One-Channel Simple Frontal Electroencephalography Detection of Tinnitus and Related Distress

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Research Article

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Abstract

Background: No simple objective test is available so far for diagnosing tinnitus. Thus, diagnosis is typically based on the patients' medical history. Herein, we propose the usefulness of a simple one-channel electroencephalography (EEG) with a newly developed analysis technique to objectively detect tinnitus.

Methods: We developed a portable EEG device to measure frontal Fp1 activities. The recorded data of 31 patients with chronic tinnitus and 29 healthy controls were analyzed with a support vector machine.

Results: We identified tinnitus by analyzing the frequency obtained by frontal Fp EEG. We discovered that 9- and 13-Hz changes were critical for identifying tinnitus.

Conclusions: One-channel Fp1 measurement reliably detected tinnitus (sensitivity, 72%; specificity, 96%). EEG measurement may also be related with tinnitus-related distress in patients. Further EEG studies are warranted to determine more accurately the pathophysiology of tinnitus.

1. Introduction

Tinnitus is the conscious perception of sound that cannot be attributed to an external sound source. Patients with tinnitus often complain of significant emotional distress. Evaluation of tinnitus is usually dependent on the patient's self-reporting of symptoms. Although functional neuroimaging methods based on positron emission tomography or magnetoencephalography have been proposed as an objective assessment for the presence or absence of tinnitus, these techniques are not easy to introduce in daily clinical settings.

Subsequently, analysis of tinnitus using quantitative electroencephalography (EEG) was proposed by Shulman and Goldstein in 2002[1]. In their study, 16-channel EEG was used for patients with severe tinnitus, and the results suggested that the temporal and temporofrontal regions are involved in tinnitus. The detailed characteristics of EEG abnormalities in these regions in the setting of tinnitus remains unclear. In contrast to the findings of Shulman and Goldstein[1], those reported by Weisz et al. showed that in patients with tinnitus, alpha waves of 8–12 Hz decreased in the temporal lobe region, whereas δ waves of 1.5–4 Hz increased in the temporal lobe regions compared with those in healthy controls. In addition, strong relationships between distress caused by tinnitus and EEG patterns in the right and left temporal lobes were observed[2]. However, Weisz et al. did not investigate the specific EEG features in patients with tinnitus.

In the present study, we investigated the classification of patients with and without tinnitus and the level of distress caused by tinnitus using EEG of the prefrontal cortex. In tinnitus, sounds can be heard in the ear in an environment where no external sound source exists. Currently, 10-20% of the population suffers from tinnitus[3,4], and the demand for the treatment of tinnitus is increasing.

The mechanism of tinnitus has not been elucidated owing to its varied causes, and no single treatment method for all patients with tinnitus has been established. One of the causes of tinnitus is brain abnormality, and many studies on the relationship between tinnitus and the brain have been conducted. Therefore, the relationship between tinnitus and frontal and temporal lobes of the brain has been clarified[5,6]. In addition, associations of the frontal lobe with the level of distress[6,7] and loudness[8,9] and pitch level in tinnitus[10] have been reported. Focusing on the relationship between tinnitus and the brain, we believe that measuring brain activity is effective for understanding the state of tinnitus. Thus, in this study, we used brain wave measurements with the highest practicality among brain activity measurements. For EEG measurement, a simple EEG device was used to measure the prefrontal cortex site.

In the present study, we examined the EEG patterns in patients with tinnitus and successfully identified the presence or absence of tinnitus using these findings. In addition, simple EEG measurement of the frontal Fp area was sufficient to determine the status of tinnitus; i.e., 9 and 13 Hz of EEG are crucial for separating patients with tinnitus from healthy people.

This section describes the relationship between tinnitus and EEG findings. The brain comprises temporal and frontal lobes that are involved in hearing[11–14]. The temporal lobe has an area called the auditory cortex, which is key to recognizing sounds[11,12]. The frontal lobe is responsible for the judgment of feelings such as comfort and discomfort; this lobe may play a role in the interpretation of sound stimuli[13,14]. EEG records those electric signals transmitted to electrodes placed on the scalp that are generated by the activity of the cranial nerve cells as a potential on the surface of the cerebral cortex. EEG is recorded as a waveform with various frequencies that can be classified into five bands. The frequency band of EEG is divided into 0.5–4, 4–8, 8–13, 13–30, and 30 Hz, which represents the δ, θ, α, β, and γ waves, respectively[15].

For EEG analysis, it is important to analyze which wave of the frequency band is included in EEG in detail, and the unit of amplitude of EEG before translating to the frequency domain is [μV].

