Review Article

Surgical approaches to tinnitus treatment: A review and novel approaches

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Abstract

Background: Tinnitus, a profoundly widespread auditory disorder, is characterized by the perception of sound in the absence of external stimulation. The aim of this work is to review the various surgical treatment options for tinnitus, targeting the various disruption sites along the auditory pathway, as well as to indicate novel neuromodulatory techniques as a mode of tinnitus control.

Methods: A comprehensive analysis was conducted on published clinical and basic neuroscience research examining the pathophysiology and treatment options of tinnitus.

Results: Stereotactic radiosurgery methods and microvascular decompressions are indicated for tinnitus caused by underlying pathologies such as vestibular schwannomas or neurovascular conflicts of the vestibulocochlear nerve at the level of the brainstem. However, subsequent hearing loss and secondary tinnitus may occur. In patients with subjective tinnitus and concomitant sensorineural hearing loss, cochlear implantation is indicated. Surgical ablation of the cochlea, vestibulocochlear nerve, or dorsal cochlear nucleus, though previously suggested in earlier literature as viable treatment options for tinnitus, has been shown to be ineffective and contraindicated. Recently, emerging research has shown the neuromodulatory capacity of the somatosensory system at the level of the trigeminal nerve on the auditory pathway through its inputs at various nuclei in the central auditory pathway.

Conclusion: Tinnitus remains to be a difficult disorder to treat despite the many surgical interventions aimed at eliminating the aberrant neuronal activity in the auditory system. A promising novel neuromodulatory approach using the trigeminal system to control such a bothersome and difficult-to-treat disorder deserves further investigation and controlled clinical trials.

Key Words: Cochlear implant, microvascular decompression, neuromodulation, stereotactic radiosurgery/stereotactic radiotherapy, Tinnitus, trigeminal nerve stimulation, trigeminal nerve

INTRODUCTION

Definition and incidence

Tinnitus, commonly known as "ringing in the ear," is an auditory disorder characterized by perception of internally generated "phantom auditory sensations" without the trigger of an external stimulus.[16,24,34] Tinnitus affects approximately 35 to 50 million Americans every day, with 2 to 3 million Americans severely disabled by the disorder.[1,2] Though there are a wide variety of surgical treatment options,[4-6,8,9,13,14,17,31,38,43,48] tinnitus remains a very difficult disorder to treat. Many patients continue to live with persistent unbearable symptoms that are often debilitating and destructive to their daily quality of life.

