Comparison of Custom Sounds for Achieving Tinnitus Relief

James A. Henry*†
Betsy Rheinsburg*
Tara Zaugg*

Abstract

Tinnitus masking has been a widely used method for treating clinically significant tinnitus. The method, referred to herein as "sound-based relief," typically uses wearable ear-level devices ("maskers") to effect palliative tinnitus relief. Although often effective, this approach is limited to the use of broadband noise with the maskers. We hypothesized that the effectiveness of treatment can be improved by expanding the auditory-stimulus options available to patients. A pilot study was conducted to determine for each of 21 subjects the most effective of custom sounds that are designed to promote tinnitus relief. While sitting in a sound booth, subjects listened to white noise and to custom sounds that are available commercially for providing tinnitus relief. Three sound formats ("E-Water," "E-Nature," and "E-Air") were provided by the Dynamic Tinnitus Mitigation (DTM-6a) system (Petroff Audio Technologies, Inc.). Additionally, seven sounds were provided by the Moses/Lang CD7 system (Oregon Hearing Research Center). Considering group data, all of the sounds provided a significant reduction in tinnitus annoyance relative to the annoyance of tinnitus alone. Two of the commercial sounds (DTM E-Nature and E-Water) were judged significantly more effective than the other sounds.

Key Words: Hearing disorders, perceptual masking, tinnitus

Abbreviations: 2-D = two-dimensional; 3-D = three-dimensional; DTM = Dynamic Tinnitus Mitigation; OHRC = Oregon Hearing Research Center; TRT = Tinnitus Retraining Therapy

Sumario

El enmascaramiento del acúfeno ha sido un método ampliamente utilizado para tratar un acúfeno clínicamente significativo. El método, que llamaremos aquí "alivio basado en el sonido", utiliza dispositivos para usar en el oído (enmascaradores) para lograr una mejoría paliativa en el acúfeno. Aunque a menudo efectivo, este enfoque es limitado al uso de ruidos de banda ancha en dichos enmascaradores. Planteamos la hipótesis de que la efectividad en el tratamiento puede mejorarse expandiendo las opciones de estímulo auditivo disponibles para los pacientes. Se condujo un estudio piloto en 21 sujetos, para determinar los sonidos adaptados más efectivos, entre aquellos utilizados para promover un alivio en el acúfeno. Los sujetos, sentados en una cabina sonoamortiguada, escucharon ruido blanco y sonidos comercialmente disponibles para obtener alivio del acúfeno. Se utilizaron tres formatos de sonido ("E-Agua", E-Naturaleza" e "E-aire") aportados por el sistema Mitigación Dinámica del Acúfeno (DTM-6a) (Petroff Audio Technologies, Inc.). Además, siete sonidos fueron aportados por el sistema Moses-Lang CD7 (Centro de Investigación Auditiva de Oregon). Considerando la información por grupo,

---

*VA RR&D National Center for Rehabilitative Auditory Research (NCRAR), Portland VA Medical Center, Portland, OR; †Department of Otolaryngology, Oregon Health & Science University, Portland, OR

James A. Henry, Ph.D., RR&D National Center for Rehabilitative Auditory Research, VA Medical Center (NCRAR), P.O. Box 1034, Portland, OR 97207; Phone: 503-220-8262, ext. 57466; Fax: 503-402-2955; E-mail: james.henry@med.va.gov

todos los sonidos contribuyeron con una reducción significativa en la molestia causada por el acúfeno. Se consideró que dos de los sonidos comerciales (DTM E-Naturaleza y E-Agua) fueron significativamente más efectivos que los otros sonidos.

Palabras Clave: Trastorno auditivo, enmascaramiento perceptual, acúfeno

Abreviaturas: 2-D = bi-dimensional; 3-D = tri-dimensional; DTM = Mitigación Dinámica del Acúfeno; OHRC = Centro de Investigación Auditiva de Oregon; TRT = terapia de re-entrenamiento en acúfeno

Externally generated sound to provide tinnitus masking has been used as a clinical technique since 1976 (Vernon, 1976). This approach uses wearable ear-level devices to provide masking sound to patients. These devices include noise generators (tinnitus maskers), hearing aids, and combination devices that incorporate both a noise generator and amplification (Vernon, 1992). Although hearing aids have been reported to provide masking relief for about 12% of tinnitus clinic patients, broadband noise is used for most patients (Vernon, 1988).

Some explanation is necessary regarding the clinical objective of masking treatment for tinnitus. The preponderance of papers by the founder of this method (J. Vernon) initially described the purpose of masking as providing palliative relief by making the tinnitus inaudible (Vernon, 1976, 1977). The tinnitus-replacing masking sound therefore had to be a sound that was more acceptable to listen to than the tinnitus. With the advent of combination devices, Vernon noted "masking that is incomplete can be nevertheless acceptable" (Vernon, 1982, p. 17). He later stated that these devices sometimes produced "only a partial reduction in the tinnitus: it is still perceivable but in a suppressed form" (Vernon, 1988, p. 101). In the latter paper, Vernon reported that when masking was recommended for patients, combination devices were recommended 67% of the time (and tinnitus maskers 21%). Thus, in the 1980s, the preferred treatment was the use of combination devices, and complete masking was not necessary when using those devices. Complete masking was, however, advocated when using tinnitus maskers alone. Vernon later discriminated between the two forms of masking by referring to them as "complete" and "partial" masking (Vernon et al, 1990).

The term "masking" refers to a particular form of treatment, which has undergone changes in definition as just described. Because of the potential confusion caused by the term "masking" as a form of treatment for tinnitus, we suggest use of the term "sound-based relief" when referring to the use of sound to provide an immediate sense of palliative relief, regardless of whether the tinnitus is rendered inaudible or remains perceptible. This term is consistent with the more current definition of "masking," which can include either partial or complete masking, and for which the intent is to promote a sense of relief.

Although sound-based relief has been used to treat tinnitus clinically for over 25 years, only broadband and shapeable bands of noise have been available as the acoustic stimuli delivered from ear-level prosthetic devices. Vernon and Meikle (2000) reported the frequency ranges of noise that is generated from these devices. Although spectral output varies according to the different instruments, maximum output tends to span about 2½ octaves and to occur within the frequency range between 1000 and 6000 Hz. Some devices have adjustable noise bands to enable spectral shaping.