The cause of tinnitus has not been elucidated. In previous studies, the cause of tinnitus was believed to be the auditory conduction pathway from the external ear to the cerebral cortex[16]. Tinnitus is related to the spontaneous discharge of the auditory nerve in the cochlea as documented by Galambos et al.[17] in 1943. Spontaneous discharge is a phenomenon wherein irregular discharges are constantly observed in a state without any stimulus being applied. A fault occurs somewhere in the auditory nerve and the spontaneous discharge from that region decreases; therefore, the ability to suppress the excitation of the nerve also decreases. Tinnitus occurs through the sensation of the spontaneous discharge from a normal region. In addition, tinnitus can be caused by the damage of the hair cells of the inner ear, aging hair cells, and noise-induced damage to the hair cells. Other studies reported that tinnitus occurs due to brain abnormalities[16]. Furthermore, research has shown that tinnitus can result from stress[18] or an autonomic nervous disorder[19]. Tinnitus can worsen pain sensations[20]. An association between the brain, specifically the frontal lobe, and tinnitus is well established. We therefore performed a quantitative evaluation of tinnitus using EEG to develop an objective method for quantitatively evaluating the distress caused by tinnitus. A system for measuring tinnitus and hearing in healthy controls was required. The system also required to estimate the distress level using only the prefrontal cortex EEG obtained from the frontal region that Fp1 determined using the international 10-20 method, which is considered to be related to tinnitus[21].

The power at Fp1 increased when the healthy volunteers listened to noise, during which the participants reported negative affect. These results imply that sound-induced positive affect increases the relative left-sided activation in the prefrontal cortex, whereas the induced negative affect elicits the opposite pattern of asymmetrical activation[21].

We believe that this system can be used as a subjective tinnitus testing device in a clinical setting.

The prevalence of tinnitus in the population is estimated to range from 10–20% [4]. Tinnitus distress is associated with emotional health issues, such as depression and anxiety. Depression and anxiety were enhanced at the time of tinnitus onset in patients under high distress[4]. Therefore, tinnitus should be treated for its severe negative effects.

At the clinical site we used in this study, questionnaires and examination equipment were used to evaluate tinnitus symptoms (distress, loudness, and tone). In clinical practice, physicians typically diagnose the state of tinnitus without any measurements. These conventional methods are subjective and can take >2 hours to investigate tinnitus symptoms, which is a heavy burden to patients with tinnitus.

2. Methods

In this research, we mainly verified two aspects:

Experiment 1. Differentiating between the patients with tinnitus and healthy controls

Experiment 2. Verification of the distress level of patients with tinnitus

The institutional review board of Keio University Hospital and the bioethics committee of Keio University Science and Technology approved this study (UMIN000013657). The research was

performed in accordance with clinical research guidelines in Japan, and informed consent was obtained from all patients.

Experiment 1: Classification of patients with tinnitus and healthy controls

To verify whether there is a difference between EEG signals of patients with tinnitus and healthy controls, the EEG features of both groups were obtained and classified using only the detected features. First, filtering of the EEG data was performed as a preprocessing a step and normalization was performed after fast Fourier transformation. We then compared the amplitude spectra of the frequencies in the patients with tinnitus and healthy controls to investigate whether there was a significant difference. To demonstrate the effectiveness of the frequency features, we calculated the recognition accuracies using support vector machine (SVM), which focused on the frequency difference between those with and without tinnitus.

2.1) Participants

Overall, 31 patients with tinnitus (mean ± SD age, 63.8 ± 8.6 years; 19 males and 12 females) and 29 healthy controls (mean ± SD age, 68.2 ± 10.4 years; 15 males and 14 females), participated in this study (Table 1). No significant differences in age were found between the two groups ($p > 0.05$). In addition, no significant difference in the hearing threshold was found between the two groups ($p > 0.05$; Figure 1).

Table 1
Distress of the patients using THI

THI score	Distress	The number of patients
0-16	Nothing	3
18-36	Small	9
38-56	Moderate	9
58-100	High	10

2.2) Tinnitus handicap inventory

After the EEG measurement, the degree of distress experienced in everyday life by each patient with tinnitus was evaluated using tinnitus handicap inventory (THI)[22,23]. THI is scored on a scale of 0 to 100. Table 1 shows the relationship between THI score and severity of tinnitus[22]. From the experiments, we obtained EEG data, and information on the degree of tinnitus distress was obtained from responses to the questionnaire (Table 1).

2.3) EEG measurement

The participant sat on a chair wearing the EEG device (Figure 2). We then recorded the resting state EEG signals for 30 seconds with the participant's eyes closed. EEG measurements were conducted twice, including a 30-second break. The experimental flow is shown in Figure 3. The measurement point was only Fp1 as per the international 10-20 system. The sampling frequency was 1024 Hz.

