A computational model for tinnitus generation and its management by sound therapy

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***Abstract*—**Tinnitus is an auditory perception of sound with no external source that can be perceived in the ear(s) or in the head. There is a wide range of methods for tinnitus management. Sound therapy is considered as one of the most effective ones. In this paper, a simple, computational and dynamical model with plasticity is proposed using Bonheoffer-van der Pol (BVP) equations for a preliminary step of modeling the framework with tonotopic organization with hearing loss. Mechanisms of the generation of tinnitus and the effects of sound therapy is investigated. This model replicates tinnitus generation associated with hearing loss and the temporary inhibition of tinnitus perception following sound therapy.

***Keywords*—** tinnitus, computational model, sound therapy, hearing loss, homeostatic plasticity, oscillation, inhibition

I. Introduction

TINNITUS is an auditory perception that one perceives sound(s) in the ear(s) or in the head without any external source [1]-[6]. Several neurophysiological models have been proposed for understanding of mechanism of tinnitus [7], [8]. Previous research has widely discussed the role of neural plasticity on tinnitus [8]-[13]. It has been suggested that the damage of the peripheral auditory system decreases the activity of auditory nerve, it brings a shift in the balance of excitation and inhibition by plasticity, and consequently it results in an increase in spontaneous firings in the central auditory system [8], [9]. Anatomical neuroimaging studies employing techniques such as magnetic resonance imaging (MRI) have shown structural brain changes secondary to tinnitus [14]. However, the mechanism of tinntitus generation has not been clarified sufficiently [15].

Clinical observations show that a large number of tinnitus sufferers have hearing loss. On the other hand it is common to see individuals with normal hearing and no tinnitus. It is also common to see no tinnitus in patients with hearing loss. The emphasis of this paper is to explore the generation of tinnitus in those with hearing impairment, particularly those with sensorineural hearing loss. Hearing loss is a frequency dependent condition and there is a correlation between the perceived frequency of tinnitus and hearing sensitivity loss at that particular frequency.

For management and treatment of tinnitus, a number of approaches have been proposed by clinicians and scientists [16]-[19]. These include medications, supplemental vitamins and micronutrients therapy, surgical procedures, psychotherapy and biofeedback, electrical stimulation, transcranial magnetic stimulation, and sound therapy or acoustic therapy. Sound therapy is one of the most effective and noninvasive methods to manage tinnitus when compared to other types of tinnitus management and therapies. Sound therapy techniques for tinnitus treatment have a clinical effect on tinnitus loudness. In many cases in the loudness perception of tinnitus decreases following use of acoustical stimuli. As a result annoyance from tinnitus decreases after the sound presentation [20]-[23]. This loudness reduction is clinically effective for many tinnitus sufferers with hearing loss. Occasionally tinnitus completely disappears for a short period of time following acoustic stimulation of ears with tinnitus. This paper addresses complete cessation of tinnitus. The complete cessation of tinnitus following the presentation of external stimuli is referred to as residual inhibition.

A few computational models have been proposed as an effective approach to investigate mechanisms of tinnitus generation [24]-[28]. Previously our research team proposed computational and dynamical models with plasticity using a neural oscillator [25], [26], [29]-[31] and neuronal networks with simplified Hodgkin-Huxley (HH) equations [32]-[39] to replicate not only the tinnitus generation but also the effect of sound therapy. The original structure of our models was very simple. These models conceptually account for the tinnitus generation and its relief by sound therapy. For the purpose of modeling of tinnitus with hearing loss, it is essential to incorporate the tonotopic organization of the auditory system. This incorporation will facilitate the modeling of tinnitus and hearing loss when they are present together.

In this paper, a simple model using Bonheoffer-van der Pol (BVP) equations [40] for the representation of neurons is proposed. The structure of the model is the same as former models. The present model is a preliminary step of development of a model that expresses the tonotopic organization in the auditory system in the auditory brain structures in relation to tinnitus. BVP equations are much simpler than the simplified HH equations. This simplicity

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provides less computation time and less number of parameters that are necessary for any model with a large number of neurons such as a model with tonotopic organization.

In the previous models, the plasticity has been applied in one of the couplings between the components by use of Hebbian hypothesis [25], [26], [29]-[33], [41] or spike-timing-dependent plasticity (STDP) [34], [35], [42]. As a different approach for the explanation of the plasticity in the nervous system, homeostatic plasticity (HP) was proposed [43] and it has been investigated in a variety of neural networks [44]. It has been pointed out that HP is necessary for stability of the activities in the nervous system and it has been employed in a number of neural systems [41].

