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A neuronal network model with simplified tonotopicity for tinnitus generation and its relief by sound therapy*

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***Abstract*—Tinnitus is the perception of sound in the ears or in the head where no external source is present. Sound therapy is one of the most effective techniques for tinnitus treatment that have been proposed. In order to investigate mechanisms of tinnitus generation and the clinical effects of sound therapy, we have proposed conceptual and computational models with plasticity using a neural oscillator or a neuronal network model. In the present paper, we propose a neuronal network model with simplified tonotopicity of the auditory system as more detailed structure. In this model an integrate-and-fire neuron model is employed and homeostatic plasticity is incorporated. The computer simulation results show that the present model can show the generation of oscillation and its cessation by external input. It suggests that the present framework is promising as a modeling for the tinnitus generation and the effects of sound therapy.**

I. Introduction

Tinnitus is the perception of sound in the ears or in the head where no external source is present [1]. A variety of environmental and pathological conditions can result in the tinnitus generation. Tinnitus and hearing loss may coexist or be present independently from each other. In other words, many of individuals with tinnitus have clinically normal hearing sensitivity and not all of those with hearing loss report tinnitus.

Neurophysiological models have been proposed to understand the mechanism of the tinnitus [2]. Many researchers have discussed the contribution of neural plasticity to tinnitus in order to understand the neural correlates of tinnitus [3]-[7]. Computational modeling is another promising approach to understanding of tinnitus [8]-[11].

A number of approaches have been proposed by clinicians and scientists for management and treatment of tinnitus [12]. Sound therapy is one of the most effective methods in tinnitus management among the therapies [13]. It has the clinical effect that tinnitus disappears or reduces in its loudness after the sound presentation. The mechanisms of tinnitus management by sound therapy, however, are not clear.

Previously we proposed computational models using a neural oscillator [9], [14], [15] or a neuronal network [16]-[18] to replicate tinnitus generation and its management by sound therapy. It has been addressed that a lot of portions in the brain are related with the tinnitus. It has been pointed out that the thalamo-cortical network [5] could be essentially important for tinnitus generation [1], [7], [19]. The functional changes in the dorsal cochlear nucleus and the inferior colliculus in tinnitus generation have been also suggested [1], [20]. 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. We demonstrated that the model conceptually reproduces activity of tinnitus and its inhibition using sound stimuli. This was accomplished by incorporating neural plasticity through parameters such that their values can be modified.

In the current paper, we propose a preliminary neuronal network model with a simplified tonotopicity of the auditory system as a more detailed structure. Since the number of neurons becomes much larger in a tonotopic model than former models, we express the dynamics of the neurons by an integrate-and-fire neuron model that is simpler in calculation than those in the former models.

For synaptic plasticity, we employed Hebbian hypothesis [21] or spike-time-dependent plasticity (STDP) [22] in the previous models. Another mechanism of plasticity that has been proposed is homeostatic plasticity [23]. It can account for homeostasis of activities in the nervous system. The role of homeostatic plasticity in hearing loss-induced tinnitus has been investigated [24]. However, further modeling of a dynamical system for tinnitus with homeostatic plasticity [25] is required. In the present dynamical model, we preliminarily incorporate homeostatic plasticity for both generation of tinnitus with hearing loss and relief from the tinnitus after treatment of sound therapy.

We demonstrate the results of computer simulation of this model. The results show that the inhibition of oscillation can be replicated with appropriate input and model parameters by the effect of homeostatic plasticity, which suggests that the present framework is promising as a modeling for the generation of tinnitus and the effect of sound therapy.

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II. A Neuronal Network Model

We propose a neuronal network model with tonotopic structure. In the model the firing sequences in the nervous system are simulated. The present model is a conceptually simplified system of a tinnitus generation network. However, we believe that the neural mechanism proposed here could form components of models involving large-scale neural correlates for providing a neurophysiological framework [2].

