Changes in temporal lobe activation during a sound stimulation task in patients with sensorineural tinnitus: a multi-channel near-infrared spectroscopy study

Xiaoli Fan[1*], Bin Gong[2], Hao Yang[2], Juanjuan Yang[2], Gaowei Qi[1], Zheng Wang[1], Jie Sun[1] and Yu Fang[2*]

*Correspondence:
fxldoctor88@126.com; fangyu_
hit@126.com

[1] Department of Traditional
Chinese Medicine, Songjiang
Hospital Affiliated to Shanghai
Jiao Tong University School
of Medicine, Shanghai 201699,
China
[2] School of Mechanical
and Automotive Engineering,
Shanghai University
of Engineering Science,
Shanghai 201620, China

Abstract

Background: The subjective sign of a serious pandemic in human work and life is mathematical neural tinnitus. fNIRS (functional near-infrared spectroscopy) is a new non-invasive brain imaging technology for studying the neurological activity of the human cerebral cortex. It is based on neural coupling effects. This research uses the fNIRS approach to detect differences in the neurological activity of the cerebral skin in the sound stimulation mission in order to better discriminate between the sensational neurological tinnitus.

Methods: In the fNIRS brain imaging method, 14 sensorineural tinnitus sufferers and 14 healthy controls listened to varied noise and quiet for fNIRS data collection. Linear fitting was employed in MATLAB to eliminate slow drifts during preprocessing and event-related design analysis. The false discovery rate (FDR) procedure was applied in IBM SPSS Statistics 26.0 to control the false positive rate in multiple comparison analyses.

Results: When the ill group and the healthy control group were stimulated by pink noise, there was a significant difference in blood oxygen concentration ($P < 0.05$), and the healthy control group exhibited a high activation, according to the fNIRS measurement data. The blood oxygen concentration level in the patient group was dramatically enhanced after one month of acupuncture therapy under the identical stimulation task settings, and it was favorably connected with the levels of THI and TEQ scales.

Conclusions: Using sensorineural tinnitus illness as an example, fNIRS technology has the potential to disclose future pathological study on subjective diseases throughout time. Other clinical disorders involving the temporal lobe and adjacent brain areas may also be examined, in addition to tinnitus-related brain alterations.

Keywords: Sensorineural tinnitus, Functional near-infrared spectroscopy, Temporal lobe, Sound stimulation

Introduction

The most prevalent clinical symptom in the clinical categorization of tinnitus is sensorineural tinnitus, often known as subjective tinnitus [1]. Tinnitus symptoms affect more than 10% of the world's population, according to data [2]. Tinnitus is frequently associated with deafness, and it can progress to deafness. Both might emerge at the same time or in a different order [3]. According to clinical statistics, there are presently more than 50 million individuals in China over the age of 50 who suffer from deafness and tinnitus, and 30 percent to 50 percent of the elderly over the age of 60 suffer from deafness and tinnitus [4]. Deafness and tinnitus have become a significant element that has a negative impact on middle-aged and older people's quality of life, as well as family harmony and happiness.

Although animal models of tinnitus have been reported, tinnitus is, after all, a subjective symptom of sufferers [5]. Because there are currently few research techniques that can objectively detect the presence of tinnitus, objectively measuring the therapeutic efficacy of a particular treatment strategy on tinnitus is impossible. Functional near-infrared spectroscopy (fNIRS), a new non-invasive neuroimaging method that can quantify the degree of neural activity in the human brain through hemodynamic rate and resting-state functional connectivity, has been popular in recent years [6]. In addition, when compared to other brain function imaging technologies, fNIRS is characterized by features such as non-invasiveness, broad applicability to diverse populations, relatively high temporal resolution, and strong robustness, thus being widely applied in brain function detection [7, 8].

In 1977, Jobsis first detected brain activity optically, confirming the feasibility of using radiative spectra to probe the brain [9]. The linkage between near-infrared signals and cerebral oxygenation was established by Delpy et al., who defined the modified Beer–Lambert law, significantly advancing the detection of brain activity [10]. The activation of the cerebral cortex during wrist movement was assessed using functional near-infrared spectroscopy by Jalalvandi et al. [11]. Using near-infrared spectroscopy, Sun et al. revealed reduced prefrontal activity during a verbal fluency challenge in individuals with chronic insomnia problem [12]. Martin Schecklmann and colleagues employed functional near-infrared spectroscopy to diagnose the status and symptoms of persistent tinnitus sufferers [13]. Basura Gregory et al. measured cochlear implant performance and tinnitus perception using functional near-infrared spectroscopy [14]. To enhance the possibilities of human brain imaging, Zhai Tianqu et al. used near-infrared spectroscopy to detect tinnitus and auditory cortex [15]. These papers show that functional near-infrared spectroscopy has been tried as a technological tool for determining the severity of disease.

