

# Electrical Stimulation of the Cochlea to Reduce Tinnitus

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## ABSTRACT

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This article reviews possible neural correlates of tinnitus, including an increase in rate, a decrease in rate, periodic activity, synchronous activity across neurons, and an edge between active and inactive neurons. We make some suggestions regarding how electrical current might alter these patterns of neural activity. For example, if tinnitus were represented with periodic neural activity, then electrical stimulation would need to disrupt this periodicity. Some cases of cochlear electrical stimulation are reviewed that show the tinnitus can be reduced or eliminated with cochlear electrical stimulation although it varies across individuals. Finally, after summarizing some key observations, we suggest some next steps to bring this into a clinical application.

**KEYWORDS:** Tinnitus, cochlear implants, electrical stimulation

**Learning Objectives:** As a result of this activity, the participant will be able to (1) describe some of the possible mechanisms of the coding of tinnitus in the cochlea, and (2) describe how electrical suppression might alter tinnitus.

## MECHANISMS OF TINNITUS AND OF INFLUENCING TINNITUS

“Sensorineural tinnitus probably has many different sources, and therefore finding any single treatment”<sup>1</sup> is unlikely. The differences in perceptions and psychophysical behavior across subjects are large.<sup>2</sup> Tinnitus can be perceived as a broadband noise (buzzing or humming), a

tone (e.g., ringing), a frequency or amplitude modulated tone (crickets), or variations in between.<sup>3</sup> Each of these percepts could be coded in neuron responses in a different manner.<sup>4</sup>

It seems reasonable that tinnitus must be coded (“perceived”) in the auditory temporal lobe, although it can have its source any place in the auditory system and may be altered by other

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systems as well.<sup>5-7</sup> The importance of the central nervous system in tinnitus has been emphasized for decades. Evidence of central involvement include the following:<sup>8</sup>

- When the 8th nerve ipsilateral to the tinnitus is cut, there is often no change in the perception of the tinnitus.
- When an ipsilateral tinnitus is masked with noise in the same ear, patients sometimes remark that the tinnitus can appear in the other ear.
- Ipsilateral tinnitus can be masked at comparable and at low levels in ipsilateral and contralateral ears.<sup>9</sup>

Tinnitus can be coded in the temporal lobe in the following manner:

1. Increased spontaneous activity<sup>10</sup>
2. Periodic spontaneous activity<sup>11</sup>
3. Cross-neuron correlation<sup>11-13</sup>
4. More neurons with similar best frequency following hearing loss<sup>14</sup>

To perceive tinnitus, certain kinds of analysis must be performed in the auditory temporal lobe, such as:

1. Determining that high levels of spontaneous activity are present among some neurons but not others.
2. Determining there are periodic time intervals between action potentials on individual neurons (equivalent to performing an interval histogram).
3. Detecting synchronous activity across neurons.

Wherever the coding of tinnitus takes place, it is likely it can be influenced by cochlear activity assuming the cochlea and auditory pathway are relatively intact. Although tinnitus activity is interpreted in the auditory cortex, in many cases it might originate in the cochlea from alterations of the spontaneous activity, including:

1. An increase in rate
2. A decrease in rate
3. Periodic activity

4. Synchronous activity across neurons
5. Edge between active and inactive neurons<sup>10</sup>

Changing this spontaneous activity is the likely mechanism by which electrical stimulation of the cochlear can affect tinnitus.

## MECHANISMS OF INFLUENCING TINNITUS FROM THE COCHLEA

To change tinnitus, electrical activity in the cochlea must change the activity of auditory nerve fibers by a variety of mechanisms:

- Decreasing activity
- Increasing activity
- Desynchronizing activity across nerve neurons
- Interfering with periodic activity

Electrical stimulation with noise will not create uncorrelated activity across neurons because several nerves will fire synchronously to an electrical waveform.<sup>15</sup> For example, when a periodic electrical pulse train is the stimulus, many auditory neurons will respond at the frequency of the stimulus. This is true at least at stimulus repetitions  $< \sim 3000$  pulses per second (pps). Rubinstein et al<sup>16</sup> proposed a high rate ( $> 3000$  pps) *conditioner stimulus* driving the nerve at rates beyond which it can follow the electrical waveform. At that point, activity across the neurons more closely follows a Poisson process.

### If Tinnitus Results from a Decrease in Spontaneous Rate

If tinnitus resulted from a decrease in spontaneous rate, stimulating the auditory nerve directly with electrical current might increase the neural activity. If this created an ongoing activity that was more like the normal spontaneous rate that mirrors a Poisson process with a dead time, it could eliminate tinnitus. In addition to direct stimulation of the auditory nerve, electrical stimulation also might alter the resting state of remaining hair cells. If this resulted in an increase in neurotransmitter release, then the activity on the nerve might increase. Again, if

the resultant ongoing activity was close to the normal spontaneous rate, it could eliminate tinnitus.

