Abnormal resting state EEG power spectral in patients with tinnitus on different sides of the ear

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Abstract. Tinnitus is a symptom of sound perception in the absence of external sound stimulation, and most patients have unilateral tinnitus, with more tinnitus on the left than on the right. In this paper, the resting EEG data of 10 patients with binaural tinnitus, 10 patients with left tinnitus and 10 healthy controls were collected, and two 10-s segments of resting EEG data were intercepted from each group for approximately 10 min. The absolute and relative power was calculated by fast Fourier transform. The results showed that more frequency bands were significantly different in the left tinnitus patients compared to the bilateral tinnitus patients and the right tinnitus patients, and where significant differences were demonstrated, the absolute and relative power was higher in the Delta and Theta bands of the tinnitus patients than in the control group. In conclusion, these results compare the resting state EEG power spectrum abnormalities in patients with tinnitus on different sides with healthy controls from an electroencephalographic perspective, and are expected to be used as an evaluation criterion in the future to provide a more refined and precise treatment plan for patients with tinnitus on different sides and to improve the efficiency of treatment.

1. Introduction
Tinnitus is a symptom of sound sensation in the absence of external sound stimulation, and is one of the three major problems in otology. A rough estimate of the number of people with tinnitus in China is 120 million (10.0\%). Therefore, it is important to understand the characteristics of tinnitus and to treat it specifically. The prevalence of unilateral tinnitus is usually higher than that of bilateral tinnitus, and left-sided tinnitus is more common\cite{1}. Currently, there is no uniform and objective method for tinnitus detection and therapy, and the mechanism of tinnitus is still unclear. In this study, approximately 10 min of resting-state electroencephalography (EEG) data were selected from patients with tinnitus on different sides of the ear and healthy controls. Signal EEG waves are formed by the postsynaptic potentials of a large number of synchronized neurons in the brain and are a comprehensive expression of various types of electrical activity, which are compound waves. The EEG signal is generally classified according to frequency as Delta (0.5-3.5 Hz), Theta (4-7.5 Hz), Alpha (8-12 Hz), Beta (13-30 Hz), Gamma (30.5-44 Hz)\cite{2}. Then the resting-state EEG was compared between patients with different lateral tinnitus and healthy controls at different rhythms of absolute
power and relative power, respectively. Previous resting-state EEG/MEG studies comparing tinnitus patients with healthy controls have identified several frequency power band changes between the two groups. Since the original work of Weisz et al, an increase in Theta band power associated with tinnitus has been reported[3-7]. Several studies[4][6][8] have reported reduced alpha frequency in people with tinnitus compared to controls. It has also been documented[9] that patients with unilateral tinnitus exhibit greater Delta power compared to those with bilateral tinnitus.

Compared to past studies that focused only on the differences in resting state EEG power spectra between tinnitus patients and healthy controls, this study focuses on the resting state EEG power spectra between tinnitus patients with different lateral ears and healthy controls. Combined with some previous reports of clinical characteristics of tinnitus patients, it can be found that most tinnitus patients are unilateral tinnitus, and the left tinnitus is more than the right tinnitus. The study will find out the statistically significant regions and frequency bands by independent sample t-test statistical method, and explore whether there is a correlation between the resting EEG power spectrum difference regions and frequency bands and the tinnitus side.

2. Materials and methods

2.1. Participants

The data for this study were provided by the partner hospitals. Data inclusion criteria[10] for the tinnitus and healthy control groups were as follow: (1) All participants ranged in age from 20 to 50; (2) All participants were free of Central nervous system disease, mental illness and were not in anxiety and depression state (self-rating anxiety scale score and self-rating depression scale score, SAS and SDS < 50); (3) All participants had normal intelligence that matches their age; (4) All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield 1971); (5) To minimize the influence of hearing loss, 4-frequency (0.5 kHz, 1 kHz, 2 kHz, and 4 kHz) pure tone threshold average (PTA) of all tinnitus patients were less than 25 dB; (6) No smoking and alcohol addiction, no Addictive drug abuse. The exclusion criteria for the tinnitus group were as follows: (1) no tinnitus; (2) tinnitus frequency < 2 kHz on subjective matching test; and (3) tinnitus duration < 3 months. Information from 30 of these data groups was selected for the study, including 10 groups with left-sided tinnitus, 10 groups with right-sided tinnitus and 10 groups with bilateral tinnitus. A further 10 groups of normal control data were selected.