This study aims to utilize fNIRS technology to observe changes in temporal lobe oxyhemoglobin concentration and brain region activation responses during specific sound stimulus tasks in both healthy individuals and patients with subjective tinnitus. Following comparative experiments, acupuncture treatment was administered to tinnitus patients for one month by specialized traditional Chinese medicine practitioners, with changes in temporal lobe oxyhemoglobin concentration during sound stimulus tasks being monitored. By applying fNIRS methodology, differences in cortical neural activity between patients with sensorineural tinnitus and healthy controls during sound stimulus

Table 1 Sample characteristics

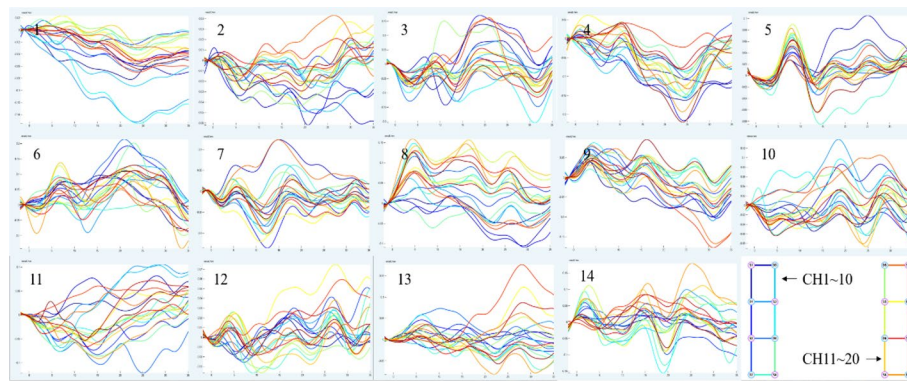| Demographics	Patient group	Healthy control group	Group difference
Age [years]	48 ± 11.68	26.86 ± 3.60	$P = 0.000$
Sex [female/male]	10/4	13/1	$P = 0.139$
THI	44.43 ± 28.16	–	–
TEQ	10.15 ± 5.02	–	–
HAMD	15.93 ± 11.24	3.79 ± 8.51	$P = 0.003$
HAMA	14.43 ± 10.37	5.43 ± 8.49	$P = 0.019$

Data expressed as mean ± standard deviation or n/n

Fig. 1 Healthy control group pink noise stimulus

tasks are sought to be discerned, aiming to enhance the distinction of sensorineural tinnitus symptoms. Leveraging sensorineural tinnitus as a focal point, promise is held by fNIRS technology in gradually unraveling future pathophysiological investigations into subjective disorders. Beyond investigating cerebral alterations associated with tinnitus, other pathological states involving the temporal lobe and surrounding brain regions may also be explored.

Results

Characteristics of population sample

Table 1 shows the characteristics of the test individuals in the sample. Between the healthy control group and the sensorineural tinnitus patients, there were statistically significant differences in THI, TEQ, HAMD, and HAMA scores ($P < 0.05$). As expected, scale scores were significantly higher in the sensorineural tinnitus group than in the control group. However, there was no statistically significant change in the scores of the scales before and after one month of therapy for patients with sensorineural tinnitus ($P > 0.05$).

fNIRS analysis

Figure 1 depicts the mean data curve of oxyhemoglobin block in the temporal lobe of healthy people activated by pink noise. Figure 2 depicts the mean data curve of oxyhemoglobin block in the temporal lobe of patients who were stimulated by pink noise. The average data curve of oxyhemoglobin block in the temporal lobe of the healthy
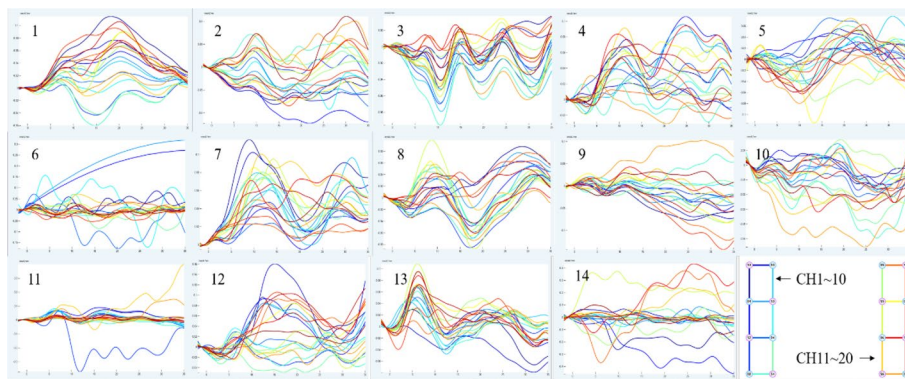
Fig. 2 Patient group pink noise stimulus