Patients who are treated with sound-based relief are encouraged by some providers to use augmentative sound that is environment-specific. Augmentative sound can include detuning an FM radio to produce

broadband noise at bedside to assist in sleeping (Vernon, 1977, 1982; Vernon and Schleuning, 1978). Patients are also advised to listen to CDs that have been specially developed to provide tinnitus relief (Johnson, 1998; Vernon and Meikle, 2000).

In the attempt to improve on the degree of tinnitus relief provided by broadband noise, acoustically engineered sounds have been developed and are available commercially on CD. The Moses/Lang CD7, developed in 1993 at the Oregon Hearing Research Center (OHRC), contains noise bands covering seven different frequency ranges—allowing the user to select the most effective band (Johnson, 1998; Vernon and Meikle, 2000). The CD7 was developed under the supervision of J. Vernon, who was the Director of OHRC at the time. Petroff Audio Technologies, Inc. (Marina Del Rey, CA; petroffml@aol.com) produces a home-use "tinnitus masking system" called Dynamic Tinnitus Mitigation (DTM-6a). CDs containing DTM sound are FDA cleared and are endorsed by J. Vernon. Although these commercially available CDs are purchased for tinnitus relief, scientific studies have not yet been conducted to document their efficacy for this purpose.

The present study was designed as a preliminary investigation to determine the effectiveness of these different sounds that have been designed to achieve improved tinnitus relief relative to broadband or spectrally shaped noise. The study was performed in anticipation of performing a larger-scale study to examine many parameters of sound with regard to their effects on tinnitus relief.

METHOD

Operational Definitions

The concept of "tinnitus relief" has received varied definitions in the literature. For this study tinnitus relief is operationally defined as any reduction in the sense of annoyance that is associated with the conscious perception of the tinnitus sound. It should be noted that the concept of "tinnitus relief" is considered an immediate palliative effect that occurs only during the presentation of the masking sound. "Annoyance" is operationally defined as any negative emotional reaction such as anxiety, irritation, frustration, anger, or displeasure.

SUBJECTS

Twenty-one subjects were recruited from ongoing tinnitus studies that are being conducted at this facility. Inclusion in the present study required subjects to report tinnitus annoyance that was at least "moderately annoying" when attended to consciously. The Tinnitus Annoyance Scale (Table 1) was used by subjects to make this judgment. Each judgment had to be a "3" or greater. If subjects rated their tinnitus below that level they were not scheduled for annoyance testing. (This criterion was imposed to include only individuals who would be likely candidates for treatment with a sound-based relief approach.) Subjects included 19 males and 2 females with a mean age of 58.6 years (SD: 9.5; range: 45 to 80). All subjects except for two had mean hearing thresholds bilaterally within 25 dB HL through 2 kHz (Table 2). Subjects had various degrees of reduced hearing sensitivity from 3 to 8 kHz.

Instrumentation

All audiological test procedures were conducted in a double-walled sound-attenuated suite constructed by Acoustic Systems (Model RE-245S) and documented for effective noise reduction according to American National Standards Institute (ANSI, 1991) standards by the manufacturer in January 2002. A Pioneer DV-353 DVD player was used to deliver sound stimuli from

Table 1. Tinnitus Annoyance Scale

0	No annoyance
1	Just slightly annoying
2	Mildly annoying
3	Moderately annoying
4	Very annoying
5	Extremely annoying
6	Worst possible annoyance

Table 2. Mean Hearing Thresholds (dB HL) for the 21 Subjects

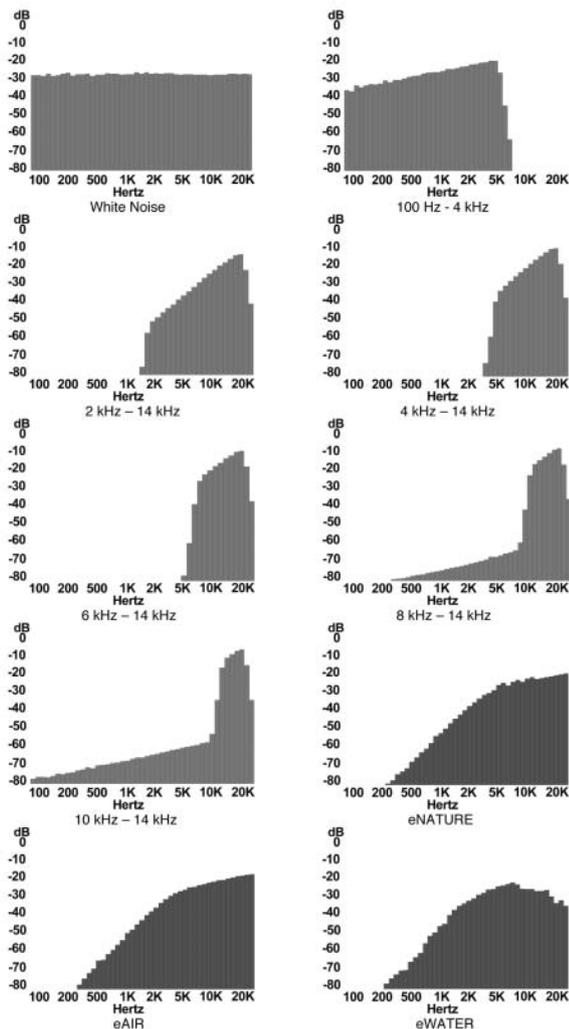| | Right Ear | | Left Ear | |
	0.25–2 kHz	3–6 kHz	0.25–2 kHz	3–6 kHz
Mean	16.2	45.7	15.4	47.6
SD	10.4	21.0	8.3	18.9

the CDs. Signals were routed and amplified through a GSI-61 clinical audiometer. Headphone transducers were Telephonics TDH-50P with MX 41/AR ear cushions. The audiometer was calibrated using ANSI (1996) standards.

Custom Stimuli Provided on CD

Commercial sound stimuli were selected on the basis of their design and use in providing sound-based relief from tinnitus

Figure 1. Two-dimensional (frequency and amplitude) audio spectrum analysis (electrical signal) of commercial sounds used for this study.

annoyance. The Moses/Lang CD7 contains seven tracks that each contain a different band of noise. The noise bands were designed by J. Vernon and were based on his clinical experience using filtered noise to successfully provide tinnitus relief. The wearable ear-level noise generators that were often dispensed to tinnitus patients had only limited noise-shaping ability. An alternative was to provide a variety of noise bands on CD so as to provide the patient with the ability to listen to these custom sounds through a different medium.

