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Tinnitus Devices

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Introduction

Tinnitus is the perception of a sound in the absence of external stimulation. The tinnitus is as real to the individual as that induced by external sound. Exposure to noise, ototoxic drugs or even aging is commonly associated with the development of tinnitus. Clinically, tinnitus is characterized as either subjective or objective. Objective tinnitus, detectable by stethoscopic examination is generally due to peripheral vascular abnormalities and will not be the topic of this entry. The majority of tinnitus is subjective, that is it non pulsatile (varying with the heart beating) and not audible by others. Approximately seventy five percent of those affected by subjective tinnitus adapt, but for the remaining twenty five percent, tinnitus can be severe and debilitating to the point of suicide.

Masking is the auditory phenomena in which a sound becomes imperceptible in the presence of another sound. The closer the masker is in frequency to the tone to be masked, less masker energy is required. Low frequency tones can mask high frequencies, if there is sufficient masker energy. This effect is termed “upward spread of masking” and is important in hearing aid processing algorithms. Conceptually, wearable devices could be developed that would eliminate the perception of tinnitus.

Tinnitus is characterized by subjective pitch and loudness; both parameters can be assessed by matching tinnitus to an external tone. Although the process is tedious, reliable data can be obtained. The majority of tinnitus patients pitch match their tinnitus to frequencies above 6 kHz. Most, but not all, have mild to moderate high frequency hearing loss (1). In the acute stage tinnitus is usually associated with an insult to the ear in the form of noise trauma or ototoxic drug exposure. There is generally an association of the hearing loss frequencies and the frequencies matched to tinnitus pitch (2), which is usually tonal in quality but can also be matched to narrow band noise. Tinnitus is typically matched in loudness to an intensity of an external tone of about 10 dB; however tinnitus annoyance may be very high. In designing a device to treat tinnitus sound its associated annoyance must be addressed. Since there is no tinnitus cure one standard form of treatment is the use of tinnitus maskers that produce a broad band of continuous external noise that masks or partially “covers” the tinnitus, but which ear to fit?

Tinnitus can be perceived as being lateralized to one ear or more often perceived binaurally. What is astonishing about the perception of tinnitus in one or both ears is that the ear is rarely the tinnitus source (3). Tinnitus arises not in the ear but in the brain. Imaging studies have conclusively demonstrated an auditory cortical activation (4). In the case of lateralized tinnitus the ear opposite the involved cortex appears to be the site of tinnitus given the illusion of the ear as the site of tinnitus. Thus the lateralized tinnitus perception suggests peripheral involvement as is it “sounds like” the tinnitus is in one ear. If the ear was the site of tinnitus, a masker should provide relief by masking according to conventional auditory theory. Since multiple neural sites are involved in generating and processing tinnitus (4,5), the masking picture is far more complicated.

The vast majority of potential tinnitus device users have long term or chronic tinnitus which can also be associated with clinical depression. There may be no direct cause effect relationship between tinnitus and depression, but rather some common biofactors may predispose an individual to both conditions. Medical treatment strategies have been multifaceted, addressing the treatment of depression and tinnitus with pharmaceuticals, maskers and behavioral therapy. The question arises as to what treatment outcomes should be selected to measured effectiveness of tinnitus devices. Two obvious measures are device purchases and device returns.

Approximate 1 of 6 patients evaluating maskers actually purchase and the return rate is about 50%, hardly a ring endorsement for the technology (6). Conventional tinnitus maskers address the initial symptom, but appear not to address the core complaint of tinnitus patients, the annoyance. The irritation, aggravation and frustration associated with the tinnitus must be addressed in neural tinnitus prosthesis design. More than masking is needed.

History of masking

The application of acoustic masking to tinnitus is attributed to the pioneering work of Vernon (7) and his colleagues at Oregon Health Sciences University in the mid 1970s. Vernon readily acknowledges Jean-Marie Gaspar Itard was the first to apply the concept of acoustic masking to tinnitus around 1825. Itard suggested sitting by a green wood fire, with its hissing and popping would mask high frequency tinnitus whereas, seasoned wood would produce a roar for masking lower pitched tinnitus. Furthermore, Itard recognized that the sound of falling water was a very effective masker. Thus the principle of frequency specific masking for tinnitus was known for a century and a half before the availability of wearable technology.