The model is composed of two layers of excitatory neurons A_i and B_i and a layer of inhibitory neurons C_i (i=1, 2, ……). Neurons A_i and B_i are mutually coupled forming a positive feedback loop. The inhibitory neurons C_i receives input from neurons A_{i-1}, A_i, A_{i+1}, B_{i-1}, B_i and B_{i+1}. It inhibits A_{i-1}, A_i and A_{i+1} making a negative feedback loop. The negative feedback loop controls the firing rate. The neurons A_i, B_i and C_i (i=1, 2, ……) represent those in thalamus, auditory cortex and thalamic reticular nucleus, respectively.

The coupling weight between neurons is denoted by W_{ij}, where i and j are the index of the postsynaptic and presynaptic neurons, respectively. The output of neuron j is denoted by z_j and expressed as a threshold function of the membrane potential of the neuron. Neuron A_i receives external stimulus S_i, afferent signal due to acoustic stimuli.

In this paper, the model is simplified moreover as shown in Fig. 1. The excitatory neurons associated with the frequency of tinnitus are represented by neurons A_1 and B_1, and those associated with other frequencies by neurons A_2 and B_2. The inhibitory neurons are represented by neuron C_1. Hence the model is composed of five neurons.

A. Formulation of the model

We express the dynamics of the model by an integrate-and-fire neuron model that is a simplified version of the model described by Burkitt [26]. Integrate-and-fire neuron models have been used widely in order to simply describe a neuron theoretically. We employed it to save the time of simulation by reducing the number of state variables for each neuron to two and describing the dynamics of them linearly. The membrane potential of a neuron j, v_j, is expressed as

$$\tau_v \frac{dv_j}{dt} = -v_j + V_R + V_{Sj}, \tag{1}$$

where τ_v is the time constant of v_j, V_R is the resting potential, and V_{Sj} is the weighted sum of input to the neuron. The neuron fires when v_j is equal to or exceeds a threshold u_j. The output of the neuron z_j is expressed as

$$z_j = \delta[H(v_j - u_j) - 1], \tag{2}$$

where $\delta[.]$ denotes the Dirac delta function and $H(.)$ denotes the Heaviside step function. The action potential of the neuron when it fires is not expressed in the equation of v_j. After the neuron fires, the threshold u_j varies with time according to the equation

$$\tau_u \frac{du_j}{dt} = -u_j + U_R + z_j, \tag{3}$$

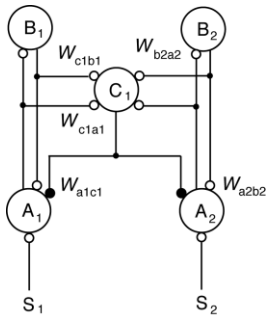

Figure 1. A neuronal network model with simplified tonotopicity.

where τ_u is the time constant of u_j, and U_R is the resting value of u_j.

The weighted sum of input to each neuron, V_{Si}, is expressed as

$$V_{Sa1} = W_{a1b1} z_{b1} - W_{a1c1} z_{c1} + S_{a1}, \tag{4}$$

$$V_{Sa2} = W_{a2b2} z_{b2} - W_{a2c1} z_{c1} + S_{a2}, \tag{5}$$

$$V_{Sb1} = W_{b1a1} z_{a1}, \tag{6}$$

$$V_{Sb2} = W_{b2a2} z_{a2}, \tag{7}$$

and

$$V_{Sc1} = W_{c1a1} z_{a1} + W_{c1b1} z_{b1} + W_{c1a2} z_{a2} + W_{c1b2} z_{b2}. \tag{8}$$

B. Formulation of plasticity

To replicate the generation of tinnitus and the effect of sound therapy, we assume that the coupling weights between neurons have homeostatic plasticity. We introduce the plasticity only to the coupling weights from neuron C_1 to neurons A_1 and A_2 as the first step of the modeling. We assume that the plastic coupling weights change depending on the activity of the postsynaptic neuron. The change of the inhibitory coupling weight from neuron j to neuron i denoted by W_{ij} due to homeostatic plasticity is simply expressed here as

$$\tau_w \frac{dW_{ij}}{dt} = -W_{ij} + W_S + p z_i, \tag{9}$$

where τ_w is the time constant of W_{ij}, W_{Sij} is the steady state value of W_{ij} when neuron i does not fire, and p is a parameter that is associate with the quantity of the modification of W_{ij}. Eq. (9) is formulated in such a way that the higher the activity of neuron i is, the larger W_{ij} grows.