The role of HP in tinnitus types that are induced by hearing loss has been investigated [45]. Treatment of tinnitus to reverse the homeostatic change also has been reported [46]. Additionally a computational model with HP for tinnitus with hearing loss has been proposed [47]. That model, however, is not a dynamical system. Further modeling of a dynamical system for tinnitus with HP is required [48]. In the present paper, we propose a computational model as a dynamical system incorporating HP in order to replicate tinnitus generation process with hearing loss and the relief of tinnitus by sound therapy as it was recommended earlier [49].

The currently proposed neuronal network model conceptually replicates the generation of tinnitus combined with hearing loss, and represents the clinical behavior of the human auditory system when the tinnitus perception is temporarily halted following the treatment by sound therapy. In this paper we show that with appropriate range of parameter values in the model, generation of oscillation in the model occurs with no input due to the HP. The inhibition of the oscillation can be obtained following the application of constant or sinusoidal input. Once again this occurs due to the HP. In this method the effects of sound therapy are replicated similarly to the previous models.

II. A Neural Network Model

The structure of the neural network model in this paper is shown in Fig. 1. The model is a conceptually simplified system of neural correlates that generate tinnitus. However, we believe that the neural mechanism proposed here could form the essential component of a large-scale and multi-layered system for tinnitus [6]. This model is composed of two excitatory neurons and one inhibitory neuron.

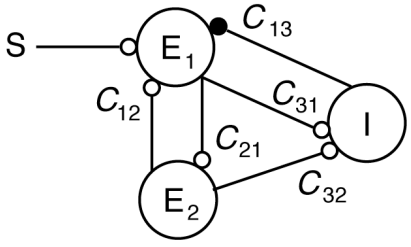


Fig. 1 A neural network model.

The excitatory neurons E_1 and E_2 make a positive feedback loop by the connection to each other. They excite the inhibitory neuron I, and the inhibitory neuron I inhibits the excitatory neuron E_1, which makes a negative feedback loop. It has been suggested that the thalamo-cortical network [50] could be essentially important for tinnitus generation [12], [14], [51]. The functional changes in the dorsal cochlear nucleus and the inferior colliculus in tinnitus generation have also been suggested [12], [52]. These studies all support the role of a range of auditory related centers in generation and perception of tinnitus. It could be stated that both positive feedback loop and negative feedback loop play important roles in regulation of auditory activities and generation of tinnitus. The model structure in our study is based on these considerations. The model can be bistable with a sustained firing state and a non-firing state.

The coupling strength between neurons is denoted by C_{ij} ($i, j \in \{1, 2, 3\}$). The neuron E_1 receives external stimuli S. It represents afferent signal generated by the acoustic stimuli that are employed in sound therapy.

A. Model equations without plasticity

Without plasticity, in other words, when all the values of coupling strength are constant in time, the model is expressed by the following equations,

$$\begin{aligned} \frac{dx_1}{dt} &= c\left(y_1 + x_1 - \frac{1}{3}x_1^{\,3}\right) + C_{12}z_2 - C_{13}z_3 + S \\ \frac{dy_1}{dt} &= -\frac{1}{c}(x_1 + by_1 - a) \end{aligned}, \tag{1}$$

$$\begin{aligned} \frac{dx_2}{dt} &= c\left(y_2 + x_2 - \frac{1}{3}x_2^{\,3}\right) + C_{21}z_1 \\ \frac{dy_2}{dt} &= -\frac{1}{c}(x_2 + by_2 - a) \end{aligned}, \tag{2}$$

$$\begin{aligned} \frac{dx_3}{dt} &= c\left(y_3 + x_3 - \frac{1}{3}x_3^{\,3}\right) + C_{31}z_1 + C_{32}z_2 \\ \frac{dy_3}{dt} &= -\frac{1}{c}(x_3 + by_3 - a) \end{aligned}, \tag{3}$$

employing BVP equations, where x_j and y_j are state variables of the neurons. The x_j is associated with the membrane potential of a neuron, y_j is associate with the activation of sodium ion channel, and z_j is the output of neuron j and expressed as

$$z_j = \begin{cases} 1 & (x_j \geq v_f) \\ 0 & (x_j < v_f) \end{cases} \tag{4}$$

where v_f is a threshold for the output to postsynaptic neurons.