### **If Tinnitus Results from an Increase in Spontaneous Rate**

If tinnitus resulted from an increase in spontaneous rate originating from a narrow region of the cochlea, then electrically stimulating a larger adjacent array of neurons might decrease the prominence of the tinnitus. Alternatively, continuous electrical stimulation of the hyperactive neurons might adapt the abnormal neurons so they could no longer transmit activity. This reduction in the prominence could eliminate the tinnitus. However, these neurons might no longer be available to code acoustic speech sounds (although they might be able to code speech with electrical stimulation).

### **If Tinnitus Results from a Periodic Activity in Spontaneous Rate**

If tinnitus was coded on a small number of neurons that exhibit strong periodicity, electrical stimulation with noise could disrupt periodicity. The use of a conditioner stimulus<sup>16</sup> might be able to accomplish this without audibility of the stimulation.

### **If Tinnitus Results from a Synchronous Activity in Spontaneous Rate across Neurons**

Tinnitus might also result from synchronous activity across many nerve fibers. Electrical stimulation could disrupt this synchronous activity. The use of noise as a stimulus could disrupt or change this periodicity but might create its own (random) synchronous activity across neurons. Again, a conditioner stimulus might be able to do this without synchrony across neurons and without perception.

### **If Tinnitus Is the Edge between Active and Inactive Hair Cells**

Another source of tinnitus might result from the difference in activity originating between the edge of normal (with normal spontaneous

activity) and no spontaneous activity (e.g., a region with hair cell loss).<sup>10</sup> This edge effect might result from a loss of inhibition from the inactive region. If the inactive region received electrical stimulation and activation of neural responses, the edge could be eliminated and the source of tinnitus might be removed.

## **REVIEW OF STUDIES USING ELECTRICITY TO REDUCE TINNITUS**

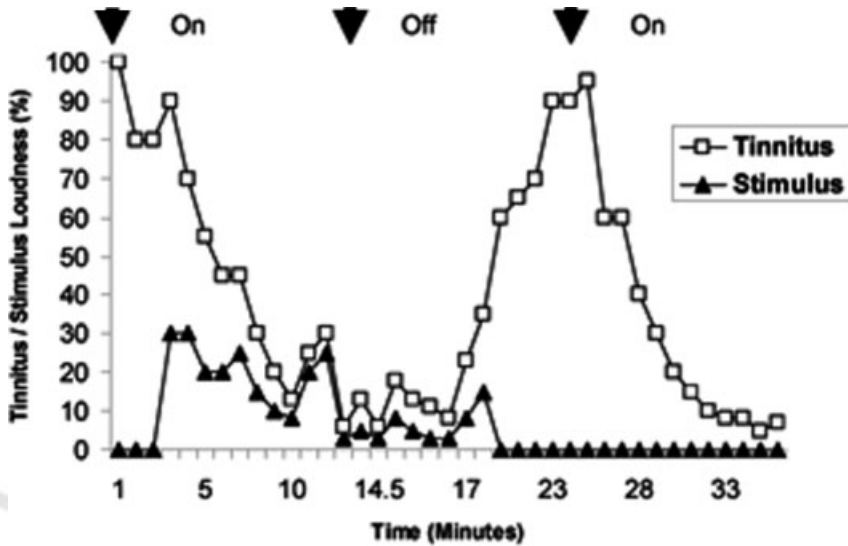
### **Cochlear Implant Studies**

Patients who have tinnitus and use cochlear implants to improve their speech perception often report a reduction in their tinnitus while they are using their speech processors. Several studies and reviews are available.<sup>17–31</sup> These are some of the more noteworthy observations:

- Some patients get tinnitus from receiving a cochlear implant.<sup>32</sup>
- Some patients experience a total elimination of tinnitus after the cochlear implant surgery.<sup>22</sup>
- Some patients report a reduction in their tinnitus only when the speech processor is turned on.<sup>19</sup>
- Some patients report a reduction in their tinnitus after the speech processor is turned off.<sup>33</sup>
- Some patients with bilateral tinnitus report a reduction of tinnitus on both sides after receiving a unilateral cochlear implant.<sup>34</sup>
- Some patients report changes in the quality or pitch of their tinnitus.<sup>33</sup>

### **Extracochlear Stimulation**

Kuk et al<sup>35</sup> used a ball electrode at the eardrum in an attempt to reduce tinnitus. They used square, sine, and triangular waveforms at frequencies from 62 to 8000 Hz. In the screening phase, they first increased the level and noted changes in the patient's tinnitus. Stimulation placebo trials were used initially but later abandoned because patients were aware if they were or were not being stimulated. Five of the 10 patients reported tinnitus reduction in the screening phase and were then tested in a second phase. Patients were required to judge