group under the stimulation of 750 Hz noise is shown in Fig. 3. Similarly, the mean data curve of oxyhemoglobin block in the temporal lobe of the patient group under 750 Hz noise stimulation is shown in Fig. 4. The mean data curve of oxyhemoglobin block in the temporal lobe of the healthy group under noise stimulation at 8000 Hz is shown in Fig. 5. Figure 6 shows the mean data curve of oxyhemoglobin block in the temporal lobe of the patient group during 8000 Hz noise stimulation.
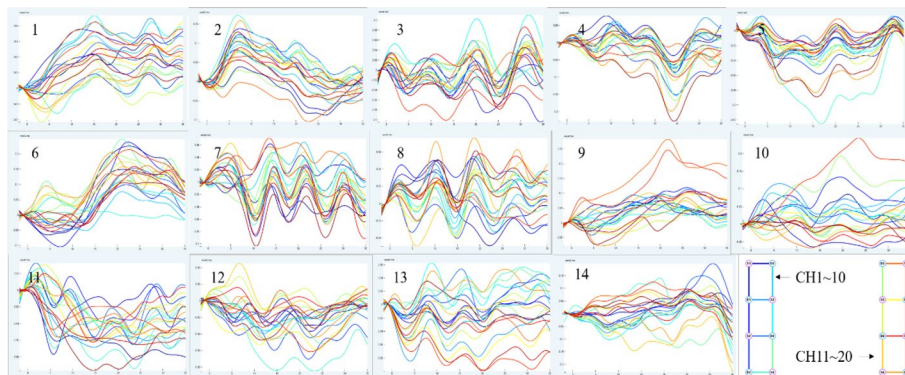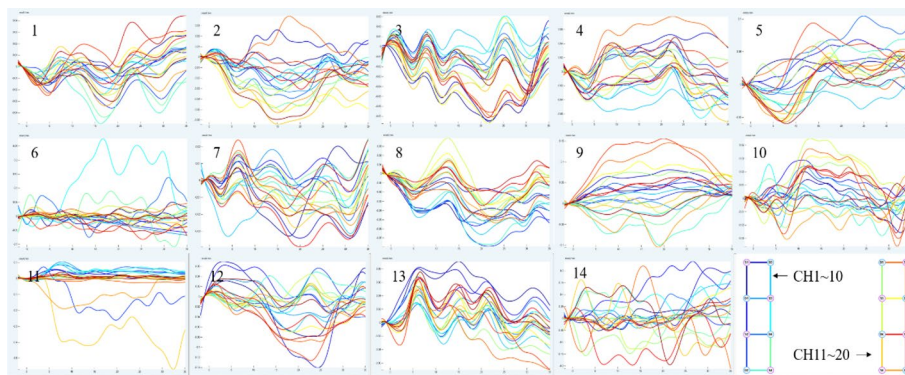

Fig. 3 Healthy control group 750 Hz noise stimulus

Fig. 4 Patient group 750 Hz noise stimulus

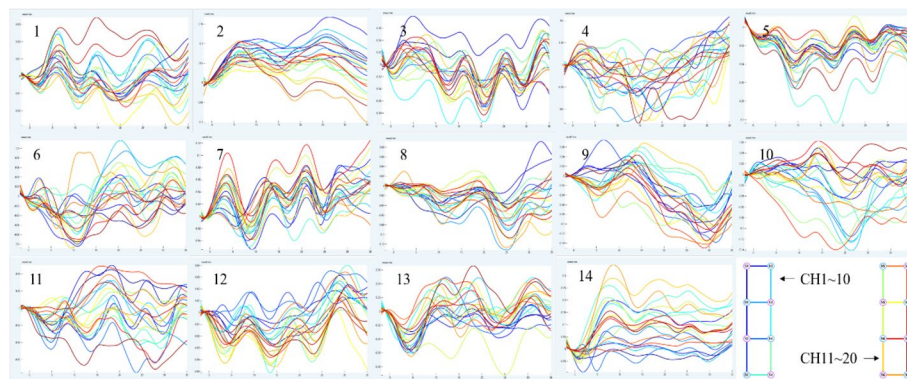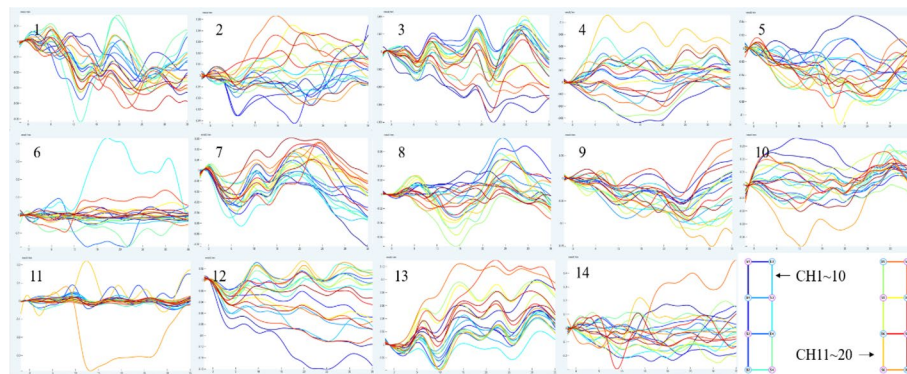**Fig. 5** Healthy control group 8000 Hz noise stimulus