B. Plasticity formulation and input

We incorporate HP in the model for the tinnitus generation and the inhibition of oscillation after feeding input. The plasticity is introduced to one of the values of the coupling strength C_{12} for simplicity as

$$\frac{dC_{12}}{dt} = \frac{-C_{12} + C_S - pz_1}{\tau}, \tag{5}$$

where C_S is the stationary value of C_{12} when E_1 does not fire,

p is a parameter that gives the quantity of the modification of C_{12}, and τ is the time constant of the plastic change.

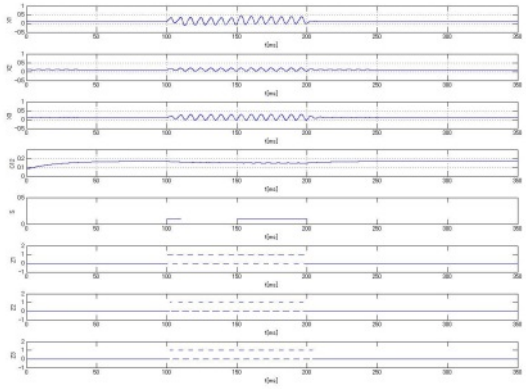
III. Results

We performed computer simulation of the model. Throughout the simulation the parameter values a=0.1, b=0.1, c=0.2, v_f=0.16, C_{13}=C_{21}=C_{31}=C_{32}=0.04 were used.

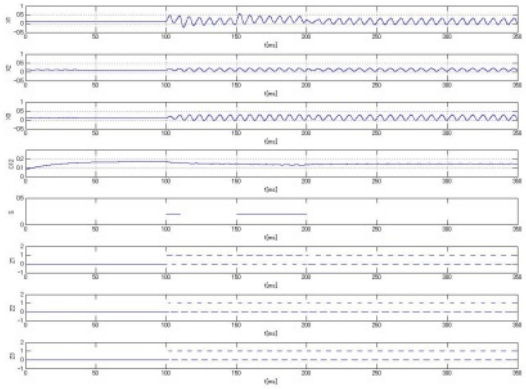
A. Solution in the model with neither plasticity nor input

In the model with neither plasticity nor input, two stable solutions exist. One is an equilibrium and the other is an oscillatory solution. In the former one the neurons do not fire and in the latter the neurons fire periodically. They are bistable for a certain parameter region.

We performed computer simulation changing the value of the coupling strength C_{12} at the interval of 0.02 for the range $0 \le C_{12} \le 0.3$. The equilibrium exits stably where $0 \le C_{12} \le 0.22$, while the oscillatory solution exists stably where $0.12 \le C_{12} \le 0.3$. Where $0.12 \le C_{12} \le 0.22$, two solutions exist stably. Which solution emerges depends upon the initial values of the state variables, x_j and y_j (j=1, 2, 3).



(a)



(b)

Fig. 2 Simulation results with constant input. (a) Inhibition is accomplished. (b) Inhibition is not accomplished.

This results are in accord with the fact that most patients of tinnitus claim that they do not always perceive tinnitus.

B. Analysis of the model with plasticity and constant input

We performed computer simulations of the model with plasticity feeding temporarily constant input with amplitude I. We employed the parameter values, C_S=0.17 and τ=20[ms].

Fig. 2 shows examples of the results of the computer simulations. Fig. 2(a) is an example when the inhibition of oscillation is accomplished, where p=0.04, I=0.1 and the duration of input is 50ms. The initial value of the coupling strength C_{12} is 0.08 and the neurons in the model do not fire. The coupling strength C_{12} increases according to Eq. (3). It approaches to C_S. The neurons do not fire since both the equilibrium and the oscillatory solution exist when C_{12}=0.17. At time t=100[ms], a short triggering input is applied to the neuron E_1. Then the sustained oscillation of the state variables begins and the neurons start to fire repeatedly. From time t=150[ms] to t=200[ms], temporarily constant input with the amplitude I=0.1 is applied to neuron E_1. The model continues to oscillate while the input is applied. However, after the input is removed, the oscillation stops. It is because the coupling strength C_{12} decreased by the input according to Eq. (3). It can be stated that this result is a reproduction of the inhibition of tinnitus by sound therapy. Fig. 2(b) is an example when the inhibition of oscillation is not accomplished, where p=0.06, I=0.2 and the duration of input is 50ms.

We examined the inhibition of oscillation changing the value of the parameter p at the interval of 0.02 for the range $0.02 \le p \le 0.12$ for the amplitude of input I=0.1 and 0.2 with input duration 50ms and 100ms. The results are summarized in Table 1. When I=0.1, the inhibition was accomplished in all cases, while the inhibition was not accomplished in some p values for input duration 50ms and all p values for input duration 100ms. When p=0.12, I=0.2 and input duration is 100ms, the inhibition occurred during the input is fed. This does not correspond to the clinical scenario.

