INTRODUCTION

Chronic tinnitus is a perception of sound in the absence of sound stimuli that affects approximately 10-15% of the adult population [1]. Various hypotheses have been proposed regarding the cause of tinnitus, however the exact pathophysiology remains unknown. Various treatments such as retraining, medication, sound stimulation, neuromonics or surgical treatments have been used, however, an effective treatment method has not been found. Among these, electrical stimulation is reportedly effective in many patients who do not benefit from other treatments.

Electrical stimulation for the suppression of tinnitus has been used in the past. Feldmann reported that Grapergiesser first suppressed tinnitus by transcutaneous stimulation with Volta’s platinum-zinc cell [2]. Since then, numerous investigators have performed electrical stimulation using different wave forms with electrodes placed at various sites. Graham [3] used a transtympanic electrode and House [4] reported a reduction in tinnitus during electrical stimulation in patients with cochlear implants. Kitahara and Okusa [5] reported the effectiveness of suppressing tinnitus with electrical promontory stimulation. In this study, we introduce electrical stimulation of the round window and brain cortex as treatments for tinnitus.

ELECTRICAL STIMULATION OF THE ROUND WINDOW

Based on the theory of abnormal electrical activity within the auditory pathways and hyperactive hair cells or neurons [6,7], a promising therapeutic approach is a device that would restore the physiological function within the auditory system and resynchronize the peripheral and/or the central neurons of the auditory pathway. Electrical stimulation has been known for more than 200 years to induce hearing sensations [8] and Grappengiesser reported this stimulation may have an effect on tinnitus.

Research on electrical promontory stimulation (EPS) showed temporary and partial tinnitus suppression. Reportedly, approximately 82% of patients experienced immediate relief of tinnitus and 45% of those patients showed longer-term tinnitus suppression.
the autonomic nervous and limbic systems are related in process
tation can provide more permanent tinnitus relief.

Electrical promontory stimulation via a transtympanic approach
ear when it occurs in connection with sensorineural hearing loss.

Portmann [7] suggested that the effectiveness of electrical stimu-
lation may be based on electrode placement and found that elec-
trical stimulation at the round window was better than stimulation
at the promontory. Additionally, positive electrical pulses were
the most effective in temporary tinnitus suppression. In the report-
ed studies, the efficacy of EPS to suppress tinnitus was achieved
using very brief stimulation in acute experimental settings. Repeat-
ability of tinnitus suppression using EPS remains uncertain and
the long-term effects of EPS on the cochlea and acoustic thresholds
have not been thoroughly investigated [10].

Using cochlear implants to suppress tinnitus implies that elec-
trical stimulation of the auditory nerve can reverse the reorganiza-
tion associated with peripheral deafferentation thus reversing plas-
tic changes which may have led to tinnitus. Additionally, increased
activation of the auditory nerve may inhibit cells in the auditory
nervous system and influence its effect on tinnitus.

Psychological factors may also contribute to tinnitus suppres-
sion obtained after cochlear implantation. For example, the recov-
ery of auditory function may help assure patients and minimize
ratory investigation of safety issues, which was beyond the scope
of this study.

1. Transcranial direct current stimulation (tDCS)

The effects of noninvasive tDCS have been studied in both healthy
individually and those with neurological disorders. Based on
stimulation polarity, tDCS can either increase or decrease the ex-
citability of the underlying cortex. Anodal stimulation increases
excitability with neuronal depolarization and cathodal stimula-
tion decreases excitability with neuronal hyperpolarization [14-
16]. Synaptic activity controls the changes in intracortical inhibi-
tion or facilitation and can affect the results of tDCS [17]. Anodal
tDCS of the left temporoparietal area (LTA) and dorsolateral pre-
frontal cortex (DLPFC) are potentially the most favorable polarity
and stimulation sites for tinnitus relief [18-21]. tDCS of LTA results
in more widespread diffused impact on cortical areas beyond the
target region. However, tDCS of DLPFC results in a more localized
impact on the target region itself [22].

Anodal tDCS of the LTA has led to transient suppression of tin-
nitus in 42% [23] and 35% [18] of participants. A comparatively
long-lasting impact on tinnitus perception, lasting up to a few days,
was observed in a recent double-blind, sham-controlled study con-
ducted by Garin et al. [18] using tDCS for 20 minutes with 1 mA
current intensity. Anodal tDCS produced more favorable effects
compared with cathodal or sham tDCS. Vanneste and colleagues
[19] explored whether tDCS of DLPFC would suppress tinnitus
and used a slightly higher current intensity (1.5 mA) than other
authors [18,23]; they reported a 29.9% positive response rate with
bifrontal tDCS using an anode on the right DLPFC and cathode
on the left DLPFC. However, a review of studies conducted since
1998 using tDCS in humans under various clinical conditions
showed that no studies used a current intensity greater than 2 mA
[24]. The use of a current higher than 2 mA would require a prepa-
ratory investigation of safety issues, which was beyond the scope
of this study.