Vernon (7) was also aware of the use of hearing aids to mask or suppress tinnitus in some patients and hearing aids could be potentially fitted with masking circuits, thus functioning as both hearing aids and maskers. The first wearable tinnitus devices resembled behind the ear hearing aids and were manufactured by Zenith. The hearing aid microphone was removed and replaced with a broad band noise circuit. Early models produced a steady broadband sound, while the output of later models was matched to the tinnitus frequency and some even employed phase cancellation techniques. This entry

will detail the evolution of such devices from simple maskers to instruments essential in comprehensive tinnitus management.

Conventional masking refers to the phenomena of the perceptual elimination of one sound in the presence of a second tone. Typically the masker and the sound to be masked must be similar in frequency content to keep the power requirements low. This was very important during the initial phase of device development in the 1970s since battery life was far more limited than today. Frequency matching of masker and maskee is based on efficiency in inner stimulation. The inner ear is effectively divided into critical bands of filters. If the masker and maskee fall within the same band, masking is accomplished with very little energy. The filtering capability of the basilar membrane of the inner ear is maximized when an externally applied tone falls within the same critical band associated with the tinnitus sound. If masking frequencies are systematically varied from low to high, the resulting values of masking is what is termed a psychophysical tuning curve, which is similar to what would be expected from an eighth nerve afferent fiber associated with that critical band (8,9,10).

Unfortunately, masking of tinnitus appears to be quite different from conventional psychophysical masking. Investigators (11,12), using maskers of varying bandwidths, have shown that tinnitus is not masked like a tone in many subjects. Instead, a wide range of frequencies typically provides roughly equivalent masking. These wide tuning curves suggest that tinnitus is not processed as if it were a pure tone. Somehow the tinnitus and masker interact in the central nervous system. This is the first evidence that suggested tinnitus masking may have a central origin and possibly tinnitus itself was generated centrally. This conclusion is reinforced by the phenomenon of contralateral masking; in some patients, masking noise presented to the contralateral ear is as effective as noise presented to the ipsilateral ear, so the interaction of tinnitus and masking noise must be at some point in the auditory pathway where there is binaural interaction (9). Evidence was mounting that tinnitus masking involves the nervous system and therefore a device that provides central masking was needed.

The observation that the frequency spectra of the masker is not always important in providing masking in some cases is compounded further by the observation tinnitus can be masked by noise not containing any of the tinnitus frequencies. Kitajima et al. (13) found that when a narrow band of noise around the tinnitus frequency had been removed (notched noise), masking was as effective as a very narrow band of noise covering the tinnitus frequency. This suggests that tinnitus could be masked by sounds higher or lower than the tinnitus frequency. .

Determining which ear to fit with the masker, given the ambiguity of the effects of central masking, i.e. contralateral masking being effective as ipsilateral masking, can be solved using bone conduction. Bone conduction involves placing the transducer on the skull, which efficiently oscillates the inner ear fluids. Bone conduction is a means to deliver broadband sound as part of a masking and habituation tinnitus therapy treatment (14). Bone conduction stimulates both ears since there is little attenuation across the head in the audiometric frequencies (15) Johnson and Hughes (16) showed that

correlated noise presented simultaneously to the two ears may be more effective at tinnitus suppression than two separate maskers in the ears due to the central neurological processes underlying tinnitus.

Masker fitting is complex in regard to tinnitus; nonetheless, masking is recognized as an effective therapy (17). Masker effectiveness is often based on continuation of masking after the masker is removed, a perception of quiet termed residual inhibition (RI). RI is frequently evoked but is variable in duration ranging from seconds to weeks (18,19). A report that only 15 minutes of masking resulted in RI for the entire day encourages masker use. Clearly the RI is a neural phenomenon (20). The dependence of RI on masker characteristics such as center frequency, bandwidth, intensity, duration and stimulating parameters are still not well understood nor are the mechanism for the wide variability in RI for individuals. Thus there is considerable experimentation in both the selection of the type of masking sound and the delivery method employed in an attempt to maximize RI. Four types of maskers that have been shown to have importance in modern tinnitus treatment are electrical stimulation, acoustic masking, vibration masking and high frequency/ultrasonic masking.

Transdermal electrical stimulation.