2.2. Resting state EEG recording

The EEG signals were recorded by Neuroscan software (version 4.5) by a 64-channel Ag/AgCl electrode cap with a common vertex (Cz) reference at 1 kHz sampling rate. Prior to each recording, the resistance of each electrode was assured to be lower than 10 kΩ. During EEG recording, the participants were asked to stay still, kept awake and close their eyes at a sound- and electrically-shielded room. The acquired EEG signals were then amplified by a NeuroScan SynAmps 2 amplifier (Neurosoft, Inc., Sterling, VA), and filtered by a bandpass filter (BPF) with a passband of 0.1–100 Hz.

2.3. EEG pre-processing

The resting EEG raw data included tinnitus and control groups, with the tinnitus group being a binaural tinnitus group, a left tinnitus group and a right tinnitus group. MATLAB for R2016b and the EEGLAB for v13.0.0 toolbox were utilized. The raw data for each subject were loaded into EEGLAB. pre-processing steps were as follows: (1) load the electrode coordinates file, corresponding to the electrode coordinates of the electrode caps; (2) browse through the data and remove EEG data with large drift periods; (3) remove electrodes not directly related to the central brain, such as those around the eyes and those located at the root of the nose (CB1, CB2, FP1, FPZ FP2, AF3, AF4); (4) remove 50 Hz industrial frequency interference by filtering 49.5 to 50.5 Hz using filtered depression filtering. Band-pass filtering from 0.5 to 80 Hz to remove signal-to-noise interference; (5) re-referencing using REST; (6) linear interpolation replacement of bad electrodes; (7) removal of independent components
associated with artifacts using independent component analysis (ICA); (8) segmentation of data (into two-second segments); (9) Referring to previous studies, electrode data were derived for ten channels around the binaural area (FT7, FT8, T7, C5, C6, T8, TP7, CP5, CP6, TP8).

Figure 1. Distribution of 64 conductive poles.

2.4. EEG data processing
(1) Two segments of 10s data were truncated from the pre-processed 10min EEG data (taking 10s data in the first 5min and 10s data in the last 5min), 20 segments of data for each group of patients with tinnitus on different sides of the ear and healthy controls, for later data calculation and analysis; (2) Fast Fourier transform using Hanning window was performed on each segment of data, and then for each segment of data 10 channels FT7, FT8, T7, C5, C6, T8, TP7, CP5, CP6, TP8 were calculated according to equation (1) for the absolute power of each rhythm, where, denotes the upper and lower limits of the frequencies of the different rhythms, respectively, indicating the absolute power values of the different rhythms.

\[
P_X = \sum_{f=f_1}^{f_h} P_{XX}(f) \tag{1}
\]

(3) Calculate the rhythm of each frequency band for each of the ten channels of data in each segment in accordance with equation (2), where, respectively, denote the upper and lower limits of the frequencies of the different rhythms and denote the absolute power values of the different rhythms.

\[
P_Y = \frac{\sum_{f=f_1}^{f_h} P_{XX}(f)}{\sum_{f=0.5}^{f=0.5} P_{XX}(f)} \tag{2}
\]

2.5. Statistical methods
Independent sample t-tests were performed on the absolute and relative power of each rhythmic band of the data. Criteria for determining significant differences between two groups of data: (1) For comparison of the difference between two groups of random numbers, first use the F-test to determine the significance of the difference between the two sample variances, \(P>0.05\): equal variance; \(P<0.05\): heteroscedasticity. (2) Then use the T-test to look at the two-tailed parameters because of the comparison of two-sample differences, and reject the original hypothesis when \(t\) two-tailed critical < \(t_{Stat}\), two-tailed \(P<0.05\), which is also a rejection of the original hypothesis. (3) The original hypothesis is that the two sets of random data are not significantly different and have the same mean.
(4) When the two sets of random data show significant differences, a reasonable hypothetical mean difference can be set to determine how much the two sets of data differ on average.

