various cortical imaging techniques (Nunez *et al* 1994). The reconstructed cortical potential may be referenced at a scalp point or at a point at infinity. When it is referenced at infinity, it may be considered as a reference-free cortical potential; however, such a property has never been emphasized in the literatures to our knowledge. The reason is that the cortical imaging technique mainly focuses on improving the spatial resolution by extrapolating the scalp potential inward to the cortical surface, and in this extrapolation process there is an amplification of the high spatial frequency components, which is a similar phenomena to that in the scalp Laplacian (Nunez *et al* 1994, Babiloni *et al* 1998, Yao 2000, 2001). Apparently, as the noise existing in the scalp EEG recordings is generally of a wide spectrum, its amplification is larger than the real EEG signal, so such an inward extrapolation is an unstable process (Dampney 1969). In order to stabilize this extrapolation process, a noise smoothing technique such as a regularization technique has to be involved. Due to the regularization, the final reconstructed cortical potential with apparent enhanced spatial resolution compared to the scalp potential then is definitely different from the actual cortical potential, so the 'reference-free' property in the temporal aspect is definitely changed by such a subjective process.

Finally, the reconstructed equivalent source distribution (ESD) is also a reference-free quantity. However, similar to the cortical potential reconstruction, regularization is a critical technique in the cortical ESD reconstruction from the scalp recordings, and it is the regularization that may change the temporal dynamics of the reconstructed equivalent source signals. In our REST (Yao 2001), from the scalp V_a to the scalp V, we did not utilize any subjective regularization, thus the result is objective with the temporal dynamics and the spectra kept the same as the original in theory.

5. Summary and conclusion

The choice of an EEG reference is an important initial step for EEG analysis, and the actual recorded EEG potential is a relative measure that compares the recording site with another (reference) site. If there is neural electric activity at the reference site, it will contribute equally to the resulting recordings of all channels; this is the case for the M reference and other similar cases, such as vertex (Cz), nose reference, etc. Based on a detailed study (Dien 1998), it was concluded that the choice of reference has substantial effects on analysis and interpretation, and it is recommended that the optimal choice of reference site depends on the study and the purpose of the analysis. Although it is sometimes argued that the mastoids are relatively inactive, this has been persuasively shown to be false (Lehtonen and Koivikko 1971, Hagemann *et al* 2001), and in some cases the use of an average reference is clearly not a proper choice (Dien 1998). Also, Hagemann *et al* (2001) concluded that the choice of the EEG reference could be a critical issue for the study of anterior asymmetry in the alpha band. Especially noted was that one should not treat the findings of different reference schemes as interchangeable based on their reviews of the empirical literature.

The new I reference is a primary attempt to restore the potential of the reference electrode in EEG recordings when it is referenced at infinity. Many researchers in the field of electrophysiology long desire to have a reference-free potential measurement. In fact, a reference-free or reference-independent potential cannot be measured or constructed, but the off-line computed I reference may be a proper choice to improve the analysis of power spectra.

In this work, the head model is the three-concentric sphere model which is widely utilized in studies where individual MRI/CT data of sufficient quality is not available. Our recent study has shown that REST can be further extended to a realistic head model with the boundary element method (Zhai and Yao 2004), thus further applications can be based on a realistic head model in the future.

In conclusion, the results of this study have demonstrated that different references induce systematic changes of AWCs in EEG power maps. In order to reduce effect of such systematic shifts on the explanation of EEG mappings, a common reference is necessary for objective use in cross-laboratory studies and clinical practices. We recommend the I reference as the proper choice as it approximates a neutral reference.

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