Petroff Audio Technologies, Inc. developed a new form of masking sound called Dynamic Tinnitus Mitigation (DTM). Unlike conventional tinnitus masking sounds (including the CD7) that are generally based on filtered white noise, DTM sounds are computer generated to characterize natural sounds, such as falling water, that patients often describe as bringing relief from their tinnitus. The DTM stimuli are based on six sound formats that are included in the commercial set of audio CDs referred to as the "DTM-6a home-use tinnitus mitigation system." The three most basic sound formats were used for the present study: E-Water, E-Air, and E-Nature. Two-dimensional (amplitude and frequency) spectrum analyses of the CD7 and DTM-6a tracks are shown in Figure 1. The 2-dimensional (2-D) graphs were obtained using TrueRTA software (True Audio, Andersonville, TN; www.trueaudio.com), and a Delta 66 24bit/96K soundcard (M-Audio, Arcadia, CA; www.midiman.net).

3-Dimensional versus 2-Dimensional Spectrum Analysis

Some of the DTM sounds use proprietary "dynamic" (changing) sound formats that are intended to enhance masking and distract hearing attention away from tinnitus. "Dynamic" acoustic technology refers to proprietary semirandom short-term amplitude and frequency domain modulation signal processing that is applied to most, but not all, of the CDs in the system. Two of the three
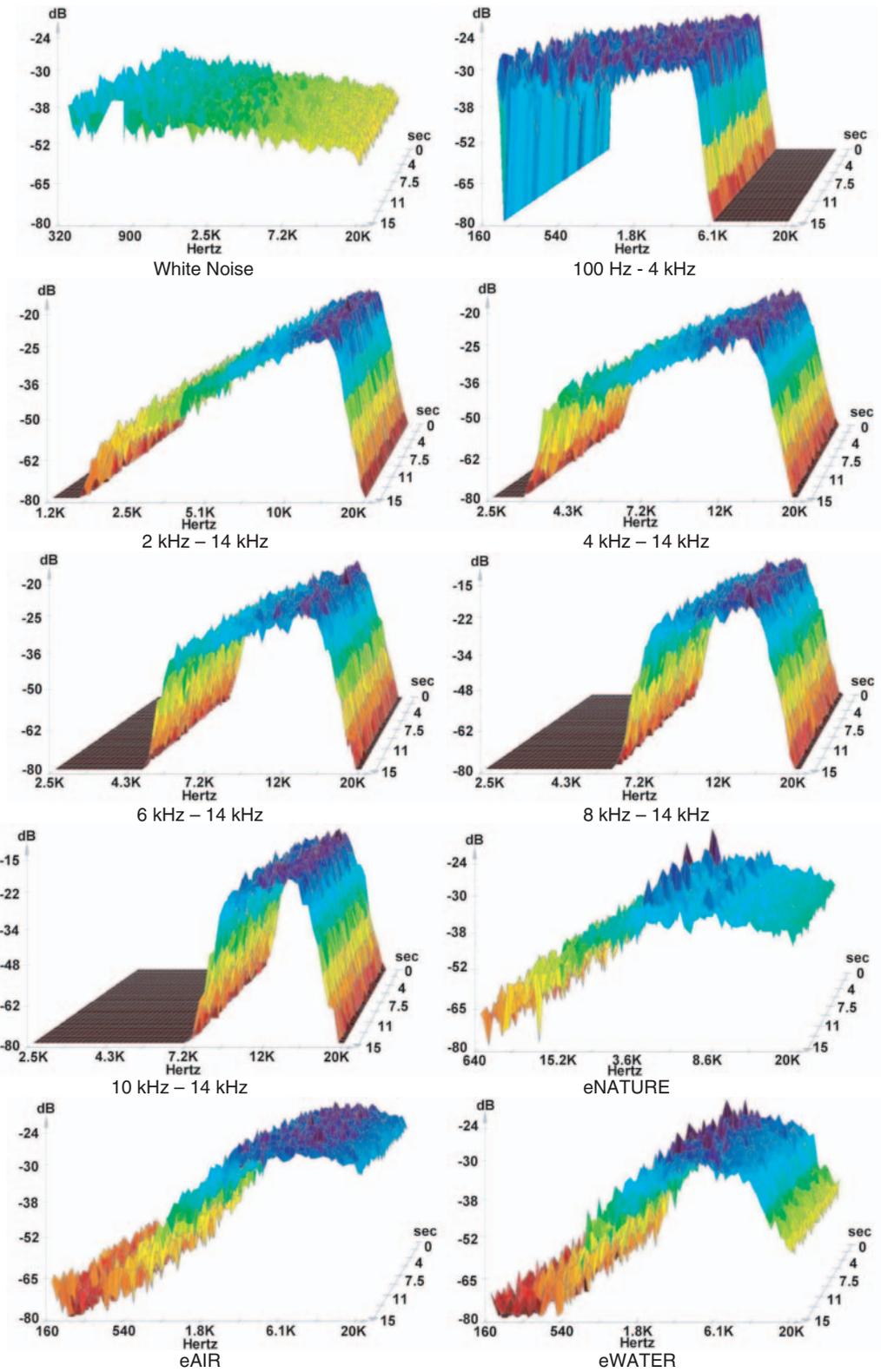
Figure 2. Three-dimensional (frequency, amplitude, and time) audio spectrum analysis (electrical signal) of commercial sounds used for this study. (Vertical scales are the same as those shown for the 2-D graphs in Fig. 1.)

DTM dynamic sounds tested in this study, E-Nature and E-Water, have been "dynamically" processed to provide expanded amplitude peaks on the order of 5 to 15 dB, over corresponding time durations on the order of 10 to 500 msec. Such time-related spectral data may be observed through amplitude/frequency/time 3-dimensional (3-D) spectrum analysis (Fig. 2). The 3-D graphs were created in the same manner that the 2-D graphs were created, except that the software used was Wavelab (Steinberg, Chatsworth, CA; www.steinberg.net).