Fig. 6 Patient group 8000 Hz noise stimulus

The average oxyhemoglobin block data acquired above were then imported into IBM SPSS Statistics 26.0 for independent sample T-test analysis, followed by the group statistical analysis stage. The eigenvalue was selected as the difference value, that is, the mean difference between the time interval between $10 \sim 15$ s and $30 \sim 35$ s after the stimulation started. The FDR correction was done at the same time as the two-tailed test. The hypothesis test has a significance level of $P < 0.05$.

The three types of stimulus noise were compared using fNIRS data. Under pink noise stimulation, there was a significant difference in blood oxygen concentration between the two groups ($P < 0.05$), as well as a significant negative connection between changes in oxygenated hemoglobin level and THI and TEQ scores. From the overall data of the 20 channels, the oxyhemoglobin trends of CH7-8, CH10-12 and CH14 channels near the parietal lobe region showed significant fluctuations. The mean concentrations of oxyhemoglobin across the 20 channels recorded at a certain moment for both tinnitus patients and healthy control groups are documented in Table 2. On the whole, lower oxyhemoglobin concentrations were observed in the healthy control group compared to the diseased group, with key channels depicted in Fig. 7. Finally, blood oxygen concentration levels were considerably higher after one month of acupuncture therapy under

Fan *et al. BioMedical Engineering OnLine*   (2024) 23:59

Page 6 of 12

Table 2 The average concentrations of oxygenated hemoglobin across 20 channels for patients with sensorineural tinnitus and normal person

Serial number	Oxyhemoglobin concentration	
	Patient	Normal person
1	0.03930815	− 0.04128
2	0.0098162	− 0.0211
3	0.0445445	− 0.00431
4	0.022166	− 0.03778
5	0.00081665	0.0254
6	− 0.03452	− 0.03919
7	− 0.0075	− 0.01948
8	0.032394	0.004043
9	− 0.00985	− 0.02543
10	− 0.01155	− 0.00887
11	0.029762	0.03378
12	− 0.03952	0.016016
13	0.009431	0.000252
14	0.012653	− 0.01779

the identical stimulation task settings, and were favorably linked with THI and TEQ scale levels.

Discussion

The study combined fNIRS technology with a stimulation task for patients with sensorineural tinnitus, aiming to detect changes in temporal lobe activation and better distinguish the symptoms of sensorineural tinnitus. fNIRS signals were collected from 14 sensorineural tinnitus patients and 14 healthy controls under different noise conditions, and the changes in oxygenated hemoglobin concentration in sensorineural tinnitus patients were analyzed.

The collected fNIRS data during the measurement process are in the form of regional averages rather than absolute quantitative values. If changes occur at a rapid rate throughout the entire measurement process, the accuracy of experimental results may be compromised [16]. However, these data can still indirectly reflect local brain activity. The regional averaging approach constrains the precision of measurements, yet fNIRS, as a non-invasive and user-friendly brain imaging technique, retains significant applications across various domains. Improvements in hardware and algorithms in the future may enhance measurement precision.

The data collection in this study encompassed only 14 patients with sensorineural tinnitus and 14 healthy controls, potentially introducing bias into the results. Adequate sample size or participant numbers are paramount for any near-infrared spectroscopy experiment, yet there exist no fixed rules to ensure statistical validity [17]. Despite efforts to minimize errors, further research is imperative to determine the optimal sample size for this experiment, thus ensuring accurate representation of broader research findings.

fNIRS, as a brain functional imaging technique based on hemodynamic changes, is quiet and has relatively good resistance to motion interference, making it more suitable
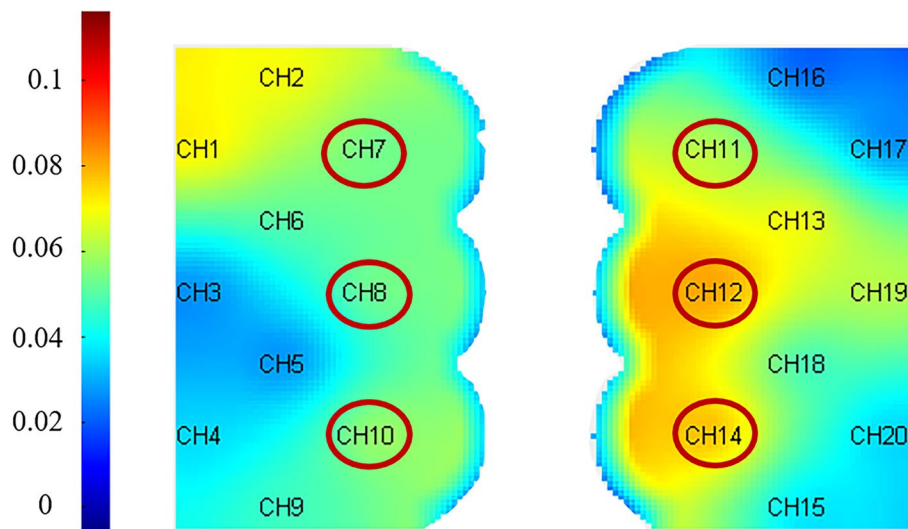
Fig. 7 Schematic diagram of significant channel