ETIOLOGY OF TINNITUS

Tinnitus can be divided into the following two categories: objective and subjective [Figure 1]. Objective tinnitus is one in which the clinician can observe the same sound that the patient perceives and whose pathophysiology is usually of a vascular, musculoskeletal, or respiratory etiology, whereas subjective tinnitus has a neurophysiological origin. Currently, it is believed that subjective tinnitus, without an underlying cause such as a vestibular schwannoma, is a result of neuronal hyperactivity in the central auditory system as a result of damage to peripheral auditory input structures.[16,24,34] Damage to the cochlea caused by auditory trauma, ototoxic agents, or other means results in neuronal hyperactivity, increasing the spontaneous firing rate of neurons in several auditory structures, including the ventral cochlear nucleus (VCN), dorsal cochlear nucleus (DCN), and the central nucleus of the inferior colliculus.[16,22-24,34] There is a reorganization of the tonotopic map at the level of the primary and secondary auditory cortices.[16,29,34] This reorganization of the tonotopic map at the level of the auditory cortex has been imaged through fMRI in human tinnitus sufferers[45] and is thought to occur as a result of neurons receiving decreased thalamocortical input, resulting in a deafferentation state yielding a subsequent reduction in intracortical inhibition; as a result, neurons begin to respond to lateral inputs from unaffected neighboring neurons through connections on their apical dendrites.[16,29,34] Of particular importance with regards to the reorganization of the cortical tonotopic map is that the majority of tinnitus patients perceive their phantom auditory sounds to be near the same frequencies covering the range of their hearing loss.[16,34] Thus, tinnitus can be thought of as a deafferentation disorder in which decreased output from the affected auditory region (e.g., caused by noise-induced trauma) leads to reduced central inhibition, resulting in neuronal hyperactivity in the central auditory system structures, along with cortical plasticity and reorganization of the tonotopic map.[16,22,23,29,34] Furthermore, subjective tinnitus can be divided into the following two subcategories: otic tinnitus, in which the phantom perceptions are caused by disorders of the inner ear and vestibulocochlear nerve, and somatic tinnitus, which is subjective tinnitus that can be modulated in pitch (frequency) and loudness (amplitude) by physical or somatic manipulation. Somatic tinnitus illustrates a unique crosstalk between the somatosensory and auditory systems at the level of the brainstem. Primary somatic sensory inputs to the auditory system from axons of the trigeminal ganglion project primarily into the ipsilateral granule cell domain surrounding the VCN and extending into the second layer of the DCN, as well as send scattered terminal branches into the magnocellular regions of the VCN and deep DCN[40,41,50,51] [Figure 2].
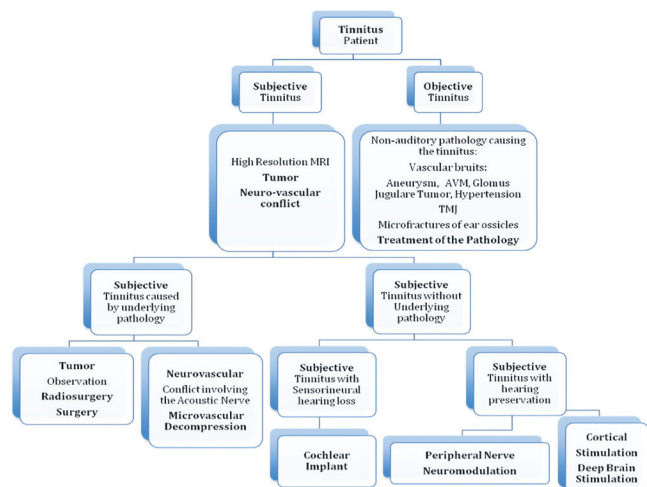

Figure 1: Flowchart illustrating tinnitus treatment options – Figure 1 demonstrates the categorization of tinnitus type and the subsequent diagnostic and surgical treatment options based upon the origin of tinnitus symptomatology
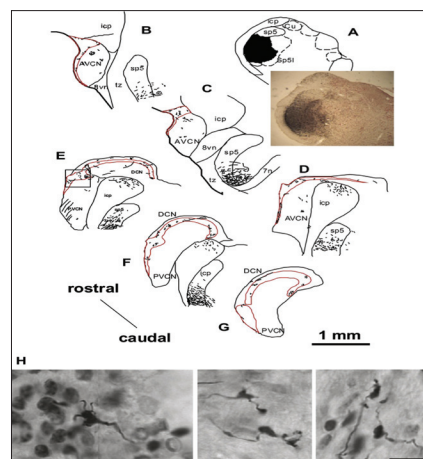

Figure 2 (A-H): Photomicrographs of rat mossy fibers showing mossy fibers from the spinal trigeminal nucleus are found restricted to the Granule Cell Domain (GCD). Tracings from the Spinal Trigeminal Nucleus projections to Ventral and Dorsal Cochlear Nuclei – Figure 2 illustrates the somatosensory inputs of the trigeminal nerve at the level of the Spinal Trigeminal Nucleus on the cochlear nuclei. This illustration shows the nuclei communication, offering the anatomical and physiological basis for stimulation of the trigeminal system as a possible therapeutic option for tinnitus. Each tick mark represents a trigeminal neuronal terminal ending

Additionally, somatosensory input from the dorsal root ganglion axons of the second cervical ganglion project primarily to the ipsilateral subpeduncular corner of the granular cell domain and lamina surrounding the antero VCN, as well as a few terminal endings in the deep DCN.[40,49] Furthermore, secondary somatosensory inputs that project to the cochlear nuclei are located in the spinal trigeminal nucleus in the brainstem as well as the ascending dorsal column pathway (through nucleus cuneatus and nucleus gracilis).[40,45,50] Given this relationship between the auditory pathway and the somatosensory system, we review the surgical options for controlling tinnitus. Attention is given to the various stages of disruption in the auditory system.