The text below describes the two-dimensional (2-D; amplitude/frequency) and three-dimensional (3-D; amplitude/frequency/time) stimuli, as shown in Figures 1 and 2, respectively. In describing a 3-D spectrum analysis for a given sound, the "amplitude versus frequency," or 2-dimensional (2-D) spectrum analysis data, plus additional data referred to as "amplitude versus time," must be provided. The amplitude versus frequency characteristics are described for the entire frequency spectrum of each sound. To avoid unnecessary complexity, the amplitude versus time characteristics are described only for the dominant, relatively high amplitude portions of the frequency spectrum of each dynamic sound (E-Nature and E-Water). The remaining "nondynamic" sounds do not display unusual amplitude versus time characteristics beyond that expected for random noise sound formats. Three-dimensional spectrum analysis graphs of the dynamic sounds display sharp, protruding topological textures that correspond to the expanded amplitude peaks, while 3-D spectrum analysis graphs of the nondynamic sounds display substantially smoother topological textures that correspond to more conventional random noise sound formats (Fig. 2). The tracks are described as follows:

CD7 Track 1 (Pink Noise)

Amplitude vs. Frequency (2-D and 3-D analysis): A flat amplitude response with increasing frequency from 100 Hz to 20 kHz (commonly referred to as "pink noise").

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

CD7 Track 2 (100 Hz–4 kHz)

Amplitude vs. Frequency (2-D and 3-D

analysis): A linear 16 dB amplitude increase with increasing frequency over a first frequency range of 100 Hz to 4 kHz, and a steep progressive-slope 58 dB amplitude decrease with increasing frequency over a second frequency range of 4 to 6 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

CD7 Track 3 (2–14 kHz)

Amplitude vs. Frequency (2-D and 3-D analysis): A steep progressive-slope 28 dB amplitude increase with increasing frequency over a first frequency range of 1.8 to 2 kHz, a linear 36 dB amplitude increase with increasing frequency over a second frequency range of 2 to 16 kHz, and a steep progressive-slope 26 dB amplitude decrease with increasing frequency over a third frequency range of 16 to 20 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

CD7 Track 4 (4–14 kHz)

Amplitude vs. Frequency (2-D and 3-D analysis): A steep progressive-slope 37 dB amplitude increase with increasing frequency over a first frequency range of 2.8 to 4 kHz, a linear 22 dB amplitude increase with increasing frequency over a second frequency range of 4 to 16 kHz, and a steep progressive-slope 26 dB amplitude decrease with increasing frequency over a third frequency range of 16 to 20 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

CD7 Track 5 (6–14 kHz)

Amplitude vs. Frequency (2-D and 3-D analysis): A steep progressive-slope 50 dB amplitude increase with increasing frequency over a first frequency range of 4 to 5.8 kHz, a linear 16 dB amplitude increase with increasing frequency over a second frequency range of 5.8 to 16 kHz, and a steep progressive-slope 26 dB amplitude decrease with increasing frequency over a third frequency range of 16 to 20 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

CD7 Track 6 (8–14 kHz)

Amplitude vs. Frequency (2-D and 3-D analysis): A linear 16 dB amplitude increase with increasing frequency over a first frequency range of 280 Hz to 5 kHz, a steep progressive-slope 44 dB amplitude increase over a second frequency range of 5 to 8 kHz, a linear 8 dB amplitude increase with increasing frequency over a third frequency range of 8 to 16 kHz, and a steep progressive-slope 26 dB amplitude decrease with increasing frequency over a fourth frequency range of 16 kHz to 20 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

CD7 Track 7 (10–14 kHz)

Amplitude vs. Frequency (2-D and 3-D analysis): A linear 20 dB amplitude increase with increasing frequency over a first frequency range of 100 Hz to 6.5 kHz, a steep progressive-slope 44 dB amplitude increase over a second frequency range of 6.5 to 10 kHz, a linear 5 dB amplitude increase with increasing frequency over a third frequency range of 7 to 10 kHz, and a steep progressive-slope 26 dB amplitude decrease with increasing frequency over a fourth frequency range of 16 to 20 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

DTM-6a E-Nature

Amplitude vs. Frequency (2-D and 3-D analysis): A linear 50 dB amplitude increase with increasing frequency over a first frequency range of 250 Hz to 4 kHz, and a linear 10 dB amplitude increase with increasing frequency over a second frequency range of 4 to 20 kHz.

Amplitude vs. Time (3-D analysis): 100 to 1000 msec duration, 10 to 15 dB dynamically expanded amplitude peaks in the high amplitude level frequency range of 3 to 6 kHz. 10 to 50 msec duration, 5 to 10 dB dynamically

expanded amplitude peaks in the high amplitude level frequency range of 6 to 8 kHz.

DTM-6a E-Air

Amplitude vs. Frequency (2-D and 3-D analysis): A linear 50 dB amplitude increase with increasing frequency over a first frequency range of 250 Hz to 3 kHz, and a linear 10 dB amplitude increase with increasing frequency over a second frequency range of 3 to 20 kHz.

Amplitude vs. Time (3-D analysis): No unusual amplitude versus time characteristics beyond those expected for random noise sound formats.

DTM-6a E-Water

Amplitude vs. Frequency (2-D and 3-D analysis): A relatively linear 50 dB amplitude increase with increasing frequency over a first frequency range of 250 Hz to 3 kHz, a relatively linear 4 dB amplitude increase with increasing frequency over a second frequency range of 3 to 5 kHz, an irregular 4 dB amplitude decrease with increasing frequency over a third frequency range of 5 to 12 kHz, and an irregular 8 dB amplitude decrease with increasing frequency over a fourth frequency range of 12 to 20 kHz.

Amplitude vs. Time (3-D analysis): 25 to 250 msec duration, 5 to 10 dB dynamically expanded amplitude peaks in the high amplitude level frequency range of 2 to 6 kHz.