2.4) Data Analyses

2.4.1) Preprocessing

Using a low-pass filter with a cutoff frequency of 30 Hz, we obtained EEG data without noise.

2.4.2) Feature extraction of data

Frequency analysis of the preprocessed EEG data was performed using fast Fourier transformation, the amplitude spectrum data were acquired, and the components of 4–22 Hz were extracted. When the frequency analysis was performed, the time window was set to 1 s, and a Hamming window was applied to the EEG data. The frequency resolution of the obtained amplitude spectrum was 1 Hz. In this study, 19-dimensional amplitude spectrum data in the 4- to 22-Hz interval were used. As the length of the time window and amount of shift was 1 s, the number of data obtained from one EEG measurement was 30. As we measured each subject twice, we obtained 60 data per person. The 60-amplitude spectrum data of each subject were averaged for each frequency. As the amplitude of EEG differed in each person, normalization was performed to eliminate individual differences. As a method of normalization, the sum of the amplitude spectra of 4–22 Hz was set to 1. This method is often used to compare the ratio of the amplitude of each frequency. Using the obtained amplitude spectrum data, the mean and standard deviation of the 60 data of all the patients with tinnitus and all healthy controls were calculated for each EEG frequency.

2.4.3) Statistical analysis

To investigate whether a frequency component with a difference in EEG exists between the patients with tinnitus and healthy controls, the statistical significance (*t* test) was examined for each frequency in the amplitude spectrum data. The statistical significance was set at <0.05 (two-tailed). In this case, when the significance level is 5%, and the p value is >0.025, it indicates no statistically significant difference between the two groups. If the p value is <0.025, a significant difference exists.

2.4.4) Classification

Classification is performed using features that show the possibility of a difference between the patients with tinnitus and healthy controls. In this study, we used the RBF kernel as a kernel function for classification using SVM. The optimum setting of the parameters γ and C often poses a problem. To set the optimal parameters, we adopted the method recommended by Chih-Wei Hsu et al.[24]. Classification was repeated while changing the possible values of parameter C to[illegible] and changing the possible value of parameter γ to, , [illegible].

This allows for the setting of the parameters to roughly increase the classes. Next, the range of the parameter searched was limited only to that parameter with the highest identification rate. Within the limited range, classification was repeated while changing the numerical value of each parameter. Using this procedure, the optimum parameter was set.

The recognition accuracy was calculated using the extracted features. If we obtain a high recognition accuracy, we could extract the difference between the patients with tinnitus and healthy controls. If a difference existed between the EEG of the two groups, the effect of tinnitus would appear in the EEG data of the prefrontal cortex. In this research, the leave-one-subject-out cross-validation (LOSOCV) method was used to calculate the recognition accuracy. The data of one person was used as the evaluation data and those of the remaining participants were set as the learning data. The recognition accuracy was calculated for all the combinations and was evaluated by setting the obtained recognition accuracy average value as the final recognition rate.

Experiment 2. Validation of distress level

To verify whether tinnitus severity can be identified on the basis of brain waves, we investigated the relationship between the EEG data and THI scores of the patients with tinnitus to classify their levels of distress. For this purpose, we performed the same procedures as in **Experiment 1**.

2.5)Data analysis

2.5.1) Statistical analysis

To investigate the difference in EEG data of the patients with tinnitus due to the difference in pain level, a significant difference test was performed using the amplitude spectrum data. The null hypothesis was “there is no difference between the data of group A and group B.” Groups A and B were defined in three ways as shown in Table 2.

Table 2
p values at each frequency of the EEG

Frequencies(EEG) [Hz]	4	5	6	7	8
$p$value	0.0732	0.0631	0.320	0.575	0.636
Frequencies(EEG) [Hz]	9	10	11	12	13
$p$value	0.403	0.751	0.131	0.0890	0.00101
Frequencies(EEG) [Hz]	14	15	16	17	18
$p$value	0.0470	0.719	0.853	0.681	0.390
Frequencies(EEG) [Hz]	19	20	21	22	
$p$value	0.511	0.752	0.212	0.211	

To investigate the difference in EEG due to distress, validation was performed except for the participants with a THI score of 0.

2.5.2) Single regression analysis

Single regression analysis was used to verify whether the distress caused by tinnitus can be estimated using EEG. A single regression analysis was applied to the different frequencies to construct a regression equation for estimating tinnitus distress. To verify how the amplitude spectrum of the EEG changes relate to changes in the distress level, a regression equation was obtained. At this time, the target variable was the amplitude spectrum of the EEG, and the explanatory variable was the THI score.