SURGICAL TREATMENT OPTIONS

Currently, there exists a wide variety of surgical treatment modalities aimed at resolving the phantom auditory sensations that underlie tinnitus[4-6,8,9,13,14,17,31,38,43,48] [Figure 1]. Attempts to resolve tinnitus have been made at various levels of the auditory system, with varying degrees of success.

COCHLEAR IMPLANTS

It is accepted that the onset of subjective tinnitus is preceded by damage to peripheral auditory systems (e.g., cochlear hair cells), which in turn sets the stage for neuronal hyperactivity and cortical replasticity.[16,22,23,24,29,34] Thus, cochlear implantation remains an important surgical treatment method for controlling tinnitus caused by sensorineural hearing loss. Cochlear implants are indicated in patients who have disruptive sensorineural hearing loss with concurrent tinnitus whose frequency is near the frequency range of the hearing loss; with this, cochlear implants have been shown to have an overall average success rate of greater than 90% cumulatively for patients with all levels of tinnitus,[2,4,5,32,43] with complete tinnitus suppression ranging from 37% to 61% of patients.[4,5,32,43] Additionally, greater suppressive relief has been observed for patients with more severe tinnitus handicaps.[4,32,43] Tinnitus reduction using a cochlear implant is primarily achieved by a masking effect when the cochlear device is implanted and turned on.[5,34] A secondary positive effect may be due to the reorganization of the central auditory system induced by the restoration of peripheral sensory auditory input.[28,29,34] To function optimally, the cochlear implant noise must be set, so that the center frequency matches or nearly matches the patient's tinnitus frequency range. This appears to be at the same range as the frequency range of hearing loss of the patient.[34] Though the suppressive and reductive effects of cochlear implants on tinnitus are clinically significant, with full tinnitus suppression on the order of 37% to 61% of all patients, it is important to note that potential tinnitus development after cochlear implantation is a risk that has been observed and documented, with approximately 5% to 12% of patients reporting a new tinnitus postoperatively.[3,4,32,33] Moreover, as mentioned earlier, cochlear implants are indicated only for patients with sensorineural hearing loss, leaving a large population of tinnitus patients who have preserved hearing without this treatment option.

STEREOTACTIC RADIOSURGERY

Tinnitus is a common symptom in patients with vestibular schwannomas, with an average incidence rate of 63% in symptomatic tumors.[27] Moreover, greater incidence rates of tinnitus have been observed for smaller tumors (e.g., an inverse correlation between tinnitus incidence and tumor extension).[27] Treatment modalities for vestibular schwannomas include conservative management with serial magnetic resonance (MR) imaging, microsurgery, and/or stereotactic radiosurgery (SRS)/radiotherapy.[44] The deterioration of hearing following the use of SRS as a treatment modality for vestibular schwannomas has been well documented and known.[26,35,46,47] At the level of the cochlea, current studies indicate a directly inverse correlation between cochlear radiation dose volumes and hearing preservation.[7,25,42,47] The improvement of tinnitus after stereotactic radiation, whether with single or multiple fractions, has been largely unpredictable; however, some patients have improved after treatment.[35] In addition, irradiation of the VCN yielding VCN toxicity leads to preferential loss of low hearing frequencies, while irradiative cochlear damage leads to preferential loss of high hearing frequencies.[26] Thus, the effects of irradiative damage as a side result of SRS can lead a loss of peripheral auditory systems, resulting in a deafferentation state within the auditory pathway, and thus lead to subjective tinnitus.[16,22,23,34]