Table 1. Inhibition of oscillation with constant input. O: Inhibition is accomplished. X: Inhibition is not accomplished.

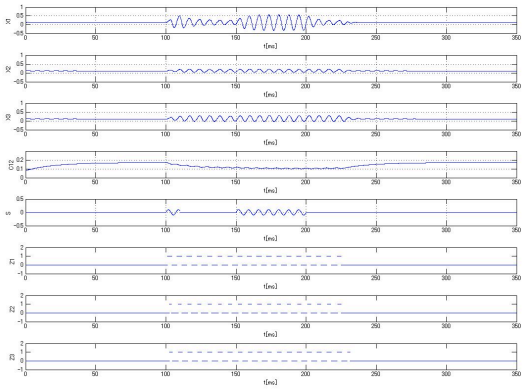
Input duration [ms]	I	p					
		0.02	0.04	0.06	0.08	0.10	0.12
50	0.1	O	O	O	O	O	O
	0.2	O	O	X	X	X	O
100	0.1	O	O	O	O	O	O
	0.2	X	X	X	X	X	

C. Analysis of the model with plasticity and sinusoidal input

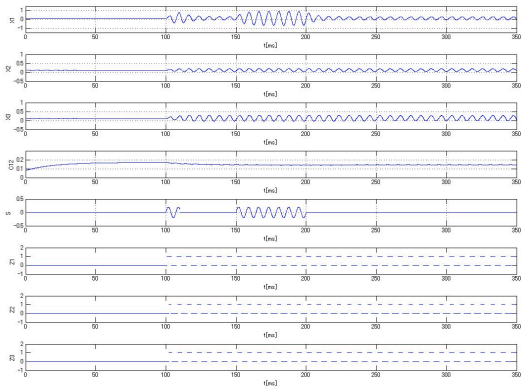
We performed computer simulations of the model with plasticity feeding sinusoidal input as

$$S = I_m \sin 2\pi ft \quad , \tag{5}$$

where I_m and f denote the amplitude and frequency of the input, respectively. We employed the parameter values, C_S=0.17 and τ=20[ms] same as the case for temporarily constant input. The frequency f of the input was set to the value that is approximately equal to the frequency of the autonomous oscillation.



(a)



(b)

Fig. 3 Simulation results with sinusoidal input. (a) Inhibition is accomplished. p=0.14, I_m=0.1. (b) Inhibition is not accomplished. p=0.06, I_m=0.2.

Table 2. Inhibition of oscillation with sinusoidal input. O: Inhibition is accomplished. X: Inhibition is not accomplished.

Input duration [ms]	p						
	I_m	0.2	0.6	1.0	1.4	1.8	2.2
50	0.1	X	X	X	O	O	O
	0.2	X	X	X	O	O	O
100	0.1	X	X	X	O	O	O
	0.2	X	X	X	O	O	O

Fig. 3 shows examples of the results of the computer simulation. Figure 3(a) is an example when the inhibition of oscillation is accomplished, where p=0.14, I_m=0.1 and the duration of input is 50ms. Figure 3(b) is an example when the inhibition of oscillation is not accomplished, where p=0.06, I_m=0.2. The initial value of the coupling strength is 0.08.

We examined the inhibition of oscillation changing the value of the parameter p at the interval of 0.02 for the range $0.02 \le p \le 0.22$ for the amplitude of input I_m=0.1 and 0.2 with input duration 50ms and 100ms. The results are summarized in Table 2. For both values of I_m and input duration, the inhibition was accomplished when p is equal to or larger than 0.14, while the inhibition was not accomplished p is equal to or smaller than 0.12.

IV. Conclusion

A dynamical neural network model for tinnitus generation with hearing loss and its relief by sound therapy was proposed in this paper. BVP model was employed for the neuron in the model as a simple model neuron. This is a preliminary step of modeling tonotopic organization. In order to demonstrate plasticity, homeostatic plasticity was employed. The results of the computer simulation of the model show that the model can replicate the generation of the tinnitus with hearing loss and it can represent the temporal cessation and inhibition of tinnitus sensation following therapeutic acoustic stimulation.

For future studies, our team will expand the present model to include the auditory centers that encompass tonotopic organization and will model their role in the generation of tinnitus.

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