2.5.3) Classification

Distress in the patients with tinnitus was identified using EEG features correlated to distress. The participants for comparison were the three types of patients with tinnitus shown in Table 2. We set the parameters and calculated the recognition rate in the same manner as in **Experiment 1**.

3. Results

Experiment 1

The average values of the amplitude spectra of all patients with tinnitus and healthy controls are shown in Table 1 and Figure 4. The amplitude spectrum at 4–7 Hz was larger for the patients with tinnitus than for the healthy controls, and the amplitude spectrum at 8–14 Hz was found to be larger for the healthy controls than for the patients with tinnitus. By comparing the outline of the amplitude spectrum in Figure 4, we found that the healthy controls were prominent near 9 Hz.

Table 2 shows the p values at each EEG frequency. A p value of <0.025 shown at the frequency of 13 Hz and <0.05 at the frequency of 14 Hz, which demonstrated significant differences, respectively. Therefore, at these frequencies, a significant difference in amplitude spectrum was observed between the patients with tinnitus and healthy controls. Accordingly, the amplitude spectral data of 13 and 14 Hz were used as features of the EEG for classification. The recognition accuracy (%) was 70.0 at 13 Hz, 71.9 at 13 Hz, and 14 Hz. The precision (%) was 67.5 in the tinnitus group and 72.5 in the control group at 13 Hz, and 78.8 in the tinnitus group and 63.6 in the control group at both 13 and 14 Hz.

Based on these results, classification was performed in two patterns. The first pattern was used when only 13 Hz was used, and the other was when both 13 and 14 Hz were used. The recognition accuracy in the frequencies showing the significant difference demonstrated that we can differentiate tinnitus at 70%.

We performed a *t* test and found a significant difference at 9 Hz at a significance level of 0.05%. When the healthy controls and patients with tinnitus were distinguished using only 9 Hz, a sensitivity of 72% and specificity of 96% were obtained. From these results, the presence or absence of tinnitus could be distinguished only by observing EEG data of the frontal lobe at approximately 9 Hz.

Experiment 2

To validate the difference in EEG characteristics on the basis of the distress caused by tinnitus, patients with tinnitus were classified according their level of distress caused by tinnitus, and a test for significant difference was performed with the healthy controls.

We analyzed the two-group comparison in Table 3, and the results of averaging the amplitude spectra of groups A and B are shown in Figures 5–7. The *x* axis represents the frequency; the *y* axis, the amplitude spectrum; and the error bar, the standard deviation. The blue graph represents a group of low severity whereas the yellow graph represents a group of high severity. The results presented in Figures 5–7 show that the EEG of the patients with high distress tended to have a high amplitude of approximately 9 Hz (9, 12, or 13 Hz) compared with the EEG of the patients with low distress. We adopted these frequencies for a two-pattern classification using SVM. The results are shown in Table 4 and 5.

Table 3
Comparison target for significance test

Pattern	Group A	Group B
1	None (2-16)	Mild or better (18-100)
2	Mild or less (2-36)	Moderate or higher (38-100)
3	Moderate or lower (2-56)	Severe (58-100)

Table 4
Detected frequencies showing the significant difference.

Comparison	Frequency where significant difference existed [Hz]	
	Significant level 5%	Significant level 10%
Mild tinnitus patients and control (healthy)	13	13
Moderate or higher tinnitus and control	13	9,13
Severe tinnitus and control	9,13	9,13,21

Table 5
The classification accuracy between tinnitus and controls.

<table>
<tr><th rowspan="2">Comparison</th><th rowspan="2">Significant difference</th><th rowspan="2">Classification accuracy [%]</th><th colspan="2">Precision [%]</th></tr>
<tr><th>Tinnitus</th><th>Controls</th></tr>
<tr><td>Mild or more symptoms tinnitus vs controls</td><td>13 Hz</td><td>67.1</td><td>75.8</td><td>60.0</td></tr>
<tr><td rowspan="2">Moderate or more symptoms tinnitus vs controls</td><td>13 Hz</td><td>65.6</td><td>83.3</td><td>55.0</td></tr>
<tr><td>9,13 Hz</td><td>70.3</td><td>79.2</td><td>65.0</td></tr>
<tr><td rowspan="2">Severe symptoms tinnitus vs controls</td><td>9,13 Hz</td><td>79.2</td><td>12.5</td><td>97.5</td></tr>
<tr><td>9,13,21 Hz</td><td>86.8</td><td>69.2</td><td>92.5</td></tr>
</table>

Table 4 shows a significant difference in the frequencies of 13 Hz at all comparative subjects ($p<0.05$). A significant difference was confirmed at 9 Hz in the patients with tinnitus of moderate or higher severity and in the healthy controls. A significant difference was confirmed at a frequency of 21 Hz in the patients with severe tinnitus and healthy controls. For the classification of the patients with tinnitus and the healthy controls for each distress level, we used the features in which these significant differences existed and those in which a significant difference between the two groups was found. Classification was performed using the above-mentioned features, and the obtained recognition and precision rates are shown in Table 5.