COCHLEAR AND VESTIBULOCOCHLEAR NERVE ABLATION

As previously alluded to, DCN hyperactivity is one of the hallmarks in the pathophysiology of subjective tinnitus.[23,34] More importantly, DCN hyperactivity remains even after ipsilateral cochlear ablation,[2,48] implying that the neuronal hyperexcitability and spontaneous firing underlying tinnitus originates centrally. Additionally, surgical ablation of the vestibulocochlear nerve has been hypothesized as a potential treatment for tinnitus, under the premise that auditory efferent input dysfunction may be an underlying cause of the phantom perceptions. However, surgical ablation of the auditory nerve has not been shown to significantly improve or worsen tinnitus.[6]

Furthermore, ablation of the DCN (under the premise that ablation will reduce neuronal hyperactivity) does not improve tinnitus and may even aggravate it.[8] Though there are documented cases of surgical ablation of the vestibulocochlear nerve resulting in the relief of tinnitus,[20,21] the relief of tinnitus was only due to a secondary relief of symptoms related to a primary pathology; the primary reason for vestibulocochlear neurectomy in the documented cases was for the surgical treatment of an underlying pathology which presented with tinnitus as an associated symptom, such as a vestibular schwannoma[20] or Ménière's disease and chronic labrynthitis.[21] Therefore, the relief of tinnitus was not primarily attributable to the sectioning of the auditory nerve but more so from the cure of the primary pathology. Thus, surgical treatment modalities targeting destruction of the cochlea, vestibulocochlear nerve, or the DCN for tinnitus relief may prove ineffective.

MICROVASCULAR DECOMPRESSION

Microvascular compression of the vestibulocochlear nerve in the cerebellopontine angle has also been shown to be an underlying cause of tinnitus.[13,14,17] Patients with unilateral tinnitus and an abnormal Auditory Brainstem Response (ABR) were found using MR imaging to have neurovascular conflicts between the vestibulocochlear nerve and the vertebral artery loop, posterior inferior cerebellar artery loop, and/or anterior inferior cerebellar artery loop.[12-14,17] Seemingly, the vascular pathology involving vestibulocochlear nerve compression leading to tinnitus is similar to the microvascular compressions of the trigeminal nerve entry zone resulting in trigeminal neuralgia and hemifacial spasm.[12,14,19,30] Surgical decompression of the auditory nerve from the insulting vessels significantly reduced tinnitus and normalized patients' ABR; decompression success rates averaging between 51% and 66% were observed postoperatively, with long-term success rates averaging approximately 52%.[12,14,17,31] Complication rates averaging 26% were also observed, with the majority of complications being cerebrospinal fluid leaks requiring backup surgery to seal the breached mastoid air cells.[17,31] Furthermore, an inverse correlation has been observed between the success rates of microvascular decompression on tinnitus and the average duration of patients' tinnitus in years: patients who had tinnitus averaging longer than 4 years were less likely to find relief of tinnitus symptoms after decompression than patients who had tinnitus for an average of less than 4 years.[12,14,17,31] Thus, microvascular decompression of the vestibulocochlear nerve within the cerebellopontine angle could be a potential treatment option for patients whose tinnitus is associated with neurovascular conflicts confirmed by high-resolution magnetic resonance imaging.

DEEP BRAIN AND EXTRADURAL STIMULATION

In recent studies, patients with movement disorders and concomitant tinnitus who underwent Deep Brain Stimulation (DBS) reported a reduction in tinnitus loudness (amplitude) when stimulation was initiated.[9,36] In patients with Parkinson's disease or essential tremors who had concomitant tinnitus, relief was observed with DBS of the subthalamic nucleus or ventral intermediate nucleus (VIN) of the thalamus.[9,36] The DBS, which was primarily intended for treating the movement disorder, was found to suppress the tinnitus as well. Specifically, tinnitus suppression was observed through DBS of a locus of caudate neurons (area LC) in the body of the caudate nucleus.[9] The DBS lead traversed through or was adjacent to area LC in six Parkinson's disease and essential tremor subjects with concomitant tinnitus who underwent implantation of the subthalamic or VIN; in the five patients whose DBS lead tips traversed through area LC, tinnitus loudness was modulated and suppressed bilaterally.[9] In the single patient whose DBS lead tip was outside area LC, tinnitus was not reduced.[9] No stimulation-induced changes in hearing or hearing threshold were observed.[9,36]