3. Results & Discussion

3.1. Absolute power of each rhythm

The results of the statistical analysis of the absolute power of each channel in the different lateral tinnitus patients and the control group are shown in Table 1, Table 2 and Table 3.

From the t-test results of the absolute power in 10 channels between the bilateral tinnitus group and the control group in Table 1, it can be seen that there is a significant difference in the Theta band for the FT8, C6, T8, CP5, CP6 and TP8 channels (p<0.05) and a significant difference in the Beta band for the C6 and CP6 channels (p<0.05).

From the results of the t-test between the left tinnitus group and the control group in the 10-channel absolute power in Table 2, it can be seen that there is a significant difference in the Delta band for all 10 channels (P<0.05); there is a significant difference in the Theta band for the FT7, C5, and C6 channels (P<0.05); there is a significant difference in the Alpha band for the FT7, FT8, C5, C6, and CP6 channels (P<0.05); significant differences in the Beta band of FT7, FT8, C5, C6 and CP5 channels (P<0.05); and significant differences in the Gamma band of FT8, C5, C6, CP5 and CP6 channels (P<0.05).

From the results of the t-test between the right tinnitus group and the control group in the 10-channel absolute power in Table 3, it can be seen that there were significant differences in the Alpha band for channels C5, C6, CP5, (P<0.05) and the Beta band for channels FT7, T7, C5, C6, T8, CP5, CP6 (P<0.05); There was a significant difference (P<0.05) in the Gamma band for the channels C5, C6, CP5, CP6(P<0.05).

Table 1. Absolute power t-test results of bilateral tinnitus group and control group.

| Channels | Delta  | Theta  | Alpha  | Beta   | Gamma |
|----------|--------|--------|--------|--------|-------|
| FT7      | 0.942  | 0.052  | 0.208  | 0.141  | 0.286 |
| FT8      | 0.966  | 0.010* | 0.167  | 0.065  | 0.787 |
| T7       | 0.515  | 0.080  | 0.173  | 0.083  | 0.140 |
| C5       | 0.715  | 0.016  | 0.183  | 0.079  | 0.405 |
| C6       | 0.899  | 0.006* | 0.108  | 0.026* | 0.314 |
| T8       | 0.878  | 0.027* | 0.162  | 0.085  | 0.585 |
| TP7      | 0.481  | 0.062  | 0.165  | 0.104  | 0.250 |
| CP5      | 0.697  | 0.017* | 0.182  | 0.065  | 0.862 |
| CP6      | 0.405  | 0.007* | 0.117  | 0.047* | 0.481 |
| TP8      | 0.307  | 0.017* | 0.081  | 0.079  | 0.862 |

Table 2. Absolute power t-test results of left ear tinnitus group and control group.

| Channels | Delta  | Theta  | Alpha  | Beta   | Gamma |
|----------|--------|--------|--------|--------|-------|
| FT7      | 0.006* | 0.038* | 0.004* | 0.002* | 0.061 |
| FT8      | 0.044* | 0.091  | 0.026* | 0.029* | 0.022* |
| T7       | 0.006* | 0.714  | 0.110  | 0.548  | 0.630 |
| C5       | 0.001* | 0.003* | 0.006* | 0.000* | 0.001* |
| C6       | 0.010* | 0.005* | 0.008* | 0.033* | 0.003* |
| T8       | 0.008* | 0.511  | 0.168  | 0.348  | 0.091 |
Table 3. Absolute power t-test results of right ear tinnitus group and control group.

| Channels | Delta  | Theta  | Alpha  | Beta   | Gamma  |
|----------|--------|--------|--------|--------|--------|
| TP7      | 0.006* | 0.625  | 0.740  | 0.754  | 0.080  |
| CP5      | 0.012* | 0.143  | 0.169  | 0.043* | 0.002* |
| CP6      | 0.032* | 0.384  | 0.033* | 0.552  | 0.024* |
| TP8      | 0.007* | 0.793  | 0.771  | 0.874  | 0.097  |

Table 4. Relative power t-test results of bilateral tinnitus group and control group.