White Noise Provided from Audiometer

Although it has been reported that the frequency of the stimulus is not a reliable predictor of the tinnitus-suppression effect (e.g., Feldmann, 1971), many tinnitus patients have tinnitus that seems to be suppressed most effectively by band-pass noise in the frequency region that encompasses the tinnitus. The common stimulus used with an approach of sound-based relief is wide band noise, often modified by frequency shaping (Vernon and Meikle, 2000). When evaluating patients for the effectiveness of white noise in providing relief, the white noise is often generated from a clinical audiometer. We therefore included white noise generated from the GSI-61 clinical audiometer as one of the auditory stimuli, described by the audiometer

manufacturer as a broadband signal containing acoustic energy at all frequencies between 125 and 12,000 Hz. The spectra for white noise are shown in Figure 3A. It should be noted that the white noise spectral trace was obtained acoustically through the TDH-50P earphones and a Bruel and Kjaer model 4153 ear simulator (the spectra shown in Figures 1 and 2 were obtained electronically).
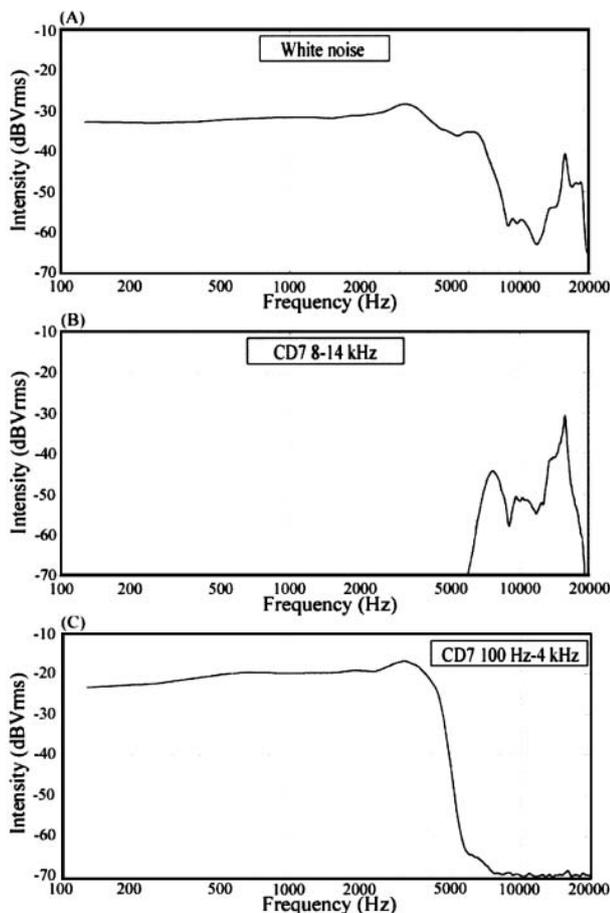
Acoustic Spectra

The white noise spectra shown in Figure 3A reveal the response characteristics of the TDH-50P. There is a sharp roll-off in output in the 7 to 8 kHz frequency range, with some recovery in output above 13 kHz. All stimuli presented in this study containing high-frequency energy would accordingly have reduced output in the high-frequency region

between 7 and 13 kHz. In the same way that the white noise spectra were generated, the acoustic spectra for the commercial sounds used in this study were also obtained. Two of these acoustic spectra are shown in Figures 3B and 3C. Figure 3B shows the spectra for the CD7 8–14 kHz noise band. Although the output from 7 to 13 kHz is significantly reduced, the earphone does reproduce some of the energy in this high-frequency region. Figure 3C shows the spectra for the CD7 100 Hz–4 kHz noise band, which might also be thought of as 4 kHz low-pass filtered white noise. Figure 3C reveals that the high-frequency "spike" that is seen to occur at about 16 kHz in Figures 3A and 3B is not an artifact but actually indicates that the earphone reproduces energy around 16 kHz. When the high-frequency noise is filtered above 4 kHz, the high-frequency spike disappears, as shown in Figure 3C.

Calibration of Auditory Stimuli

White noise presented from the audiometer was calibrated according to ANSI (1996) standards. The audiometer white noise and the ten sounds from the two CD systems were measured for dB SPL output in relation to the audiometer settings using a Bruel & Kjaer 2231 sound level meter and 4153 artificial ear. These measurements were made using A weighting (the most frequently used filter that discriminates against low-frequency and very high-frequency sounds, approximates the equal-loudness response of the ear at moderate sound levels, and correlates well with both hearing damage and annoyance from noise). The A-weighted adjustment values are shown in Table 3. For each of the sounds, the level shown on the audiometer was compared to the value displayed on the sound level meter. The measurements demonstrated a linear growth of output for all of the sounds. The adjustment values shown in Table 3 reflect the average difference between the audiometer values and the measured values (the sound level meter values were always higher than for the audiometer).

Procedures

All testing was conducted during a single session for each subject. Subjects were first asked to rank the annoyance of their tinnitus on the 0 to 6 Tinnitus Annoyance Scale (Table

Figure 3. Two-dimensional (frequency and amplitude) audio spectrum analysis (acoustic response) of three of the sounds used in this study, as measured through the TDH-50P earphones and an acoustic coupler. White noise (GSI-61 clinical audiometer)*(A)*. Moses/Lang CD7 8–14 kHz *(B)*. Moses/Lang CD7 100 Hz–4 kHz *(C)*.

1) in response to the question "How annoying is your tinnitus when you listen to it?" Subjects then listened to the different auditory stimuli: (a) white noise from the GSI-61 audiometer; (b) the three basic soundtracks from the DTM-6a CD system; and (c) the seven tracks from the Moses/Lang CD7. These sounds were presented in random order, and for each sound subjects were instructed to guide the audiologist to establish the output level that provided the "greatest degree of tinnitus relief." Subjects then ranked the annoyance (using the same annoyance scale) of the composite of their tinnitus and the tinnitus-relief sound in response to the question "When you listen to this sound, how annoying is the combination of this sound and your tinnitus?"

Each sound presentation lasted only as long as was required for subjects to make an annoyance judgment. These presentations lasted from 3 to 30 sec, including the time necessary to adjust the level for maximum tinnitus relief. There was the potential for these sounds to induce "residual inhibition," that is, temporary reduction in tinnitus loudness following exposure to sound. Although none of the subjects reported any changes in their tinnitus perception during testing, the operator did not mention to subjects the possibility that residual inhibition could occur during testing.

Data Analysis

The degree of relief from tinnitus was measured using the 0 to 6 Tinnitus Annoyance Scale (Table 1). Although these types of subjective ratings are often analyzed in tinnitus studies using parametric statistics, we have chosen to employ nonparametric statistics for the following reasons: (a) the responses obtained were subjective rankings, which are ordinal data; (b) the Tinnitus Annoyance Scale is not a validated outcomes measure; (c) individuals who rated their tinnitus annoyance as 0, 1, or 2 were excluded from participation, thus precluding a normal distribution of the data.

The objective of the analysis was to determine if there were differences in the relative rankings between the 11 sound formats and the "tinnitus alone" condition. The nonparametric analyses utilized the Friedman test and the Wilcoxon Signed Ranks test, which are the nonparametric equivalents of, respectively, repeated-measures ANOVA and paired t-test (Norman and Streiner, 2000).