III. Results ans discussion

We demonstrate the results of computer simulation of the model. Throughout the simulation the parameter values τ_v=5[ms], τ_u=1[ms], U_R=0.1, V_R=0, W_{a1b1}=W_{a2b2}=1, W_{b1a1}=W_{b2a2}=0.4, W_{c1a1}=W_{c1b1}=0.1, W_{c1a2}=W_{c1b2}=0.01, are employed.

A. Analysis of the model without input or plasticity

Without input or plasticity, the neuron A_1 has two stable solutions, an oscillatory state by sustained firings and a non-firing state. They are bistable for a parameter region.

We performed the simulation changing the value of the coupling weight W_{a1c1} by 0.1 in the range $0 < W_{a1c1} \leq 2$. The non-firing state exists for any values of the coupling weight. On the other hand, the oscillatory state exists when $W_{a1c1} \leq 0.5$. That is, the two states coexist when $W_{a1c1} \leq 0.5$. The larger W_{a1c1} brings the smaller basin of the oscillatory solution in the state space of the model. It corresponds to the clinical fact that a number of patients of tinnitus claim that they do not always hear sound when there is no external sound. Some triggering stimulus invokes tinnitus and it lasts until some other stimulus make the tinnitus perception stop.

B. Analysis of the model with input and plasticity

The inhibition of oscillation by constant input with amplitude I_1 and I_2 as stimulus S_1 and S_2 to neuron A_1 and A_2, respectively, was examined with plasticity. In this paper we show the results of the simulation in which only A_1 is stimulated. It corresponds to the stimulation with the frequency of tinnitus, which is masking therapy. The parameter values in Eq. (9) τ_w= 20[ms] and W_S=0.3 were employed for plasticity. The time constant of the change of the coupling weight is much smaller than the clinical process. Such a small time constant was given so that the simulation is completed in a reasonable time. The value W_S=0.3 is in the range where both oscillatory and non-firing solutions exist. The initial values of the coupling weights W_{a1c1} and W_{a2c1} were given as 2 and 1, respectively. They are the values in which only non-firing solution exists. The amplitude I of the input was changed by 0.01 in the range of $0 < I_1 \leq 0.2$.

Fig. 2 shows an example of simulation results with p=80. In the figure, the rows illustrate the membrane potentials v_{a1}, v_{b1}, v_{a2}, v_{b2} and v_{c1}, the threshold values u_{a1}, u_{b1}, u_{a2}, u_{b2} and u_{c1}, the coupling weights W_{a1c1} and W_{a2c1}, input S_1 and S_2, and output of the neurons z_{a1}, z_{b1}, z_{a2}, z_{b2} and z_{c1}, respectively, from the top. At first from t=0[ms] to t=100[ms] S_1=0, while S_2 has some pulses. Because it is assumed that there is no input to neuron A_1 due to hearing loss for the corresponding frequency band, while input often comes to neuron A_2 since that part is normal. The inhibitory coupling weight W_{a1c1} decreases according to homeostatic plasticity so that the firing of neuron A_1 is easier to occur. It decays to the value in which oscillatory solution also exists. At t=100[ms] a trigger input is given to A_1. Then neurons A_1, B_1 and C_1 start firing, and the firing is sustained. The coupling weight W_{a2c1} does not decay to such a value since neuron A_2 fires occasionally. From t=150[ms] to t=200[ms] constant input I_1=0.1 was applied to neuron A_1. Neuron A_1 fires with much higher rate for this period. Consequently the coupling weight