4. Discussion

A statistically significant difference was found between the patients with tinnitus and healthy controls at 13 and 14 Hz. Although the 9-Hz components of the healthy controls' EEGs were prominent compared with those of the patients with tinnitus, the latter showed a tendency for the spectrum to reduce as the frequency increased. Previous studies have shown that the components of the δ-band of the EEG of patients with tinnitus were greater than those of the healthy controls, and peaks existed in the α-band of the patients with tinnitus and healthy controls, indicating that the healthy controls had a more prominent δ-band component [25]. Another conventional study showed that the components of the β-band are larger for the patients with tinnitus[26]. In this study, the α-band of the healthy controls was prominent, which is similar to the findings of a previous study. Conversely, for the β-band, a significant difference was observed at 14 Hz; however, as no significant difference was found in the other frequencies, our findings differ from those of the previous study. We also evaluated the relationship between tinnitus-induced distress and EEG. To prove that the EEG frequency is not a reaction to unpleasant sounds, the EEG frequency of 23 Hz was higher than any other frequencies when listening to the unpleasant sound (selected from the database of sounds generally considered as unpleasant). We can conclude that 13 and 14 Hz are the reactions to tinnitus rather than reaction to the unpleasant sound.

In the significance test, the 9-Hz frequency of the EEG component was important for classifying distress into a high level. Moreover, the 13-Hz component of EEG significantly differed between the healthy controls and patients with tinnitus regardless of distress levels. To summarize our results, in the α-band, a significant difference in EEG was found between the patients with tinnitus and healthy controls. The components of 9 Hz were related to the distress caused by tinnitus and those of 13 Hz were considered a universal characteristic of patients with tinnitus.

5. Conclusions

We found that 9, 13, and 21 Hz are important features for classification. Classification by applying SVM using these as features led to maximum discrimination rates of 67.1%, 70.3%, and 86.8%, respectively.

As a result of the classification using the EEG amplitude spectrum of 9 Hz for no pain, mild or greater, mild to moderate, moderate or greater, moderately less severe, and patients with tinnitus, 92.1%, 76.3%, and 65.8% recognition accuracies were obtained respectively. The two verifications showed the possibility of classifying patients with tinnitus and healthy controls and clarifying the distress classification using EEG of the prefrontal cortex alone (Fp1).

Declarations

Acknowledgement

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Author Contributions

S.K. and Y.M conceived the study and designed the experiments. S.K collected the data. Y.M. measured and analyzed the data. M.M. provided comments and supported our study. All authors approved the final version of the manuscript.

Conflict of interests

There is no conflict of interest.