RESULTS

In general, presentation of these sounds resulted in reduced tinnitus annoyance (Table 4 shows the mean annoyance ratings as well as the mean ranks for statistical analysis). Two of the three soundtracks from the DTM-6a provided the lowest composite annoyance ratings (mean annoyance ratings of 1.1 for E-Nature and 1.3 for E-Water, which correspond with mean ranks of 4.00 and 4.65, respectively). The remainder of the stimuli had mean annoyance ratings ranging from 1.8 to 2.1 (with corresponding mean ranks ranging from 5.68 to 7.05). The mean annoyance rating for tinnitus alone was 3.2 (mean rank of 10.88). It should be noted that in some instances there was no reduction in tinnitus

Table 3. Differences in Output (between readings from audiometer and sound level meter) for the 11 Sounds Used in This Study

Sound Source	Measured Output Level (dB) above Audiometer Reading
White noise (audiometer)	20
DTM E-Nature	17
DTM E-Water	21
DTM E-Air	16
Moses/Lang pink noise	19
Moses/Lang .1–4k	22
Moses/Lang 2–14k	7
Moses/Lang 4–14k	7
Moses/Lang 6–14k	5
Moses/Lang 8–14k	3
Moses/Lang 10–14k	3

Note: The dB values displayed on the sound level meter were always higher than the levels shown on the audiometer.

annoyance—11 subjects indicated that at least one of the sounds did not provide any relief. Also, four of the subjects experienced increased annoyance with at least one of the sounds.

The Friedman test revealed that there were significant differences in the mean ranks of the annoyance ratings between the 12 conditions (p < .0001). Paired comparisons using the Wilcoxon Signed Ranks test revealed that there were significant differences in mean annoyance ratings between (a) all soundtracks and tinnitus alone (all p's <.0001), (b) E-Nature and E-Water relative to all other sound formats (all p's <.05). Thus, statistically, all of the different sounds provided significant reduction in tinnitus annoyance for the group. Annoyance ratings were significantly lower for E-Nature and for E-Water compared to all of the other sounds.

Prior to providing annoyance ratings, subjects selected the optimal output level of each sound. The audiologist recorded these levels as displayed on the audiometer. The means of these levels, as well as the calibration-adjusted levels, for the different sound stimuli are shown in Table 4. The adjusted means ranged from 48 to 78 dB SPL.

DISCUSSION

This pilot study demonstrates the feasibility of conducting clinical testing to identify sounds that patients select for providing the greatest relief from their tinnitus. The subjects in this study had no difficulty conducting the task, and they often commented that the sounds were "soothing." Whereas all of the stimuli provided a significant reduction in tinnitus annoyance relative to "tinnitus alone," the combined tinnitus plus masking stimuli annoyance ratings from E-Water and E-Nature (from the DTM-6a system) were significantly lower than for all of the other stimuli.

"Dynamic" versus Conventional Sounds

It is noteworthy that the two sound formats that provided the greatest reduction in tinnitus relief, E-Water and E-Nature, were the only two stimuli used in this study that utilized the "dynamic" acoustic technology that is proprietary to Petroff Audio Technologies, Inc. "Dynamic" refers to the use of computer-generated algorithms to enhance short-term variations in the amplitude of sound stimuli. Dynamic tinnitus-relief sounds are uniquely differentiated from more conventional filtered-noise sound formats that do not incorporate such changes in amplitude and instead are perceived to be constant in amplitude over time. It can be demonstrated through three-dimensional (amplitude/ frequency/time) spectrum analysis (see Fig. 2) that E-Nature and E-Water exhibit substantially greater dynamic changes in

Table 4. Mean Output Levels, Annoyance Ratings, and Rankings of Tinnitus Annoyance for the Various Sound Stimuli

Sound	Mean Output (dB Level on Audiometer)	Adjusted Mean Output (dB SPL)	Mean Annoyance (0–6 Scale)	Mean Rank	Squared Sum
DTM E-Nature	39	56	1.1	4.00	80
DTM E-Water	36	57	1.3	4.65	93
Moses/Lang 4–14k	62	69	1.9	5.68	114
Moses/Lang 6–14k	65	70	1.8	6.03	121
DTM E-Air	39	55	1.8	6.08	122
Moses/Lang 8–14k	71	74	2.0	6.58	132
White noise (audiometer)	28	48	1.9	6.63	133
Moses/Lang .1–4k	32	54	2.0	6.70	134
Moses/Lang pink noise	33	51	2.0	6.83	137
Moses/Lang 10–14k	75	78	2.0	6.93	139
Moses/Lang 2–14k	57	64	2.1	7.05	141
Tinnitus alone	-	-	3.2	10.88	218
SUM					1564

amplitude over short-term intervals relative to conventional filtered noise, including E-Air.

E-Air, which has virtually the same spectra as E-Nature as measured by classical two-dimensional (amplitude/frequency) spectrum analysis (see Fig. 1), did not perform as well as E-Nature. Considering only the two-dimensional spectra of these two sound formats, they should not have performed substantially differently from one another. E-Nature is considerably more dynamic as measured by three-dimensional spectrum analysis (Fig. 2), which characteristics may reasonably account for the otherwise unexplainable results. E-Water is significantly rolled-off in high-frequency amplitude relative to E-Air, and, since high-frequency tinnitus is common, by clinical "tinnitus masking" considerations E-Air should have performed at least as well if not better than E-Water. Yet, E-Air did not perform as well as E-Water, and again the only objective accountability of this difference can be seen in the substantially different dynamic characteristics and corresponding three-dimensional analyses of the two sound formats.

Two previous studies may have relevance to the significantly reduced tinnitus annoyance observed by the "dynamic" sounds E-Nature and E-Water. In the seminal paper by Feldman (1971), two important aspects of tinnitus were observed: (a) the suppression of tinnitus with the use of external sound is not frequency specific, and (b) "the inhibitory effect of the external stimulus outlasts the duration of the stimulus, i.e., the tinnitus remains silent for a certain period of time after cessation of the stimulus." (Feldman 1971, p. 142) This poststimulus inhibitory effect is referred to as "residual inhibition," and Feldman used bursts of narrowband noise to demonstrate residual inhibition of tinnitus lasting 400 to 1200 msec. The observation of residual inhibition suggests the existence of some neural mechanism that may be triggered by certain auditory stimuli to inhibit the neural activity that causes tinnitus. Feldmann's data indicated that the effect was primarily a function of the intensity and duration of the auditory stimulus and, to a lesser degree, of stimulus frequency.