**Figure 1** The amount of acoustic masking in the contralateral ear required to mask the tinnitus before, during, and after 10 minutes of electrical stimulation at the eardrum. Adapted from Kuk et al (1989). Individual results are shown for five subjects.

loudness ratings and to mask their tinnitus acoustically in the nonstimulated ear before, during, and after the 10-minute electrical stimulation. Fig. 1 shows data from five subjects for whom tinnitus could be reduced. This study is important because it used a psychoacoustical measurement that was the amount of masking required to mask the tinnitus to document the tinnitus reduction. Tinnitus reduction was accomplished without stimulus audibility in 60% of patients and the reduction was restricted to the stimulated ear in 75% of patients with bilateral tinnitus. Tinnitus was completely eliminated in three patients. The optimum stimuli varied among patients. The poststimulation reduction lasted from 40 seconds to 4 hours. Hazell et al<sup>36</sup> and many others<sup>25</sup> also reported being able to reduce tinnitus with a platinum ball electrode on the round window.

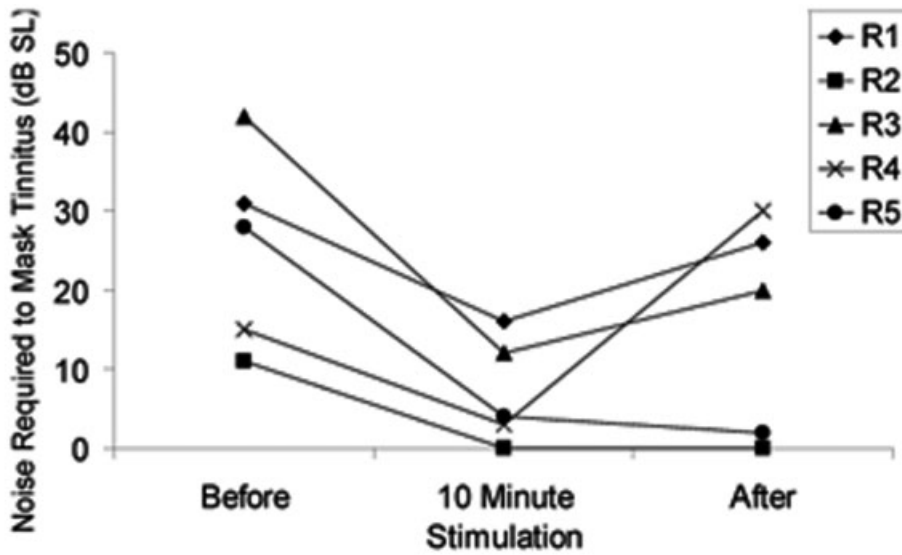
### Intracochlear Stimulation

McKerrow et al<sup>37</sup> used an inaudible 2- to 6-MHz carrier and a 30-minute broadband noise (stimulating the speech processor) at a comfortable level to stimulate six cochlear implant patients electrically. Five of six patients reported a rapid decrease to inaudible tinnitus. Fig. 2 shows data from one patient implanted

in the right ear. A 2- to 6-MHz inaudible electrical stimulation was presented to the right ear for ~5 minutes. This reduced the tinnitus in both ears, but after ~15 minutes the stimulation was no longer effective. A noise was then presented through the speech processor at a comfortable level, which also reduced the tinnitus in both ears. This remained effective for 20 minutes. When the electrical noise was turned off, the tinnitus returned gradually in the left ear but remained absent in the right ear for another 20 minutes. Similar findings were reported by Dauman et al<sup>38</sup> and Dauman and Tyler.<sup>39</sup>

Rubinstein et al<sup>16</sup> and Rubinstein and Tyler<sup>25</sup> used a high-frequency conditioner stimulus and were able to suppress tinnitus in subjects with cochlear implants and with round window electrodes. For some subjects it required several minutes of stimulation before the tinnitus was suppressed. Once tinnitus suppression was achieved, continuous stimulation with the conditioner stimulus sometimes became ineffective. Changes in the amplitude or repetition rate of the pulse train sometimes reinstated tinnitus suppression.

Fig. 3 reports some previously unpublished results from one subject. Shown are both the loudness of the tinnitus and the loudness of the electrical pulse train stimulus. During



**Figure 2** Intracochlear stimulation in a cochlear-implant patient. The loudness of the tinnitus is plotted for the right and left ear as a function of time during the trial. First a 2- to 6-MHz inaudible carrier is presented, followed by the application of a broadband noise stimulation to the speech processor (both presented unilaterally to the right ear). Tinnitus loudness was judged on a scale from 10, extremely loud, to 0, not heard. (Adapted from McKerrow et al, 1991.) SL, sensation level<sup>Q1</sup>.