for tinnitus research than other imaging methods. However, fNIRS can only measure the hemodynamic activity of the superficial cortical regions, and not the deep brain activity [18]. In this study, although all participants had sensorineural tinnitus, the acupuncture treatment received in the last month may have been influenced by other physical and mental factors, leading to uncertainties in the result analysis. Future research may consider adopting a more rigorous experimental design and conducting more detailed measurement and statistical adjustments of potential confounding factors.

Conclusions

As fNIRS technology advances, this approach will become increasingly useful in studying subjective diseases in humans. In this work, sensorineural tinnitus illness was used as a starting point, and a sound stimulation task was used to determine that under pink noise stimulation, fNIRS data from the temporal lobe indicated a significant difference between the patient and control groups. These findings might reveal new information about the pathophysiology of sensorineural tinnitus, and this novel and highly inventive way to imaging the brain using fNIRS technology could give a more comprehensive and non-invasive approach. The widespread use of fNIRS to examine central auditory circuits in humans will help us better understand the normal and aberrant circuits that exist after hearing loss and tinnitus in the future.

Materials and methods

Subject of the experiment

In this study, 14 patients with sensorineural tinnitus (10 men and 4 females) were recruited and selected among the outpatients of the Central Hospital of Songjiang District in Shanghai, ranging in age from 27 to 67 years. The following were the criteria for

inclusion: (1) those between the ages of 18 and 75; (2) those who presented with tinnitus as their primary complaint and were diagnosed as having subjective tinnitus; (3) those who fully comprehended the tinnitus handicap inventory (THI), tinnitus evaluation questionnaire (TEQ), Hamilton Depression Scale (HAMD), and Hamilton Anxiety Scale (HAMA); (4) those who were able to complete the fNIRS test; (5) the specialized examination revealed no external ear disease or acute inflammatory disease of the middle ear [19].

Both the sick group and the healthy control group met the following selection criteria in this experimental study: (1) all subjects were right-handed; (2) all subjects were native Chinese speakers; (3) all subjects had normal color vision and eyesight; (4) in the first three days of the experiment, there was no significant quantity of rigorous exercise or significant mood swings [20]. Before the commencement of the trial, the 28 subjects were told about the nature of the trial and its safety concerns, and they signed an informed consent form for the trial's implementation that met the ethical committee's requirements. And, guided by the Helsinki Declaration, to protect their legitimate rights and interests [21].

Clinical assessment (case report form)

The subjects filled out the case report form with the help of a competent doctor, and the degree of sensorineural tinnitus was determined by the THI and TEQ [22]. The HAMD and HAMA were added to the case report form in order to assess the presence and severity of depressive and anxiety symptoms in the subjects [23, 24].

Sound stimulation task

Throughout the test, the subjects wore noise-cancelling headphones to guarantee that they were not bothered by the surrounding surroundings [25]. Figure 8 depicts the passive listening block paradigm design plan for the sound stimulus task. There are three auditory stimulus blocks in total: 18 s of pink noise with 1/f-characteristics (It was frequently used to facilitate synchronization of neural oscillatory activities), 18 s of 750 Hz noise, and 18 s of 8000 Hz noise [26]. Following that, each auditory stimulus block was alternated with 18-s quiet blocks that were played in six cycles for around 11 min [27]. The sound pressure level of all auditory stimulus blocks was controlled at 50 dB, and a 5-min silence interval was set before and after the use of the paradigm to calculate the resting-state brain functional connection [28].