Additionally, extradural electrical stimulation of the auditory cortices with implanted electrodes in the primary and/or overlying the secondary auditory cortices has been shown to be successful in suppressing severe refractory tinnitus.[11,15] It is also important to note that extradural stimulation, with electrodes implanted superficial to the dura mater, stimulates the trigeminal nerve as well because of somatic sensory innervation of the cranial dura mater by the trigeminal nerve.

These results suggest that DBS as well as extradural electrical stimulation of the auditory cortices can modulate tinnitus with reductive or suppressive effects, warranting further investigation as a potential surgical treatment option for patients suffering from severe tinnitus.

SOMATOSENSORY NEUROMODULATION OF THE TRIGEMINAL NERVE

Electrical stimulation of the trigeminal nerve produces neuronal excitation in the VCN, and evokes a complex mixture of excitation and inhibition in the DCN.[10,37,38] In addition, electrical stimulation of the dorsal column and the second cervical dorsal root ganglion modulates the rate and timing of neuronal responses to acoustic stimulation by evoking a short- and long-term neuronal inhibition, separated by a transient excitatory peak in the DCN.[10,37] Furthermore, the crosstalk between somatosensory inputs and the cochlear nuclei is heightened after noise-induced

hearing loss.[39] Thus, trigeminal input to the auditory system at the level of the cochlear nuclei [Figure 2] may modify the response characteristics of cochlear nuclei neurons (i.e., neuronal firing rate).[37,38,40] This modulation of the auditory pathway by the somatosensory system may have important effects on the deafferentation state of these nuclei.[24,37,38] With this in mind, potential treatment modalities for reducing or eliminating subjective tinnitus could include neuromodulation of the trigeminal nerve through electrical stimulation[10,37] by either percutaneously stimulating the ophthalmic (V1) division of the trigeminal nerve as it exits the supraorbital foramen or the mandibular (V3) division through auriculotemporal or mental nerves, as well as directly approaching the trigeminal ganglion. Neuromodulation of the trigeminal nerve using ionizing radiation can also be achieved through SRS methods,[18,19] thus also warranting further investigation.

CONCLUSION

Tinnitus remains to be a difficult disorder to treat despite the many surgical interventions aimed at eliminating aberrant neuronal activity in the auditory system. Tinnitus caused by underlying pathologies such as vestibular schwannomas or neurovascular conflicts of the vestibulocochlear nerve at the level of the brainstem may be treated successfully through SRS methods and microvascular decompressions, respectively. Care must be taken to prevent hearing loss and subsequent refractory tinnitus as a result of damage to the cochlea and inner ear structures, explaining the mixed results of stereotactic radiation on tinnitus when treating acoustic neuromas.

For tinnitus whose pathophysiological etiology is preceded by noise-induced, drug-induced, or other forms of damage to peripheral auditory structures, surgical control remains more elusive. At present, the most accepted treatment modality for tinnitus is cochlear implants, which mask the patient's tinnitus, though on rare occasions, cochlear implantation itself may run the adverse risk of postoperative or secondary tinnitus development. Attempts to resolve tinnitus through surgical ablation of the cochlea, vestibulocochlear nerve, or DCN have been ineffective with potential worsening of tinnitus symptoms, likely due to further increased deafferentation-induced neuronal hyperactivity in central auditory pathways. Emerging research shows the ability to modulate neuronal output at various nuclei in the central auditory pathway through somatosensory stimulation at the level of the trigeminal nerve. This promising and noninvasive neuromodulatory approach using the trigeminal system to control such a bothersome and difficult-to-treat disorder deserves further investigation and controlled clinical trials.

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