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Figures

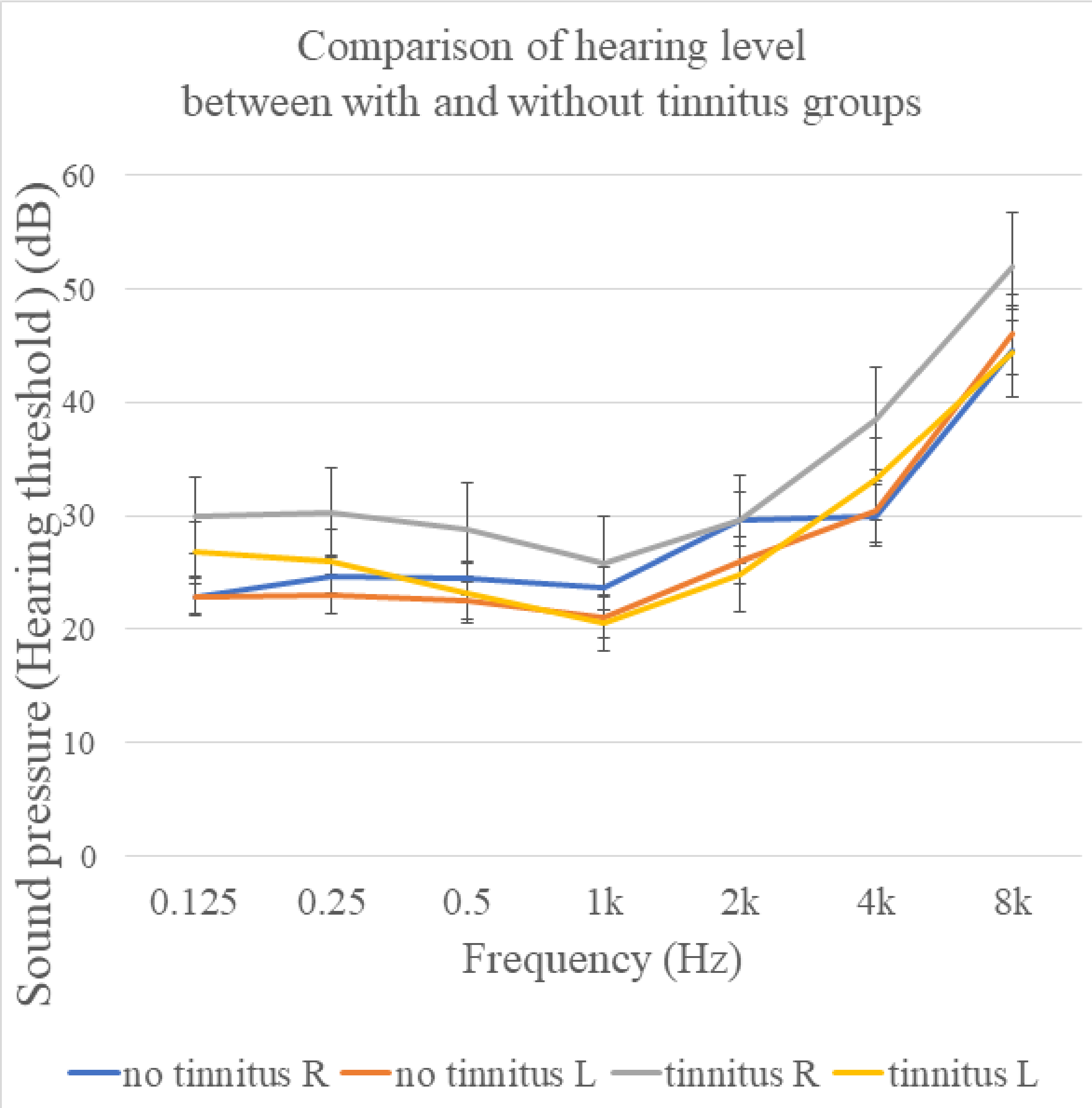

Figure 1

Comparison of hearing level between the groups with and without tinnitus The x-axis represents the frequency, and the y-axis represents the amplitude spectrum. The error bars indicate the standard deviations. The blue graph represents patients with tinnitus and the yellow graph, healthy controls.