Tinnitus is present in many severely hearing impaired and totally deaf patients (21) with the incidence as high as 87% (22). Since many severely hearing impaired people seek hearing improvement using a cochlear implant, which stimulates the nerve fibers in the absence of sensory cells, a logical measurable outcome of implantation procedure is the assessment of electrical stimulation on tinnitus. In some cases pre operative electrical stimulation is applied to the cochlear wall to determine if the nerve fiber population can be activated by the implant. The electrical stimulation of the cochlear wall is in the region of high frequency coding since it is the most accessible, i.e. nearest to the middle ear. Electrical stimulation of the cochlear wall can suppress tinnitus in 69% of the deaf patients. Cochlear implantation is not as effective, completely suppressing tinnitus in 35% and partially suppressing it in 42%. Residual inhibition for several hours after deactivation of the implant is possible (22). These findings suggest that activation of the nerve, including the high frequency fibers suppresses tinnitus and provides RI.

Years before the availability of cochlear implants, a form of transdermal electrical stimulation was explored to treat tinnitus. Transdermal electrical stimulation is applied by electrodes placed on the preauricular and postauricular regions and on the two mastoids (see Fig 1). Electrical stimulation consisted of slowly varying tones between 0.2 and 20 kHz multiplied by a 60 kHz carrier (full amplitude modulation). This approach literally passed the audio-frequencies "under the skin" via external electrodes placed on both mastoids. Electrical stimulation in this mode provided 60% positive success in suppressing tinnitus (23). An additional study (24) revealed that in 50 patients tested, 14 (28%) obtained relief that met the criterion of a reduction in the tinnitus by 40% or more with RI usually extended for several hours. Further there was only one positive response in the placebo trial; nonetheless the authors concluded electrical transcutaneous stimulation was not practical. More powerful randomized, double-blind crossover study

resulted in a reduction in tinnitus severity in only two of 20 patients with the active device and four of 20 patients with the placebo device (25). A large series of 500 patients treated with electrical stimulation twice weekly for a total of six to ten visits (26) revealed 53% reported a significant benefit, defined as an improvement of at least two points on a 10-point scale of tinnitus intensity. Despite some positive and some ambiguous results the transdermal electrical stimulation device was withdrawn from the market. This was unfortunately premature, since electrical stimulation in the form of FDA approved cochlear implants would provide the physiological rationale for transdermal tinnitus treatment. The transdermal stimulation provided additional design value in regard to demonstrating that high frequency stimulation is possible without distortion associated with air conduction hearing. While not specifically recognized at the time, high frequency stimulation is an essential element in modern masking and treatment of high frequency tinnitus.

Acoustic Masker Designs

Masking a low level high pitch tinnitus percept at first does not seem to be a formable task. If, for example, tinnitus is matched to an 8 kHz tone, delivering a tone or narrow band of noise to the cochlea at 10 dB above threshold should accomplish the predictable masking. Assuming that the tinnitus patient prefers the masking to the presence of tinnitus, providing a tinnitus masker should be the obvious, simple solution. Surprisingly, about one third of the tinnitus patients report no masking even if the masker is at very high intensities. One third report masking with frequencies much different in frequency from their pitch match and only one third respond as predicted from classical auditory masking theory. It appears that tinnitus masking involves other processes, different from classical masking, which likely involving different pathways in the brain.

The first approach in developing an acoustic masker was to select a form of stimulation that would be effective in the majority of cases and the logical candidate was broadband noise. The concept of masking an internally generated sound with an external sound didn't occur to researchers in the field until the 1970s. Dr. Jack Vernon, the pioneer in tinnitus masking, (17) relates his experience with a physician suffering tinnitus who, when standing in one location near a water fountain, declared his tinnitus has disappeared. The sound of water falling was replicated in the laboratory and the synthetic water falls was found to be effective as a masker of tinnitus. The challenge was to incorporate that masking sound into a wearable device.

The faucet test, as it were, (I can't hear you while the water is running) is an excellent means of getting a preliminary assessment on the maskability of tinnitus. Water generated noise is an outstanding source of almost flat and full spectrum (Fig 2). Synthetic water noise, essentially white, was the first masking stimulus incorporated into wearable and desk version maskers and it is still used today.