fNIRS measurement

Because it is necessary to work back and forth between hospitals and universities during the data collection process, and in order to reduce measurement results caused by equipment errors during the data collection process, the near-infrared spectrum
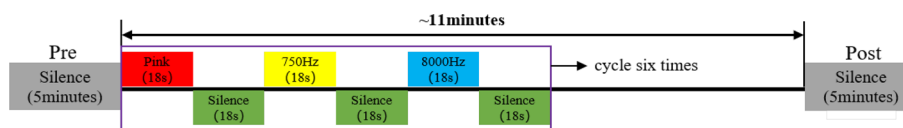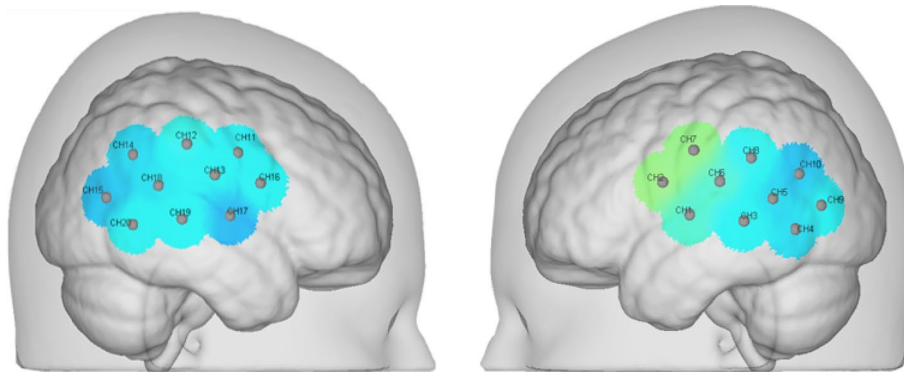

Fig. 8 fNIRS record paradigm

Fig. 9 Temporal lobe measurement channel layout

functional imaging equipment used in this article must have extremely high portability and robustness [29]. As a result, Huichuang's independent model, the NirSmartII-3000c near-infrared brain function imaging system, is used in this study [30]. This gadget satisfies all of the test conditions outlined in this article. During the acoustic stimulus task, the relative concentrations of oxyhemoglobin, deoxyhemoglobin, and total hemoglobin were assessed using a modified Beer–Lambert equation [31, 32]. The temporal lobe, according to the requirements of Brodmann division, is primarily responsible for language and auditory perception, as well as long-term memory and emotion [33]. To evaluate bilateral temporal lobe areas of the brain, a total of 20 channels (CH1–CH20) were established for fNIRS signal collection [34]. The emission bands of near-infrared light were 730 nm and 850 nm, and the sampling rate was set to 20 Hz [35]. Figure 9 depicts the channel configuration for the 20 channels.

Statistical analysis

Except for the Chi-square test for gender, a two-sample *T*-test was employed to compare the average values between sensorineural tinnitus sufferers and healthy controls in this study's examination of sample characteristics and clinical evaluation [36]. Before
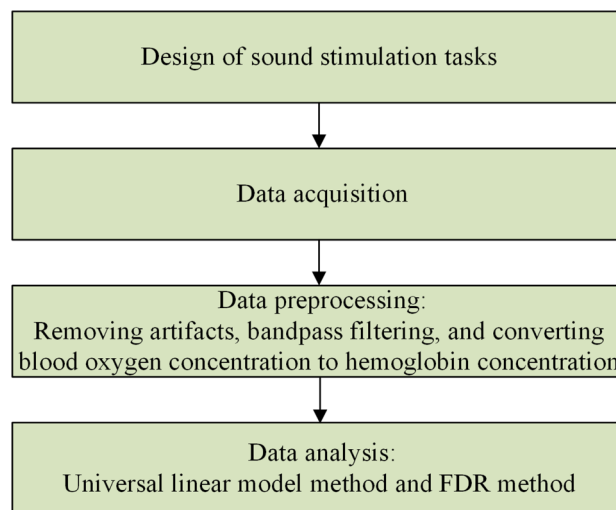

Fig. 10 Data flowchart in near-infrared spectroscopy research

statistical analysis of collected fNIRS data, the data must first go through a series of pre-treatments, which include deleting unrelated intervals from the experiment, eliminating artifacts that have nothing to do with the experimental data, and filtering the data with low-pass and high-pass filters, and finally calculating the ultimate oxygenated hemoglobin concentration data using blood oxygen [37]. The mean value of the first 2 s of the auditory stimulus and the mean value of the 35-s interval after the stimulus were calculated for the block design measurement analysis of the stimulus task to remove the gradual drift in the measurement [38]. The average trajectory for each stimulus was derived by averaging six repeats. The goal of calculating block average is to use superposition average to remove the random noise from each trial of the same task, resulting in the task's average blood oxygen response function [39]. We utilized the average oxygenation amplitude during the stimulation for statistical analysis. The sluggish drift in the signal is minimized in event-dependent designs by utilizing a high-pass filter with six discrete cosine basis functions [40]. We used the general linear model method to do the analysis on MATLAB (MathWorks, USA) through a homemade script [41]. Statistical analysis software was IBM SPSS Statistics 26.0 (SPSS Inc, USA) [42]. A false detection rate (FDR) approach was employed for the repeated comparison analysis of the 20-channel fNIRS data to verify that no more than 5% of false positives were found on average [43]. The data flow diagram is illustrated in Fig. 10.