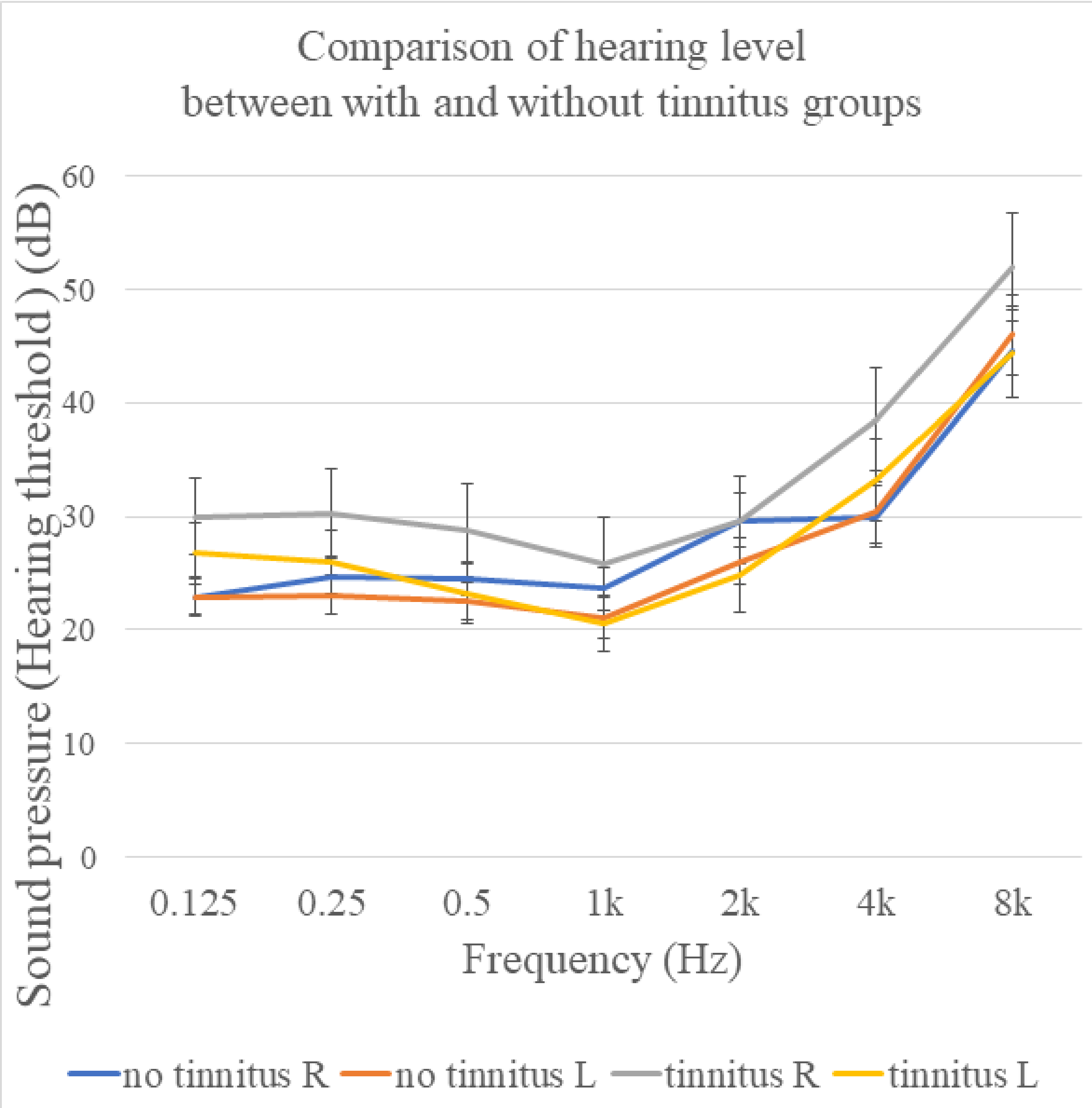

Figure 2

Electroencephalography measurement device The device was set up on the scalp, and measurement was obtained in the frontal position.

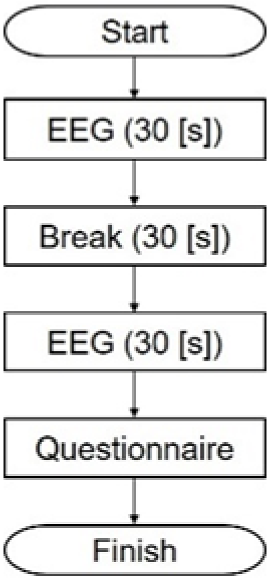

Figure 3

Experimental flow Electroencephalography measurements (30 s) were performed twice.

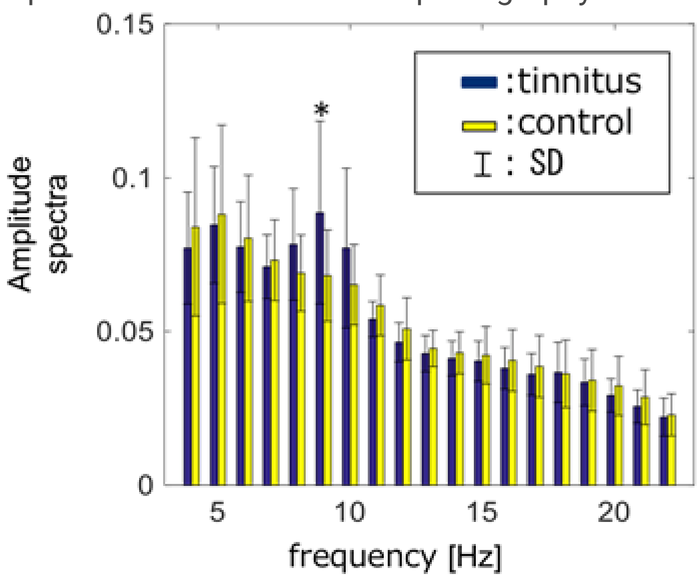

Figure 4

Mean and standard deviation of the amplitude spectrum for each frequency The amplitude spectrum at 4–7 Hz was greater for patients with tinnitus than for healthy controls, and the amplitude spectrum at 8–14 Hz was found to be greater for the healthy controls than for patients with tinnitus. Compared with the patients with tinnitus, the healthy controls were prominent near 9 Hz.