The logical candidate of a personal wearable masker was a modified hearing aid. A prototype wearable noise generator was evaluated in by Vernon's group in 1974. Although the circuit was capable of wide frequency response, the high frequency output

was limited by the driver characteristics (<3 kHz) of the hearing aid. In the digital realm, a white noise chip will provide full high frequency content, but the miniature speaker limits high frequency fidelity. Most maskers are limited to about 6 kHz of effective output, which is not surprising in that the middle ear resonance is about 3 kHz and its high frequency rolls off at about 26 dB/octave (see Lenhardt this volume). Additionally most tinnitus sufferers have high frequency hearing loss placing increased intensity demands on high frequency maskers, which can result in distortion and possible device rejection. The goal of wearable synthetic water falls proved difficult to obtain with conventional hearing aid technology.

FM Masking

There are alternative choices to wearable maskers; desktop maskers and pillow maskers are available which generally provide a broad range of acoustic masking but are also limited in the high frequencies by their transducer response. A mistuned FM radio can provide white noise amplified through high fidelity speaker system. While the mistuned radio advice has been often offered to tinnitus sufferers, its general utility and long term acceptance is low. There persists the occasional report of a tinnitus sufferer only able to fall asleep sitting in front of a full volume television producing white noise after station sign off.

Personal Stereos

Vernon readily appreciated that wearable maskers of the mid 1970 vintage had intrinsically limited high frequency response, acknowledging patients report their tinnitus matches to frequencies above 6 kHz. Vernon recorded higher frequencies on cassette tape, creating a type of desk based masker for home use. The high frequency response of most cassette players was usually about 16 kHz, but again the limiting element was the response of personal earphones, even some rated to 20 kHz. The high frequency response of the stereo earphones varies by construction. An example of a relatively inexpensive set vs. "high fidelity" earphones is depicted in Fig 3. The high fidelity earphones (right panel) can extend the frequency response to a degree. Even with exact reproduction, wavelengths above 14 kHz and canal dimensions interact, depending on individual geometry, resulting in cancellation of some high frequencies.

With the advent of relatively inexpensive compact disks (CD) and players, high frequency masking could be achieved by a "maskman". Digital sampling rates of 44.2 kHz are commonly used in CD recording which extends the frequency range to about 20 kHz (anti-aliasing filters limit the upper frequencies). Nonetheless, the concept of a wearable "maskman" never achieved popularity in spite of much cheaper alternative to tinnitus maskers (27). Perhaps wearable maskers and stereos were providing more high frequency output, but full high frequency fidelity is not obtainable. The need for full treble in tinnitus treatment has only been demonstrated in the past few years. It is the lack of high frequencies delivered to the ear that may determine the success of tinnitus masking; however some other central factor must be involved in tinnitus persistence (28). For these reasons, alternative vibration based maskers were developed.

Vibration maskers

There is one report (29) in the literature of 60% success in tinnitus relief using low frequency vibration as form of acoustic masking in a small sample of patients . The approach was exploited by De Mino who developed a vibrating rod that is applied to the skin behind the ear (mastoid area). The stimuli consisted of a 60 Hz fundamental with adjustable harmonics up to 1000 Hz. The device (Aurex3) provides air conducted, bone conducted and tactile stimulation and received FDA approval [510(K)] for tinnitus masking. The device was not well accepted, possibly due to cosmetic reasons. It was assumed that the acoustic energy delivered by bone conduction was the principle feature related to successful masking; however the key effect may not have been auditory at all.

The somatosensory system has been shown to have inputs into the auditory system as low as the first synapse in the dorsal cochlear nucleus. Stimulation of the muscle body behind the ear (post auricular muscle) results in inhibition in the dorsal cochlear nucleus (30). The tinnitus inhibition effect was not due to air conducted hearing as removing the transducer from the muscle eliminates the effect. Light touch is also ineffective, suggesting that touch or refocusing attention was not the responsible mechanism. Thus it appears that the Aurex3, may be effective when the vibrating rod stimulates the post auricle muscle and not the ear directly. The salient point is that if tinnitus can be modified by a sensory system different from audition, clearly complete masking may require multisensory stimulation, as sound and muscle vibration (31). Tinnitus inhibition via the somatosensory system provides fast immediate relief, but there is no RI, In contrast very high frequency vibration has no tactile component and can provide long term tinnitus relief. High success in masking tinnitus and producing RI was reported with low frequency ultrasound (20-40 kHz) delivered through bone conduction (32). Lenhardt et al. (33) demonstrated that hearing through bone conduction can extend up to about 100 kHz.