In a later paper, Feldmann (1983) explored different intensities and durations of stimuli that produced the effect of residual inhibition, which he also referred to as "forward masking." He first established the level of the stimulus, when presented continuously, that would completely suppress (mask) the tinnitus. He then presented the stimulus at a fast repetition rate, using various durations for each impulse, for example, 100 msec. The train of impulses was presented with gradually increasing inter-stimulus intervals until the patient reported that the tinnitus was again audible. The length of residual inhibition measured in this way was found to be between 50 and 1000 msecs. Feldmann concluded that the time course of tinnitus suppression reveals it to be a "dynamic process which is characterized by different types of temporal patterns" (1983, p. 594) Based on Feldmann's work, it may be hypothesized that "dynamic" sounds, which provide amplitude modulations on a similar order of magnitude as the train of impulses utilized by Feldmann, may in fact function equivalently to such brief impulses in the inducement of short-term residual inhibition. While these dynamic sounds do in fact exhibit the above-described amplitude modulations, they are inherently less abrupt in sound character than trains of impulses that exist only in "on" or "off" states. As such, dynamic sounds may induce ongoing repetitious intervals of residual inhibition while the stimulus sound is being applied, in a manner similar to that observed by Feldmann. By definition, the amplitude of the tinnitus-suppressing stimulus required during such intervals of residual inhibition may be either zero or minimized, depending on the desired sound character and other subjective factors. It appears logical that such intervals of residual inhibition, and the corresponding intervals of minimized amplitude of stimulus sound, may serve to reduce the average required amplitude of the stimulus over extended periods of time. Conversely, it follows that for equal average amplitude of sound stimulus, such dynamic sounds may suppress tinnitus more effectively than more conventional nondynamic sounds.

Based on the above reasoning, the reduced annoyance reported by our subjects for E-Nature and E-Water dynamic sounds might be attributed to more substantial lessening of the loudness of their tinnitus during presentations of such stimuli. Although these findings support dynamic acoustic technology as potentially superior in providing sound-based tinnitus relief, replication studies are certainly recommended. If the findings are

repeatable, however, they would suggest the need to adopt similar kinds of sound processing when treating tinnitus patients with an approach of sound-based relief.

Relevance of Findings to Tinnitus Retraining Therapy

A comment is necessary regarding the findings of this study in relation to the method of tinnitus treatment known as Tinnitus Retraining Therapy (TRT) (Jastreboff and Jastreboff, 2000). The use of sound with TRT is considered "sound therapy," and sound therapy is used in a specified manner in conjunction with "directive counseling."

TRT patients who require extended treatment are encouraged to utilize one of three types of ear-level devices to achieve optimal sound therapy. For patients without subjectively significant hearing loss, wearable ear-level devices that produce broadband noise are recommended. When hearing loss is present, combination devices (sound generator plus amplification) are recommended. In some cases, hearing aids alone can be used. When hearing aids are used, however, their main goal is to amplify the enriched background sound.

For the wearable ear-level devices that produce broadband noise (sound generators and combination devices), there can be no variation in the type of noise used, or in the level of the noise presentation. Only specific models of sound generators or combination devices are fitted to patients (unlike Tinnitus Masking that allows any type of device to be used) (Henry et al, 2002). The noise band with these devices typically spans about two octaves or less, and even when it is possible to expand to broader or higher frequencies (as is possible with some devices), this is purposely not done because people generally do not like to listen to enhanced high frequencies (P. Jastreboff, personal communication, 2003).

It should be emphasized that although ear-level devices are considered optimal for providing sound therapy with TRT, the more critical issue is that patients maintain an "enriched sound environment" throughout each day (Jastreboff, 2000; Jastreboff and Jastreboff, 2001). Regardless of whether they are fitted with ear-level devices, all patients are instructed to maintain a background of low-level sound at all times. Importantly, the type of background sound that is used for sound-environment enrichment should not induce any negative reactions because sounds that cause annoyance would activate the limbic and autonomic nervous systems, which would in turn increase the tinnitus-related annoyance (Jastreboff and Jastreboff, 2001). Since the primary objective of TRT is to facilitate habituation to tinnitus, the presence of annoying background sounds would be counterproductive to achieving this objective.

For the use of background sound with TRT, certain "natural" sounds are preferred, provided they are not associated with danger or anything else that might be construed as negative. Sounds will affect people in different ways, due to inherent and learned preferences associated with different sounds (Iversen et al, 2000). It is thus important for patients to use background sounds that are relaxing (that would activate the parasympathetic division of the autonomic nervous system) and to avoid exposure to sounds that are negative or annoying (that would activate the sympathetic division). The two sounds in the present study (E-Nature and E-Water) that reduced tinnitus annoyance significantly more than any of the other sounds are both digitally synthesized sounds that closely resemble sounds of nature. Based on their "natural" sound quality, and the results of this study, it would seem that either of these sounds would be appropriate for producing background sound enrichment for TRT. That is to say, E-Nature and E-Water might be background sounds of choice for promoting tinnitus habituation in TRT patients.

Differences in Perception Caused by Hearing Loss

Subjects in the present study typically had hearing thresholds within normal limits up to 2 kHz and some degree of reduced hearing sensitivity above 2 kHz (Table 2). At low presentation levels these subjects would be expected to typically hear more of the low-frequency components of each stimulus. When each stimulus was presented, subjects were instructed to first find the level that provided the greatest reduction in tinnitus annoyance. With any increase in level, subjects would then be expected to perceive more of the high-frequency acoustic energy. Thus, the same auditory stimulus would be perceived differently between individuals depending on their hearing threshold configuration and their selected presentation level. This is an important variable to consider with respect to the use of bands of noise in the attempt to suppress

tinnitus or to reduce tinnitus annoyance.

Earphone Limitations Affecting Sound Output to the Ear

The audio spectra shown in Figures 1 and 2 represent the electrical signals of the sound stimuli prior to their transduction to acoustic signals by the headphones. The earphones used in this study were TDH-50P, which represent the types of earphones typically used for audiology testing. These earphones have reduced output at frequencies between 7 and 13 kHz, as revealed in Figure 3, which includes a spectral analysis of the acoustic output for white noise generated from the audiometer. Although high-frequency output is reduced relative to the lower frequencies, the TDH-50P earphones do provide significant output in the 8–16 kHz frequency range, particularly when the sound stimuli are rich in high-frequency content. This can be seen in Figure 3B, which shows the acoustic output for the Moses/Lang CD7 Track 6 (8–14 kHz). Figure 3B shows clearly that there is output at frequencies above 10 kHz, which rises about 30 dB above the noise floor. The acoustic spectral traces shown in Figures 3B and 3C can be compared with the corresponding traces shown in Figure 1, which are the same signals analyzed for their electrical spectra.