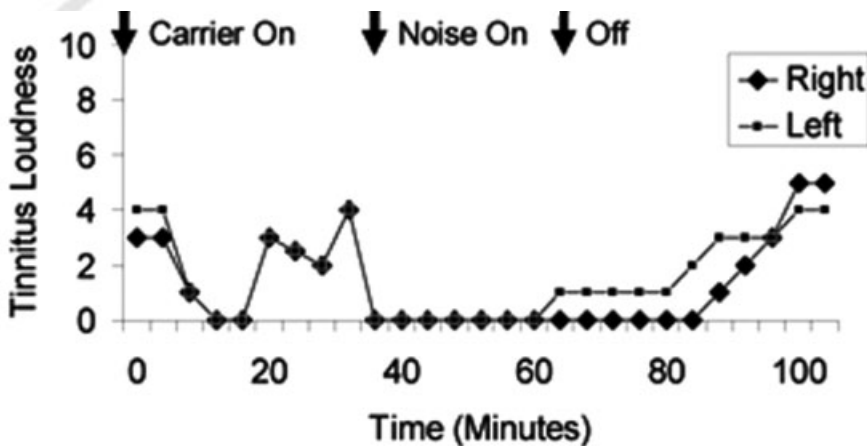
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~10 minutes of stimulation, the loudness of the tinnitus gradually decreased while the electrical stimulation was perceived at a soft loudness. When the stimulus was turned off, the tinnitus remained at a soft level for ~5 minutes and then gradually returned to its initial level over the next 10 minutes. The electrical stimulation was turned on again, and

once again the tinnitus reduced in loudness over ~10 minutes; this time without any perception of the conditioner.

### Summary of What Is Known

Although no large-scale studies have been reported to clarify the important parameters



**Figure 3** Tinnitus perception over time for one cochlear implant subject. The loudness of the tinnitus and of the high rate electrical pulse train is plotted as a function of time during the trial. The electrical stimulus was turned on, off, and then on again. Tinnitus loudness was judged on a scale from 100, the loudness of their normal tinnitus, to 0, not heard.

necessary to produce a clinical device to suppress tinnitus electrically, we have several leads:

- Electrical stimulation of the cochlea can suppress tinnitus in some patients.
- The optimal stimulus parameters are likely different for different subjects.
- The optimum place in the cochlea for electrical stimulation of tinnitus is likely different for different subjects.
- Unilateral stimulation of the cochlea usually produces a monaural tinnitus reduction, but some subjects report a binaural reduction of tinnitus.
- It is possible to suppress tinnitus without perceiving the stimulation.
- There is a possible advantage to a conditioning stimulus to suppress tinnitus without perceiving the electrical stimulus.
- The effectiveness of electrical stimulation for tinnitus can decrease over time (over several minutes).
- When the effectiveness of electrical stimulation decreases over time, the effectiveness can be recovered by changes to the stimulus parameters.
- In some patients, tinnitus can be reduced for several minutes and even hours after the electrical stimulus is turned off.

### Next Steps

Electrical stimulation of the cochlea can suppress tinnitus in some subjects. There appears to be great potential to develop a clinical device to treat tinnitus using this approach. The following are the next steps to accomplish this:

- Studies are needed to determine what changes in the stimulus are needed to continuously suppress tinnitus during continuous stimulation.
- Studies should include both placebo and replication trials to provide broader validity.
- The long-term time course (hours) of tinnitus reduction during continuous stimulation needs to be better mapped out.
- Studies with more subjects are needed to determine which patient characteristics identify subjects who will show significant

tinnitus suppression from electrical stimulation of the cochlea.

- Studies are needed to explore the effectiveness of short and long intracochlear electrodes as well as extracochlear stimulation.

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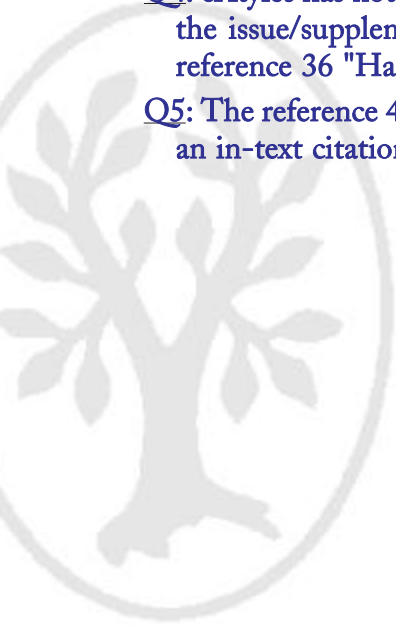
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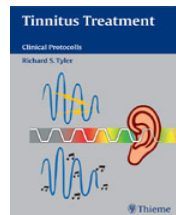
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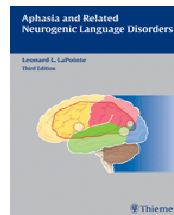
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