| Channels | Delta  | Theta  | Alpha  | Beta   | Gamma  |
|----------|--------|--------|--------|--------|--------|
| FT7      | 0.585  | 0.862  | 0.102  | 0.004* | 0.143  |
| FT8      | 0.297  | 0.596  | 0.102  | 0.072  | 0.181  |
| T7       | 0.579  | 0.836  | 0.068  | 0.005* | 0.109  |
| C5       | 0.824  | 0.101  | 0.003* | 0.000* | 0.003* |
| C6       | 0.992  | 0.407  | 0.013* | 0.001* | 0.005* |
| T8       | 0.862  | 0.769  | 0.436  | 0.022* | 0.093  |
| TP7      | 0.977  | 0.873  | 0.634  | 0.131  | 0.149  |
| CP5      | 0.329  | 0.089  | 0.037* | 0.006* | 0.016* |
| CP6      | 0.629  | 0.674  | 0.052  | 0.004* | 0.001* |
| TP8      | 0.843  | 0.876  | 0.396  | 0.053  | 0.112  |

3.2. Relative power of each rhythm

The results of the statistical analysis of the relative power of each channel in the different lateral tinnitus patients and the control group are shown in Table 4, Table 5 and Table 6.

As can be seen from the results of the t-test between the bilateral tinnitus group and the control group on the 10-channel relative power in Table 4, there was a significant difference in the Delta band for the TP7 channel (p<0.05); a significant difference in the Theta band for the FT7, T7, C5, TP7, CP5 and TP8 channels (p<0.05) and a significant difference in the Beta band for the TP7 channel (p<0.05).

From the t-test results of the relative power of the left tinnitus group and the control group in the 10 channels in Table 5, it can be seen that there is a significant difference in the Delta, Theta and Beta bands for all 10 channels (P<0.05); there is a significant difference in the Alpha band for the C5 channel (P<0.05).

From the t-test results of the relative power of the right tinnitus group and the control group in the 10 channels in Table 5, it can be seen that there is a significant difference in the Theta band for channel TP7 (P<0.05).

Table 5. Relative power t-test results of left ear tinnitus group and control group.

| Channels | Delta  | Theta  | Alpha  | Beta   | Gamma  |
|----------|--------|--------|--------|--------|--------|
| FT7      | 0.094  | 0.014* | 0.784  | 0.141  | 0.487  |
| FT8      | 0.756  | 0.135  | 0.561  | 0.154  | 0.533  |
| T7       | 0.098  | 0.027* | 0.895  | 0.057  | 0.427  |
| C5       | 0.152  | 0.010* | 0.988  | 0.162  | 0.242  |
| C6       | 0.221  | 0.140  | 0.835  | 0.138  | 0.516  |
| T8       | 0.274  | 0.087  | 0.840  | 0.151  | 0.756  |
| TP7      | 0.009* | 0.004* | 0.410  | 0.016* | 0.273  |
| CP5      | 0.094  | 0.014* | 0.784  | 0.141  | 0.487  |
Table 5. Relative power t-test results of left ear tinnitus group and control group.

| Channels | Delta | Theta | Alpha | Beta | Gamma |
|----------|-------|-------|-------|------|-------|
| FT7      | 0.000*| 0.000*| 0.641 | 0.000*| 0.064 |
| FT8      | 0.039*| 0.001*| 0.821 | 0.003*| 0.576 |
| T7       | 0.000*| 0.000*| 0.465 | 0.000*| 0.061 |
| C5       | 0.000*| 0.009*| 0.044*| 0.001*| 0.595 |
| C6       | 0.000*| 0.007*| 0.091 | 0.000*| 0.133 |
| T8       | 0.003*| 0.001*| 0.373 | 0.001*| 0.145 |
| TP7      | 0.002*| 0.000*| 0.145 | 0.001*| 0.375 |
| CP5      | 0.005*| 0.009*| 0.133 | 0.004*| 0.511 |
| CP6      | 0.035*| 0.003*| 0.962 | 0.001*| 0.620 |
| TP8      | 0.003*| 0.001*| 0.131 | 0.001*| 0.932 |

Table 6. Relative power t-test results of right ear tinnitus group and control group.