Interpretation of these findings must keep in mind the above factors (hearing loss and earphone limitations) that affected the sound spectra perceived by these subjects during testing. These factors would have caused some level of spectral modification for each of the signals, specifically an attenuation of high-frequency energy. For any future study of this type, it would be desirable to perform the testing through earphones that provide better high-frequency response.

Related Research

We are aware of only one study that has reported the use of a variety of sound stimuli in the effort to achieve maximum tinnitus relief. Terry and Jones (1986) obtained annoyance ratings using 36 different digitally generated masking sounds to determine the acceptability of using these sounds with tinnitus maskers. The sounds included pure tones, interrupted tones, amplitude-modulated tones, frequency-modulated tones, triangular waves, and a series of noise stimuli that included various low-pass, high-pass, and band-pass noises. Annoyance ratings were compared between a group of tinnitus patients (N = 8) and a group of normal-hearing individuals without tinnitus (N = 20). For both groups the wide-band and high-pass noise bands were judged as the least annoying. The authors suggested that their data indicated that noise bands used in tinnitus maskers should be "tailored" according to individual preference rather than using a general purpose broadband masker. The authors further noted that future technical developments would result in a wider choice of sounds available through masking devices. To date, however, the only "technical development" has been an increase in the capability of shaping broadband noise to emphasize certain frequency regions.

CONCLUSIONS

The pilot data obtained in this study suggest that specially designed "dynamic" tinnitus-relief sounds are more effective than the use of filtered bands of noise. A larger scale study is suggested to confirm the superior efficacy of "dynamic" sound formats having various spectral and dynamic parameters. Such evidence could significantly improve the therapeutic efficacy of using sound to promote immediate relief from tinnitus annoyance.

There were two factors that reduced the high-frequency audibility of the sound stimuli used in this study. First, the subjects with tinnitus had various degrees of high-frequency hearing loss, which is typical of tinnitus patients. Second, the TDH-50P audiological testing headphones have significantly reduced high-frequency response capability. The present results should be interpreted with these caveats in mind, and any future study should ensure that high-frequency signals are perceived as much as possible. It is thus important to utilize earphone transducers with good high-frequency response capabilities.

At present, the ability to play back digital sound files directly to the ear is not possible through use of an ear-level wearable device. We hope that this study will serve as an incentive to improve upon the efficacy of sound-based tinnitus relief by the addition of the types of sounds that have been described

for this investigation. The provision of such evidence would create a demand for ear-level devices that could reproduce any type of sound file, which could, in turn, serve as the impetus for hearing aid companies to develop these kinds of therapeutic devices.

REFERENCES

American National Standards Institute. (1991) *American National Standard Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms.* ANSI S3.1-1991. New York: American National Standards Institute.

American National Standards Institute. (1996) *American National Standard: Specification for Audiometers*. ANSI S3.6-1996. New York: American National Standards Institute.

Feldmann H. (1971) Homolateral and contralateral masking of tinnitus by noise-bands and by pure tones. *Audiology* 10:138–144.

Feldmann H. (1983) Time patterns and related parameters in masking of tinnitus. *Acta Otolaryngol* 95:594–598.

Henry JA, Schechter MA, Nagler SM, Fausti SA. (2002) Comparison of Tinnitus Masking and Tinnitus Retraining Therapy. *J Am Acad Audiol* 13:55–581.

Iversen S, Kupfermann I, Kandel ER. (2000) Emotional states and feelings. In: Kandel ER, Schwartz JH, Jessell TM, eds. *Principles of Neural Science*. New York: McGraw-Hill, 982–997.

Jastreboff PJ. (2000) Tinnitus habituation therapy (THT) and tinnitus retraining therapy (TRT). In: Tyler RS, ed. *Tinnitus Handbook*. San Diego: Singular Publishing Group, 357–376.

Jastreboff PJ, Jastreboff MM. (2000) Tinnitus Retraining Therapy (TRT) as a method for treatment of tinnitus and hyperacusis patients. *J Am Acad Audiol* 11:162–177.

Jastreboff PJ, Jastreboff MM. (2001) Tinnitus Retraining Therapy. *Semin Hear* 22:51–63.

Johnson RM. (1998) The masking of tinnitus. In: Vernon JA, ed. *Tinnitus Treatment and Relief*. Needham Heights: Allyn and Bacon, 164–186.

Norman GR, Streiner DL. (2000) *Biostatistics: The Bare Essentials*. Hamilton, Ontario: B.C. Decker, Inc.

Terry AMP, Jones DM. (1986) Preference for potential tinnitus maskers: results from annoyance ratings. *Br J Audiol* 20:277–297.

Vernon J. (1976) The use of masking for relief of tinnitus. In: Silverstein H, Norrell H, eds. *Neurological Surgery of the Ear: Volume II*. Birmingham: Aesculapius Publishing, 104–118.

Vernon J. (1977) Attempts to relieve tinnitus. *J Am Audiol Soc* 2:124–131.

Vernon J. (1982) Relief of tinnitus by masking treatment. In: English GM, ed. *Otolaryngology*. Philadelphia: Harper and Row, 1–21.

Vernon JA. (1988) Current use of masking for the relief of tinnitus. In: Kitahara M, ed. *Tinnitus. Pathophysiology and Management*. Tokyo: Igaku-Shoin, 96–106.

Vernon JA. (1992) Tinnitus: causes, evaluation, and treatment. In: English GM, ed. *Otolaryngology*. Rev. ed. Philadelphia: JB Lippincott, 1–25.

Vernon J, Griest S, Press L. (1990) Attributes of tinnitus and the acceptance of masking. *Am J Otolaryngol* 11:44–50.

Vernon JA, Meikle MB. (2000) Tinnitus masking. In: Tyler RS, ed. *Tinnitus Handbook*. San Diego: Singular Publishing Group, 313–356.

Vernon J, Schleuning A. (1978) Tinnitus: a new management. *Laryngoscope* 88:413–419.