High audio and ultrasonic bone vibration maskers

A new trend in tinnitus treatment is the use of very-high-frequency maskers, including ultrasound, delivered by bone conduction (18,32). Masking and long-term inhibition may involve inducing neuroplastic changes in the brain. The bone conduction application of either high audio frequencies (10–20 kHz) or ultrasound (20-100 kHz) provides binaural high frequency stimulation for high pitched tinnitus masking, a requirement recognized by Vernon decades ago.

The principle obstacle in delivering high frequencies to the head was the development of a suitable transducer. An aluminum ceramic (PZT) bimorph with a resonance frequency about 40 kHz in air was designed to stimulate the head from 5-45 kHz. There multiple transducer resonances, which are compounded with head resonances (22), making calibration a challenge. Nonetheless, the transducer is light, comfortable and has a relatively flat frequency response when mass loaded to the head (18).

Bone conduction calibration standards are not available for high audio and ultrasonic frequencies. Reference can be made to calibration procedures based in part on bone-anchored measurements for some frequencies (34), but ultrasonic bone conduction standards do not exist (35). The transducer can be placed on a water surface in a small tank assuming brain and water impedances are similar (36). This approach provides reliable results using a high frequency hydrophone, but provides no exact measurement of the energy acting in the ear in that the boundary condition of skin and bone are ignored in this approach. Alternatively acceleration can be measured and this proves to be the best method of calibration.

High-frequency accelerometers have impedances closer to bone than to brain. Using acceleration (m/sec^2), the hearing threshold for bone conduction can be referenced as -30 dB relative to $1 \text{ m}/\text{sec}^2$ from 0.25 to 6 kHz. This reference is applicable to higher frequencies, including ultrasound. A standard point of measurement is 1 gravity unit (g) rms, or $9.81 \text{ m}/\text{sec}^2$ (37). One g is also the U.S. Occupational Safety and Health Administration (OSHA) hearing protection reference for body-coupled ultrasound (38).

Tones or narrow bands of noise can be applied to the head as ultrasonic bone conduction tinnitus maskers. This would simply be a variation on acoustic maskers, but the delivery method would be bone conduction. However, if the masker is similar in pitch and intensity to the patient's tinnitus most would reject just substitution one annoying sound for a masker. If however, the sound stimulus has an attention focusing temporal quality, like music, rejection is rare.

Thus if music or similar sound is multiplied by a high frequency or ultrasonic carrier and the carrier and lower sideband is canceled, a high frequency patterned stimulation will result. Patterned auditory stimulation in the high audio range (10 - 20 kHz), using bone conduction has been shown to be an efficient means of high frequency tinnitus masking (18). It differs from the conventional masker in that little of the sound overlaps the range of reported tinnitus (Fig 4 right panel). In this technique amplitude modulated and processed music is presented through a bone conduction transducer at a low level, 12 dB sensation level (SL) that is 12 dB above threshold, for periods of 30 - 60 minutes (fig. 4 right panel). The goal is to induce changes in the central nervous system mechanisms of tinnitus, resulting in long-term inhibition.

In the case of high-frequency bone-conducted stimulation, not all patients with a similar profile experienced immediate masking; in fact immediate masking is generally a positive predictor of long-term relief. The overall percentage of tinnitus relief was 60 - 70% (18). If masker is shifted into the ultrasonic range, tinnitus relief is also reported (32). Ultrasound, as will be seen below, maps on to the high audio area of the inner ear, so both high audio and ultrasonic stimulation have similar sites of peripheral and central action.

How is Ultrasonic Hearing possible?

Reports that humans could hear ultrasound have appeared more than a dozen times over the last half century (33). Dr. Roger Maass detailed the phenomenology of ultrasonic hearing, perceptible only bodily (bone conduction) vibration, with pitch characterizing as like audiofrequencies in the 10-15 kHz range, with crude frequency discrimination. Maass further reported some deaf subjects could also hear ultrasound at high levels. These observations were confirmed, and speech discrimination in deaf subjects was verified using modulated ultrasound (33). The primary auditory cortex is active in ultrasonic hearing in normal hearing subjects, using magnoelectroencephalography, activating sites associated with very-high-frequency hearing (39). A lower frequency cortical site for ultrasound for the deaf was observed, the significance of which will be discussed later in regard to neural plasticity (40).