ELECTRICAL STIMULATION OF THE BRAIN CORTEX

The neurophysiological hypothesis by Jastreboff implies that
the autonomic nervous and limbic systems are related in process-
ing behavioral problems and tinnitus neuronal activities [12]. If

Tinnitus can be influenced by electrical stimulation of the inner
ear when it occurs in connection with sensorineural hearing loss.
Electrical promontory stimulation via a transtympanic approach
or round window stimulation can provide temporary tinnitus sup-
pression. In patients with profound hearing loss, cochlear implant-
ation can provide more permanent tinnitus relief.
tDCS can potentially be applied in clinical settings for patients with tinnitus, although more research is needed in this area.

2. Repetitive transcranial magnetic stimulation (rTMS)

Transcranial magnetic stimulation (TMS) is a non-invasive tool that can be used to modulate neural activity. TMS delivers a high intensity and short-lasting current pulse via an insulated stimulating coil. This produces a magnetic field perpendicular to the coil which penetrates the underlying scalp and brain at a reduced intensity ultimately affecting the activity of cortical neurons in the brain region beneath the coil (Fig. 1). TMS can be administered as a single pulse or as paired pulses.

The magnetic field reaches a maximum of 1.5-2 T (same size as a MRI scanner) in approximately 100 μs and then decays back to zero [25]. The magnetic coils have different shapes. Round coils are the most powerful. Figure-eight-shaped coils or double-cone coils are more focused with a maximal current delivered at the intersection of the 2 round components which can deliver the current to the targets more precisely (Fig. 2).

Reportedly, single magnetic pulses have no long-lasting effects on the brain. Cortical excitability was repeatedly decreased with low-frequency (≤ 1 Hz) rTMS [26], while high-frequency (5-20 Hz) rTMS resulted in increased excitability [27]. These types of stimulations are used for neurophysiological exploratory purposes. rTMS administers multiple TMS pulses to a patient’s head during a single period [28]. Repetitive magnetic fields produced by rTMS can decrease neural overactivity in cortical areas and alleviate tinnitus [29]. Specifically, rTMS of the auditory cortex is effective in the treatment of tinnitus [30]. Neuroplastic changes in the brain, as a reaction to sensory deafferentation, are considered a cause of tinnitus [31]. Networks of several cortical areas may cause tinnitus, but the exact area remains unknown. Progress in functional imaging has helped explain the pathophysiology and identified brain lesions related to tinnitus [32]. Several studies have reported that positron emission tomography (PET) can be used to identify the region of unbalanced cortical activity where rTMS could be applied [33,34]; however, controversy remains regarding the usefulness of PET for rTMS targeting [35] and the function of PET and other neuroimaging modalities in determining the stimulation site is debatable. Rossi [36] reported that stimulation (5 days, 1-Hz rTMS) in the left temporoparietal area was effec-
tive and not related to tinnitus laterality. Moreover, only a few studies showed that stimulation of the left temporoparietal cortex produced better results than stimulation of the right cortex [36,37].

Since rTMS showed positive outcomes in treatment for tinnitus, many groups have reported their own treatment protocols and results. Specifically, Eichhammer [30] reported significant improvement in 3 patients treated with brain stimulation. Subsequently, many other studies have reported the effectiveness of rTMS stimulation in the temporoparietal region [37-39] ranging from 8-50%. Kim et al. safely applied rTMS to the temporoparietal cortex daily for 5 days with long-term benefits [40].

rTMS is widely used to treat various psychological diseases. Specifically, stimulation of the prefrontal area with rTMS was proven effective in patients with depression [41]. rTMS of the auditory cortex showed positive effects in the treatment of chronic tinnitus [30]. However, stimulation-related issues, including intensity, duration or predictors of response, are uncertain. Recently, rTMS of multiple brain cortices including the auditory cortex was performed to treat tinnitus [42]. Kleinjung reported that combined rTMS of the temporal and frontal brain cortices was more effective than rTMS of the temporal area alone [43]. Park et al. reported that combined rTMS of the auditory and prefrontal cortices was more beneficial than rTMS of the auditory cortex alone to treat tinnitus in patients with depression [44]. However, low-frequency left temporal rTMS combined with low-frequency right DLPFC rTMS did not show increased benefit [45].

Previous studies reported adverse effects including sensorineural hearing loss after temporal rTMS or epileptic seizures after high-frequency and high-intensity rTMS [46]. However, to date, the results reported showed rTMS is a well-tolerated and safe technique [47].

**CONCLUSION**

Electrical stimulation is an effective treatment for chronic tinnitus, but this conclusion is based on a small number of studies and should be interpreted carefully. Studies with a larger number of participants and longer follow-up period are necessary to prove the short- and long-term therapeutic effects of electrical stimulation. In addition, protocols for stable treatments should be designed.
REFERENCES