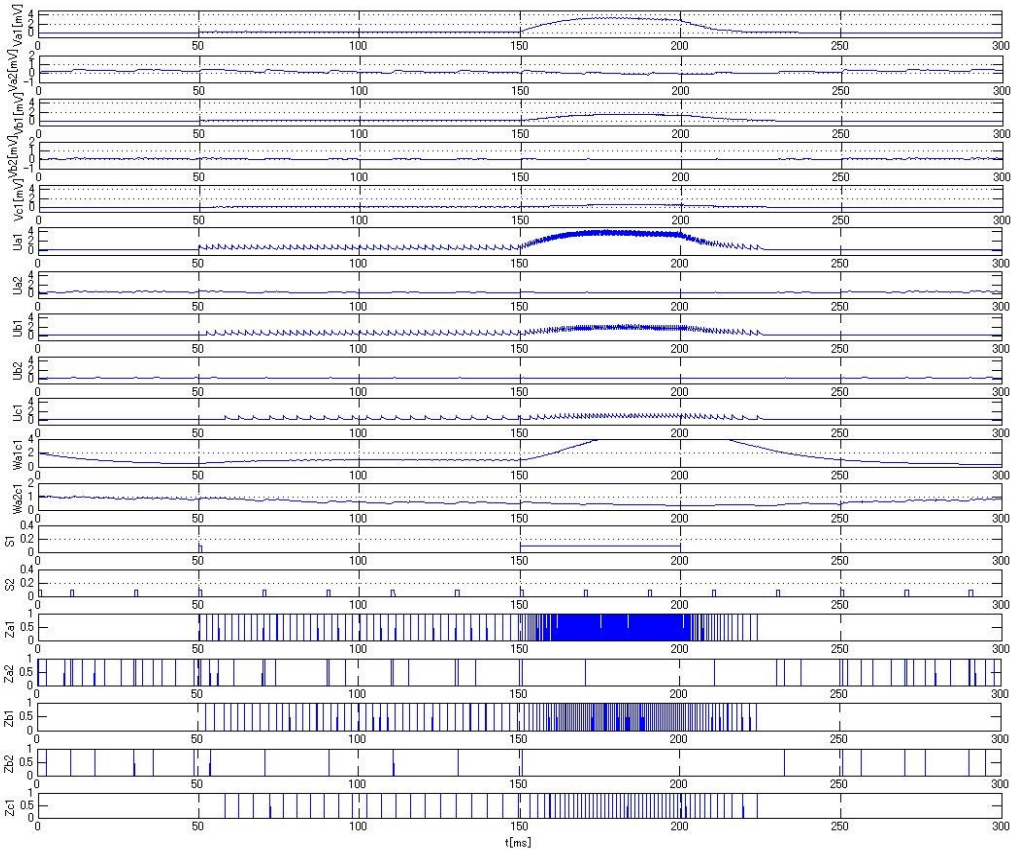

Figure 2. A simulation result. I_1=0.1.

W_{a1c1} increases according to Eq. (9). After removing the input at t=200[ms], neuron A_1 stops firing. The input to neuron A_1 makes the neurons A_1, B_1 and C_1 stop the autonomous oscillation after the input is removed. However, the coupling weight W_{a1c1} decreases again since neuron A_1 does not fire. After W_{a1c1} decay to the value in which the oscillatory solution exists, neuron A_1 starts oscillation again with a trigger input. It corresponds to the regeneration of tinnitus. When p=80, the input with the amplitude $I_1 = 0.06$ was brought inhibition of oscillation. When p=60 and 100, the input with the amplitude $I_1 = 0.12$ and $I_1 = 0.02$ was required, respectively, to make the network stop the oscillation after the input is removed. When p=20 or 40, the input with the amplitude $0 < I_1 \le 0.2$ did not bring the inhibition of oscillation. The smaller p needs the larger amplitude of input which gives higher rate of firing. The oscillation starts and stops due to change of the coupling weight W_{a1c1}. Hence, both the generation of oscillation and its cessation are obtained by homeostatic plasticity of the neuronal network. In summary, it was suggested that the present framework is promising as a model for the role of neural plasticity on the generation of tinnitus and the effect of sound therapy.

IV. Conclusion

In the present study a conceptual and computational neuronal network model as a dynamical system with homeostatic plasticity in the human auditory system is proposed for a preliminary model for the generation of tinnitus with hearing loss and its management by sound therapy. The model structure is a very simple expression of tonotopicity of the auditory system. In the present model, the generation and inhibition of the oscillation is realized by the change of coupling weight between neurons as homeostatic plasticity. It suggests that the present framework is promising as a modeling for the generation of tinnitus and the effect of sound therapy. For future work we will extend the model to a layered network with tonotopic structure, examine the inhibition of oscillation by other types of input, and explore better stimulation for tinnitus management.

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