When ultrasonic energy is applied to the head, some form of demodulation occurs. The site of the demodulator could be any place in that only some form of half wave rectification induced by a non-linearity is required. However the pitch of ultrasound suggests the site must have a resonant frequency above 10 kHz. A potential candidate for the ultrasound demodulator is the brain itself. The calculated brain resonant frequency, assuming a homogenous fluid filled spherical model (41-42) using the formula:

$$F = c/2\pi r$$

where F is the fundamental frequency of the sound generated by the sphere, c is the velocity of sound in brain tissue (1460 m/sec) (41,42), and r is the sphere radius, and assuming a 7-cm head radius, is 13.4 kHz. Neglected in the model is the skull and skin, together act as a boundary condition. A higher resonant frequency (41) of $F = 15.6$ kHz would be predicted with the boundary condition. Since the brain is not truly spherical, the exact brain resonant frequency is probably a value between the free and boundary states. Individual brain resonant frequencies are likely to fall between 11 and 16 kHz, with the exact value being determined by skull geometry (15).

If the brain is set into vibration by ultrasound the sound produced by brain resonance will propagate to the ear via fluid channels. The most likely fluid channel is the cochlea adequate that allows direct fluid communication with the brain via the cerebral spinal fluid (43,44,45). If the brain, and not the skull is vibrated auditory nerve discharges verify the brain-ear mechanism. Transcranial ultrasonic Doppler imaging has added additional support to brain demodulation. Patients report hearing a high audio sound, much like tinnitus when the beam is focused in the center of the brain, but the sound disappears when the beam is focused on the ear (46).

The position (P) of maximal stimulation of each on the basilar membrane can be calculated using a formula devised by Fay (47):

$$P = \frac{\log_{10} [\text{fHz}/.008 \text{ fHz max}] + 1}{2.1}$$

where P is the proportion of base to apex on the basilar membrane, fHz is the frequency of interest, and fHz_{max} is the maximal audible frequency by air conduction in young adults.

Further, the position (P) on the basilar membrane is determined by:

$$P = 1 - P \times \text{cochlear length (31.5 mm)}$$

The positions on the basilar membrane for brain resonance would fall between 1.5 mm from the base of the cochlea for 16 kHz to 3.9 mm for 11 kHz. These data clearly support the hypothesis of physical demodulation of ultrasound by brain resonance and the detection of this resonance in the base of the cochlea. The spherical model data also supports the theory that ultrasound, regardless of its frequency, stimulates an area on the basilar membrane that codes the fundamental resonant frequency on the brain. Further ultrasound is a method to deliver high frequency tinnitus masking.

Applications of ultrasonic tinnitus maskers to the Deaf

With progressive high-frequency hearing loss, pitch perceptual range collapses. Ultrasonic thresholds also increase with the degree of high-frequency hearing loss (33). Presumably, the increased ultrasonic energy increases the displacement spread on the basilar membrane toward the apex, thus accounting for the observation that the ultrasonic pitch is related to the highest frequency detectable by air conduction. In the case of severe deafness, with ultrasonic thresholds approximately at 30 dB above normal, insufficient surviving hair cells exist in the apex to detect the basilar membrane motion. Lenhardt et al. (33) argued that the saccule may be stimulated in the case of severe deafness. Assuming that maximal displacement of the basilar membrane is at the place corresponding to the brain's fundamental frequency, bulk inner-ear fluid displacement, permitted by compliant oval and round windows at very high intensities (100 SL+), could conceivably create fluid flow in the saccule, not unlike the Tullio effect (48). The very short cilia of saccular hair cells, not mass-loaded by gel or otoconia (49) in the striola region, are likely fluid velocity-sensitive. Stimulating the saccule, an organ having input into the auditory pathways in mammals (50), may explain ultrasonic detection in the deaf. Treating tinnitus in severely deafened individuals with ultrasound has not been systematically studied, surprising in due to high incidence of tinnitus in this population (21) and the lack of alternatives to implant electrical stimulation. An ultrasonic tinnitus masker is commercially available.