Declarations

Ethics approval and consent to participate
The study was approved by the Medical Ethics Committee of Shanghai Songjiang District Central Hospital (no. 2024SQ004; 1.24.2024). The study was performed in strict accordance with the Declaration of Helsinki, Ethical Principles for Medical Research Involving Human Subjects.

Informed consent
Informed consent was obtained from all subjects involved in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflicting interests.

References

1.   Møller AR. Sensorineural tinnitus: its pathology and probable therapies. Int J Otolaryngol. 2016;2016:1–13.

2.   Martinez C, Wallenhorst C, McFerran D, Hall DA. Incidence rates of clinically significant tinnitus: 10-year trend from a cohort study in England. Ear Hear. 2015;36:e69-75.

3.   Marek A. Auditive Phänomene als Differenzialdiagnostik zum Tinnitus. Laryngorhinootologie. 2021;100:712–9.

4.   Herraiz C, Diges I, Cobo P, Aparicio JM. Cortical reorganisation and tinnitus: principles of auditory discrimination training for tinnitus management. Eur Arch Otorhinolaryngol. 2009;266:9–16.

5.   Galazyuk A, Brozoski TJ. Animal models of tinnitus: a review. Otolaryngol Clin N Am. 2020;53:469–80.

6.   Lang X, Wen D. fNIRS evaluation of frontal and temporal cortex activation by verbal fluency task and high-level cognition task for detecting anxiety and depression. Front Psychiatry. 2022;12:296.

7.   Curtin A, Tong S, Sun J, Wang J, Onaral B, Ayaz H. A systematic review of integrated functional near-infrared spectroscopy (fNIRS) and transcranial magnetic stimulation (TMS) studies. Front Neurosci. 2019;13:84.

8.   Sharini H, Fooladi M, Masjoodi S, Jalalvandi M, Yousef PM. Identification of the pain process by cold stimulation: using dynamic causal modeling of effective connectivity in functional near-infrared spectroscopy (fNIRS). IRBM. 2019;40:86–94.

9.   Jöbsis FF. Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. Science. 1977;198:1264–7.

10. Delpy DT, Cope M, van der Zee P, Arridge S, Wray S, Wyatt J. Estimation of optical pathlength through tissue from direct time of flight measurement. Phys Med Biol. 1988;33:1433.

11. Jalalvandi M, Sharini H, Naderi Y, Alam NR. Assessment of brain cortical activation in passive movement during wrist task using functional near infrared spectroscopy (fNIRS). Front Biomed Technol. 2019;6:99–105.

12. Sun J-J, Liu X-M, Shen C-Y, Zhang X-Q, Sun G-X, Feng K, et al. Reduced prefrontal activation during verbal fluency task in chronic insomnia disorder: a multichannel near-infrared spectroscopy study. NDT. 2017;13:1723–31.

13. Schecklmann M, Giani A, Tupak S, Langguth B, Raab V, Polak T, et al. Functional near-infrared spectroscopy to probe state- and trait-like conditions in chronic tinnitus: a proof-of-principle study. Neural Plast. 2014;2014:1–8.

14. Basura GJ, Hu X, Juan JS, Tessier A, Kovelman I. Human central auditory plasticity: a review of functional near-infrared spectroscopy (fNIRS) to measure cochlear implant performance and tinnitus perception. Laryngosc Investig Otolaryngol. 2018;3:463–72.

15. Zhai T, Ash-Rafzadeh A, Hu X, Kim J, San Juan JD, Filipiak C, et al. Tinnitus and auditory cortex; using adapted functional near-infrared-spectroscopy to expand brain imaging in humans. Laryngosc Investig Otolaryngol. 2021;6:137–44.

16. Bonilauri A, Sangiuliano Intra F, Baselli G, Baglio F. Assessment of fNIRS signal processing pipelines: towards clinical applications. Appl Sci. 2022;12:316.

17. Yücel MA, Lühmann AV, Scholkmann F, Gervain J, Dan I, Ayaz H, et al. Best practices for fNIRS publications. NPh. 2021;8: 012101.

18. Leaver AM, Renier L, Chevillet MA, Morgan S, Kim HJ, Rauschecker JP. Dysregulation of limbic and auditory networks in tinnitus. Neuron. 2011;69:33–43.

19. Shulman A, Avitable MJ, Goldstein B. Quantitative electroencephalography power analysis in subjective idiopathic tinnitus patients: a clinical paradigm shift in the understanding of tinnitus. An electrophysiological correlate. Int Tinnitus J. 2006;12:121–32.

20. Franz B, Offutt G. Tinnitus suppression with threshold and subthreshold sound stimuli. Int Tinnitus J. 2003;9:11–6.

21. Bukantz SC. The Helsinki Declaration. Hosp Pract. 1967;2:24–5.

22. Gos E, Sagan A, Skarzynski PH, Skarzynski H. Improved measurement of tinnitus severity: study of the dimensionality and reliability of the Tinnitus Handicap Inventory. PLoS ONE. 2020;15: e0237778.