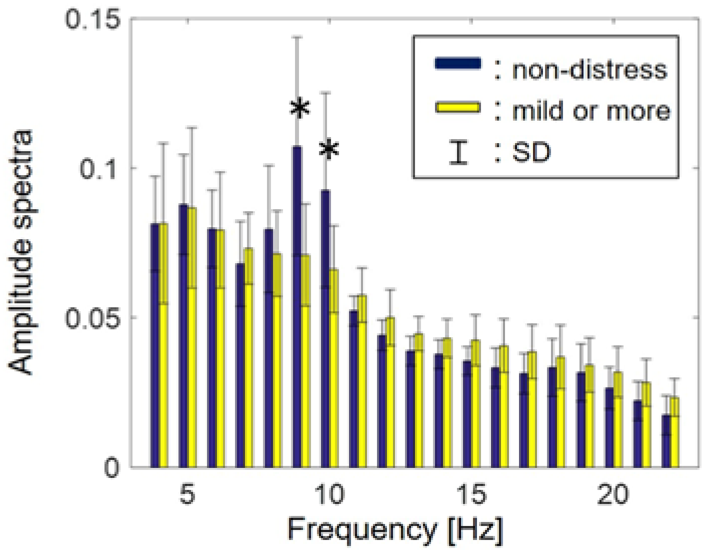

Figure 5

An averaging of the amplitude spectra between the patients with non tinnitus distress and mild distress and more Using a two-group comparison, we averaged the results of the amplitude spectra of the two groups. Electroencephalography demonstrated that the patients with higher distress scores tended to have high amplitudes of approximately 9 Hz (9, 12, and 13 Hz) compared with that of the patients with low distress. The x axis represents the frequency, the y axis represents the amplitude spectrum, and the error bar represents the standard deviation. The blue graph represents a group of low severity and the yellow graph represents a group of high severity.

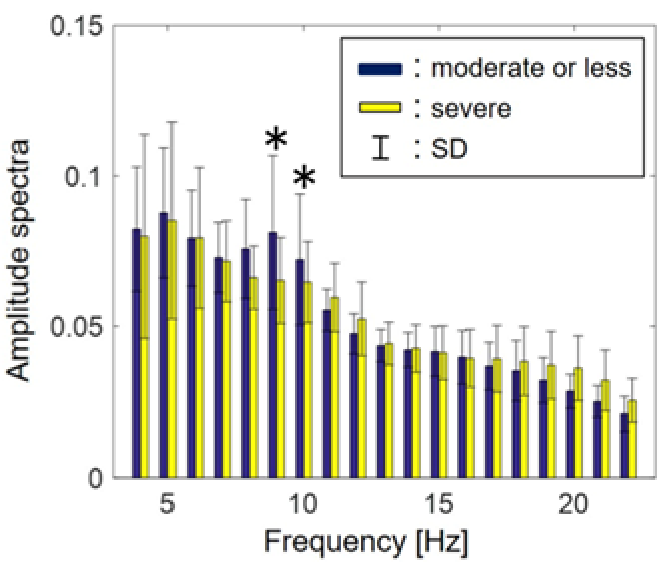

Figure 6

An averaging the amplitude spectra between the patients with moderate or less and severe distress Electroencephalography demonstrated that the patients with higher distress scores tended to have higher amplitudes of approximately 9 Hz (9, 12, and 13 Hz) than those with low distress severity. The x axis represents the frequency, the y axis represents the amplitude spectrum, and the error bar represents the standard deviation. The blue graph represents a group of low severity and the yellow graph represents a group of high severity.

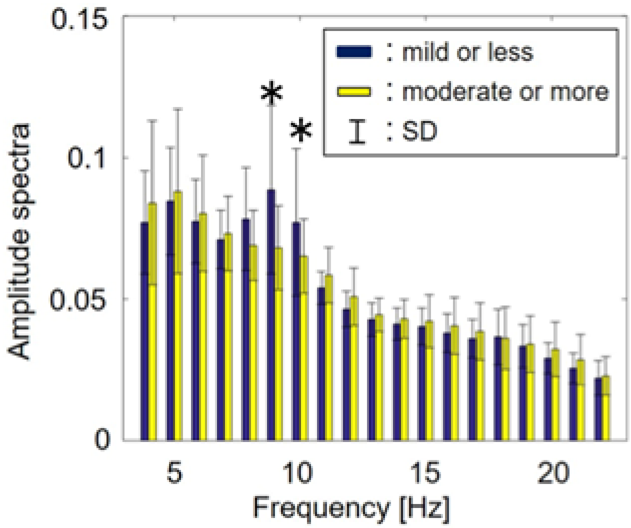

Figure 7

An averaging the amplitude spectra between patients with mild or less and moderate or less Electroencephalography demonstrated that the patients with higher distress scores tend to have higher amplitudes of approximately 9 Hz (9, 12, and 13 Hz) compared with those with low distress. The x axis represents the frequency, the y axis represents the amplitude spectrum, and the error bar represents the standard deviation. The blue graph represents a group of low severity and the yellow graph represents a group of high severity.