Neural Plasticity and Cortical Remapping; the missing element in tinnitus device design

Traditional acoustic maskers have had been available for more than a quarter of a century, yet only masking, when it occurs, seems insufficient for long term tinnitus treatment.. Compelling central processing in tinnitus.

The conventional wisdom until very recently was the adult human brain is hard wired. Imaging studies have confirmed considerable cortical plasticity after sensory loss. That is to say the brain is dynamic and it adjusts for loss in the peripheral sense organs. In monkeys, (51) the tonotopic map (frequencies laid out spatially in the neuroaxis preserving the spatial coding in the ear) reorganized months after cochlear deafening. The deprived area of the cortex reorganized and became responsive only to intact area of the cochlea. What this means is the brain “hears” only those frequencies transduced by the ear. If stimulation ceases in a particular frequency region the neurons in the brain sensitive to the damaged peripheral region change their frequency response.

Tinnitus is usually associated with hearing loss and hence cortical reorganization. Muhlnickel et al. (52) explored the reorganization of the auditory cortex in tinnitus, using magnetoencephalography and found that there was a marked shift of the cortical representation of the tinnitus frequency into an area adjacent to the expected tonotopic location. There was also a strong positive correlation between the strength of the tinnitus and the amount of cortical reorganization. Plastic changes in the auditory neural axis in severe tinnitus, particularly in the auditory cortex, may play a role in the continued perception of tinnitus by adding salience to the experience (54,55). In tinnitus patients the tinnitus frequency area expands to more than twice the size. Aberrant tinnitus neural reprogramming can be possibly reversed by increasing high-frequency stimulation (i.e., with frequencies above the tinnitus frequency), for auditory learning in primates has been shown indeed to expand the frequency map (52,53), suggesting external stimulation can change the brain. High-frequency stimulation (high audio and ultrasound) have been shown to not only mask tinnitus but also produce varying degrees of residual inhibition (18,32). The spectra of these masking stimuli are depicted in Figure 5.

Tinnitus maskers have evolved from just broadband noise generators to brain stimulators essential in comprehensive tinnitus management. The next generation devices will be smart systems with the capacities for multisensory and multimodal stimulation, likely providing greater relief (RI) in a condition that will only increase in prevalence with an aging population.

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Figure 1. Headset with electrodes for transdermal electrical stimulation for tinnitus treatment is depicted. High frequencies were modulated on an ultrasonic carrier with the device (Theraband) capacitive coupled to the head during stimulation.

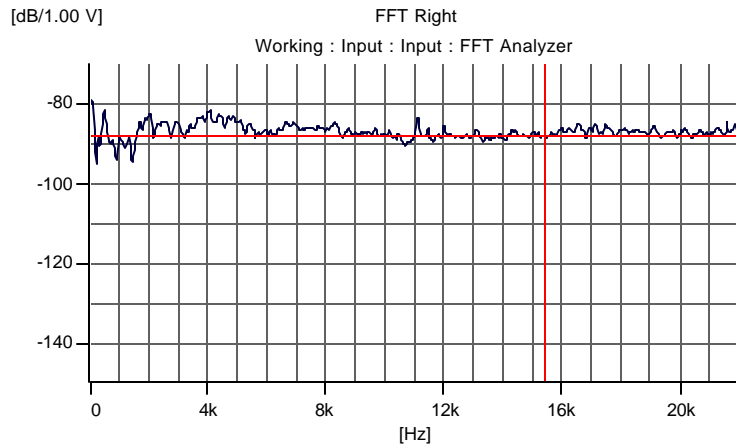


Figure 2. Spectrum of running water from a faucet is depicted. The value of -70 dBV corresponds to 80 dB SPL (C) at one meter. The flat spectrum extending into the ultrasonic frequencies is the reason this sound is effective in initial tinnitus masking.