23. Langguth B, Landgrebe M, Kleinjung T, Sand GP, Hajak G. Tinnitus and depression. World J Biol Psychiatry. 2011;12:489–500.

24. Argstatter H, Grapp M, Hutter E, Plinkert P, Bolay HV. Long-term effects of the "Heidelberg Model of Music Therapy" in patients with chronic tinnitus. Int J Clin Exp Med. 2012;5:273.

25. Michiels S, Ganz Sanchez T, Oron Y, Gilles A, Haider HF, Erlandsson S, et al. Diagnostic criteria for somatosensory tinnitus: a Delphi process and face-to-face meeting to establish consensus. Trends Hear. 2018;22:233121651879640.

26. Naal-Ruiz NE, Alonso-Valerdi LM, Ibarra-Zarate DI. Data on electroencephalographic activity while exposed to pink noise modified by the frequency responses of three headphone models. Data Brief. 2021;39: 107528.

27. Perez-Carpena P, Bibas A, Lopez-Escamez JA, Vardonikolaki K, Kikidis D. Chapter 1—Systematic review of sound stimulation to elicit tinnitus residual inhibition. Progress in brain research. 2021;262, pp. 1–21.

28. Maeda K, Honda A, Sakamoto S, Suzuki Y. Accuracy of subjective straight ahead after passive rotation of listeners: effects of time interval between visual cue and onset of sound stimulus. Acoust Sci Technol. 2020;41:425–7.

29. Cui X, Bray S, Bryant DM, Glover GH, Reiss AL. A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. Neuroimage. 2011;54:2808–21.

30. Zhu Y, Sun F, Li C, Huang J, Hu M, Wang K, et al. Acute effects of mindfulness-based intervention on athlete cognitive function: an fNIRS investigation. J Exerc Sci Fit. 2022;20:90–9.

31. Oshina I, Spigulis J. Beer–Lambert law for optical tissue diagnostics: current state of the art and the main limitations. J Biomed Opt. 2021;26: 100901.

32. Jalalvandi M, Alam NR, Sharini H, Hashemi H, Nadimi M. Brain cortical activation during imagining of the wrist movement using functional near-infrared spectroscopy (fNIRS). J Biomed Phys Eng. 2021;11:583.

33. Paquette N, Lassonde M, Vannasing P, Tremblay J, González-Frankenberger B, Florea O, et al. Developmental patterns of expressive language hemispheric lateralization in children, adolescents and adults using functional near-infrared spectroscopy. Neuropsychologia. 2015;68:117–25.

34. Kreuzer PM, Poeppl TB, Rupprecht R, Vielsmeier V, Lehner A, Langguth B, et al. Daily high-frequency transcranial random noise stimulation of bilateral temporal cortex in chronic tinnitus—a pilot study. Sci Rep. 2019;9:12274.

35. Miyata H, Tani R, Toratani S, Okamoto T. Effects of tongue pressure on cerebral blood volume dynamics: a functional near-infrared spectroscopy study. Brain Sci. 2022;12:296.

Fan *et al. BioMedical Engineering OnLine*   (2024) 23:59

Page 12 of 12

36. Zhu L, Lu W, Gamoso W, Tan Y, Johnson C, Ma GX. The association between modifiable lifestyle behaviors and depression among Asian Americans with chronic hepatitis b by medication status. Brain Sci. 2022;12:188.

37. Ghouse A, Nardelli M, Valenza G. fNIRS complexity analysis for the assessment of motor imagery and mental arithmetic tasks. Entropy. 2020;22:761.

38. Almulla L, Al-Naib I, Ateeq IS, Althobaiti M. Observation and motor imagery balance tasks evaluation: an fNIRS feasibility study. PLoS ONE. 2022;17: e0265898.

39. Khan H, Noori FM, Yazidi A, Uddin MZ, Khan MNA, Mirtaheri P. Classification of individual finger movements from right hand using fNIRS signals. Sensors. 2021;21:7943.

40. Gratton E, Toronov V, Wolf U, Wolf M, Webb A. Measurement of brain activity by near-infrared light. J Biomed Opt. 2005;10: 011008.

41. Öztürk Ö, Algun ZC, Bombacı H, Erdoğan SB. Changes in prefrontal cortex activation with exercise in knee osteo-arthritis patients with chronic pain: an fNIRS study. J Clin Neurosci. 2021;90:144–51.

42. Zhang D, Zhou Y, Yuan J. Speech prosodies of different emotional categories activate different brain regions in adult cortex: an fNIRS study. Sci Rep. 2018;8:218.

43. Salzman T, Aboualmagd A, Badawi H, Tobón-Vallejo D, Kim H, Dahroug L, et al. Prefrontal cortex involvement during dual-task stair climbing in healthy older adults: an fNIRS study. Brain Sci. 2021;11:71.

Publisher's Note