| Channels | Delta | Theta | Alpha | Beta | Gamma |
|----------|-------|-------|-------|------|-------|
| FT7      | 0.892 | 0.118 | 0.660 | 0.759| 0.658 |
| FT8      | 0.499 | 0.814 | 0.459 | 0.705| 0.239 |
| T7       | 0.517 | 0.062 | 0.807 | 0.543| 0.657 |
| C5       | 0.953 | 0.259 | 0.820 | 0.585| 0.087 |
| C6       | 0.472 | 0.166 | 0.598 | 0.560| 0.337 |
| T8       | 0.411 | 0.192 | 0.398 | 0.792| 0.430 |
| TP7      | 0.057 | 0.022*| 0.137 | 0.108| 0.759 |
| CP5      | 0.458 | 0.157 | 0.789 | 0.395| 0.611 |
| CP6      | 0.458 | 0.157 | 0.789 | 0.395| 0.611 |
| TP8      | 0.286 | 0.069 | 0.679 | 0.117| 0.520 |

3.3. Discussion
In this study, the channels and frequency bands in which the resting EEG power was abnormal differed between the different sides of the tinnitus, with more channels and frequency bands involved in the significant differences between the left-sided tinnitus patients and the control group, both in terms of absolute power and relative power. In contrast, the significant differences between the right-sided tinnitus patients and the controls involved many fewer channels as well as channels.

Combined with the comparison of the mean absolute power values of each group in Figure 2 and the relative power values of each group in Figure 3, the significant differences between the binaural tinnitus patients and the control group, whether analyzed by absolute power or relative power, were mainly in the Theta band, and the mean absolute and relative power values in the Theta band were higher in the binaural tinnitus group than in the control group. In the left-sided tinnitus group, the significant differences were mainly in the Delta, Theta and Beta bands. The mean values of relative
power in the Delta and Beta bands were lower than those of the control group, and the Theta band was higher than that of the control group; when absolute power was used as the characteristic analysis, the significant differences covered the five bands of Delta, Theta, Alpha, Beta and Gamma. In the specific analysis by absolute power, the significant differences were mainly in the Alpha, Beta and Gamma bands, and the mean values of absolute power in the three bands were lower than those in the control group. The results of this paper are generally consistent with previous studies done on EEG band power related to tinnitus.

Tinnitus is predominantly subjective and most tinnitus patients present with unilateral tinnitus, with more tinnitus on the left side than on the right. In Wang et al.'s PET examination, increased glucose metabolic activity in the auditory cortex was found to be predominantly present in the left hemisphere, and significantly higher on the left than on the right. The increased metabolism in the left auditory cortex was associated with a sense of tinnitus, suggesting that tinnitus may be more likely to occur on the left side than on the right. Lesions in one part of the intact auditory system lead to reduced activity in the peripheral auditory system, triggering reduced inhibitory activity in the central cortex in response to peripheral auditory input, synchronization of excitation and nerves in the central auditory system, and increased neuroelectrical activity, leading to tinnitus. However, the present experimental analysis has not yet revealed any correlation between the regions and bands of resting EEG power spectrum differences and the tinnitus sites. Further studies and more samples were needed to explore the relationship between the two.

Figure 2. Comparison of absolute power averages for each group.

Figure 3. Comparison of relative power averages for each group.
4. Conclusion
In this paper, resting-state EEG was used to investigate the differences in abnormal resting-state EEG power spectra in patients with tinnitus on different sides of the ear. It was found that there were more frequency bands involved in significant differences between patients with left tinnitus and controls and greater differences compared to patients with binaural tinnitus as well as patients with right tinnitus, followed by patients with binaural tinnitus and least in patients with right tinnitus. Overall, where significant differences were demonstrated, the absolute and relative power was higher in patients with tinnitus in the Delta and Theta bands than in controls, and lower in the Alpha band than in controls. These results compare the resting EEG power spectrum abnormalities of patients with tinnitus on different sides of the ear with those of healthy controls from an electroneurophysiological perspective, and are expected to provide a standard for future clinical diagnosis of tinnitus and quantitative evaluation of tinnitus treatment, providing a more refined and precise treatment plan for patients with tinnitus on different sides of the ear and improving the efficiency of treatment.

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