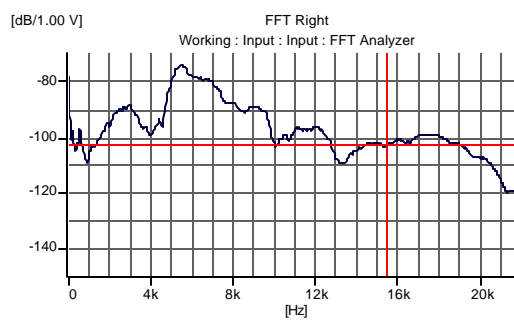
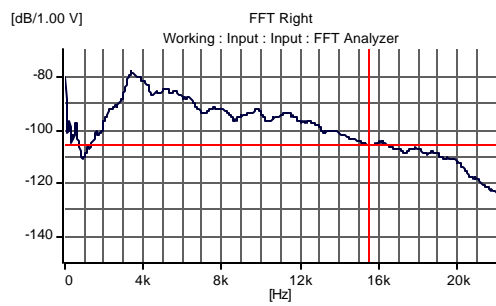


Figure 3. Frequency response of an inexpensive headset (right panel) and high fidelity earphones are shown. Overall response is similar in the low and mid frequencies and not that different at 16 kHz. Ear canal acoustics, middle ear mechanics and sensory hearing loss all contribute to inefficient high frequency audibility by air conduction.

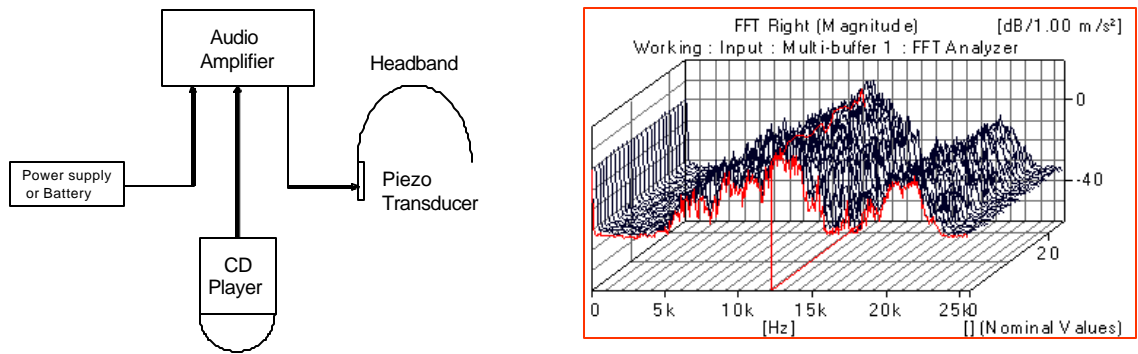


Figure 4. The high audiofrequency tinnitus device (UltraQuiet™) consists of a piezoceramic aluminum transducer, a compact high frequency amplifier and a playback system (left panel). The vibratory output of the device is depicted in the right panel. The suppressed carrier is at 16 kHz. Filtering limits the upper sideband energy to 20 kHz. Peak energy is in the region of brain resonance to utilize natural amplification.

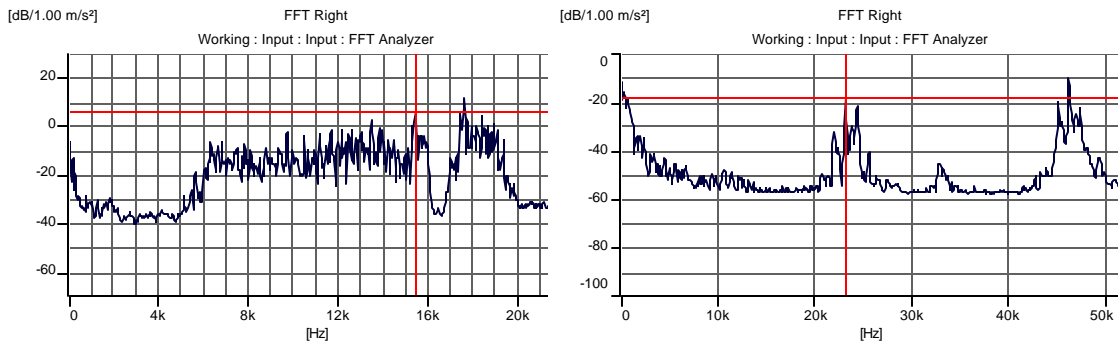


Figure 5. Pulsed pattern bone conduction stimulation is depicted with a high audiofrequency device (left panel) and an ultrasonic device (right panel). The high audio stimulation is double sideband whereas the ultrasound is full amplitude modulation. Calibration reference is vibration in acceleration re: 1 m/s^2

