The Windowed Sound Therapy: A New Empirical Approach for an Effective Personalized Treatment of Tinnitus

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Abstract: We auditorily stimulated patients affected by subjective tinnitus with broadband noise containing a notch around their tinnitus frequency. We assessed the long-term effects on tinnitus perception in patients listening to notched noise stimuli (referred to as *windowed sound therapy* [WST]) by measuring the variation of subjects' tinnitus loudness over a period of 2–12 months. We tested the effectiveness of WST using non-notched broadband noise and noise of water as control sound therapies. We found a significant long-term reduction of tinnitus loudness in subjects treated with notched noise but not in those treated with control stimulations. These results point to the importance of the personalized sound treatment of tinnitus sufferers for the development of an effective tinnitus sound therapy.

Key Words: band-erased noise; equivalent rectangular bandwidth (ERB); personalized treatment; tinnitus; tinnitus pitch; waterfall noise

Tinnitus (i.e., the perception of a sound in the absence of an external source of sound) is a disorder of the auditory system of ever-increasing social concern. Epidemiological surveys indicate that the sensation caused by the tinnitus is present in 5–15% of the human population. Tinnitus is thought to consist of an abnormal neural activity of the auditory pathways [1]. However, the physiological mechanisms and persistence of the sensation of the tinnitus have still not been fully clarified. Hence, no universal effective treatment of tinnitus has been developed to date. In addition, no treatment can be considered efficacious in providing long-term relief from tinnitus in comparison to placebo [2]. Musical sounds and pleasant noises (e.g., noise of water) are sometimes administered to patients, who experience a temporary relief by distracting attention from the perception of the tinnitus [3]. Other techniques consist of administering to patients noise signals (e.g., white noise) that comprise frequencies similar to the subjective tinnitus frequency [4]. The goal is the reduction of subjects' tinnitus perception by providing competing auditory stimuli masking the tinnitus. Sound therapy and associated psychological support (counseling), tinnitus retraining therapy (TRT) [5], or other tinnitus masking–based methods have been reported to be beneficial for tinnitus sufferers (e.g., producing greater tolerance of the complaint and consequent improvement of the quality of life). However, no firm experimental evidence supports the effectiveness of these methods in the long term: an objective reduction of the loudness of the tinnitus or the complete recovery from tinnitus.

Kroener-Herwig et al. [6] noted the lack of controlled randomized group studies in TRT research. In addition, though Jastreboff and Jastreboff [7] claimed that all types of tinnitus and intolerance to sounds can be beneficially treated with TRT, intolerances toward the wearable acoustic prostheses delivering the masking auditory stimuli (noise generators) have been reported, presumably owing to the annoyance caused by stimulation of the patient with frequencies similar to that of the tinnitus

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[8]. Indeed, anecdotal clinical evidence suggests that the exacerbation of the tinnitus sensation by exposure to sounds comprising the tinnitus frequency is a common complaint from patients suffering from tinnitus. This observation has been the foundation of our approach to the treatment of tinnitus and the key element for the development of an effective personalized sound therapy.

METHODS

We recruited tinnitus sufferers from among patients attending the Oto-Rhino-Laryngology II Clinic of the University of Parma, Italy, in the period 2004–2006. All subjects of the study were patients reporting a ringing or hissing sound in one or both ears (Table 1) and willing to take part voluntarily in the experiment and to scrupulously follow the assigned therapy. All participants were provided with informed consent, previously approved by the Ethics Committee of the School of Medicine of the University of Parma, before starting the therapy. Initially (first visit), each participant subject received an audiogram and tinnitus loudness and pitch-matching tests.

We performed audiograms and loudness-matching and pitch-matching (clinical) tests using an audiometer (AMPLAID A321; HF, Amplifon, Milan, Italy) with an extended frequency range (0.125–13 kHz), whereas we performed the experimental pitch-matching test in a small, soundproof room using a multifunction generator (see later). With a few exceptions, we noted that all patients had, in one or both ears, a more or less pronounced hearing loss at frequencies above 3–4 kHz, an important predisposing factor for the occurrence of tinnitus [9].

We determined hearing sensitivity using tonal stimuli presented in octave steps, from 125 Hz to 8,000 Hz, and 1-dB increments. We performed the loudness-matching test following the conventional procedures for the assessment of tinnitus loudness (i.e., using pure tones with a frequency similar to the tinnitus frequency). Some patients (~25%) experienced difficulty in performing reliable comparisons because of the markedly different perceptual quality of pure tones as compared to that of their tinnitus. In such cases, we instead used narrow-band noise (NBN) of one-third of an octave, having a pitch similar to the tinnitus frequency (according to patient judgment) of tones.

The matching stimulus was obtained by increasing the frequency value of the comparison stimulus (i.e., pure tone or NBN) in 500-Hz steps, from 125 Hz to 13 kHz, after setting its level a few decibels above threshold. We stopped the procedure when a patient reported that the pitch of the comparison stimulus was similar to the tinnitus pitch. This method of pitch matching, therefore, differed from the conventional one based on the binary comparisons of tones (i.e., the two-alternatives, forced-choice method; see later). It must be stressed, however, that during the loudness-matching test, no effort was made to obtain the best match to tinnitus pitch, this being determined in a separate, experimental test (see later).

Once an appropriate auditory stimulus for loudness-matching had been determined, it was transmitted through the earphones contralaterally (when tinnitus was present only, or predominantly, in one ear), or bilaterally (in case of bilateral tinnitus), and the stimulus level was increased in 2-dB steps from 0 dB HL to the level at which the stimulus was just noticeable and then increased in steps of 1 dB to the level at which the loudness of the tinnitus and that of the matching stimulus were the same according to the patient's judgment. The difference between the two measurements was the estimated loudness of the patient's tinnitus (dB*t* [decibels SL]). Comparison tones (or NBN segments) were presented consecutively for a few seconds at the interstimulus interval of about 1 second.

The experimental pitch-matching test was performed shortly after the patient had performed the loudness-matching test using pure tones as comparison stimuli. Pure tones were generated with a function generator (Kenwood model FG-273; Kenwood Corporation, Taiwan) connected to a custom portable electronic switchboard (left, right, binaural), and the output signal was sent to a pair of Sennheiser HD 202 (Sennheiser Sales, Dublin, Ireland) closed-cup headphones. In a subject

Table 1. Summary of Patients' Characteristics and Results of Tinnitus Measurements for the Three Treatment Groups

Variables*	WN (n = 11)	Wa (n = 12)	WWN (n = 20)	Significance
Age (yr)	46.1 (29–81)	56.4 (30–71)	49.3 (25–75)	K-W = 2.7 , NS
Gender ratio (M/F)	6/5	7/5	14/6	χ^2 = 0.89, NS
Max hearing loss (dB)	77 (40–100)	53 (10–110)	55 (10–100)	K-W = 5.1 , NS
Duration of tinnitus (yr)	6.3 (0.5–15)	3.3 (0.8–6)	4.3 (0.25–15)	K-W = 0.4, NS
Tinnitus frequency (kHz)	5.8 (4–7)	8.3 (6–10)	7.5 (1–13)	K-W = 2.0, NS
Tinnitus loudness (dB)	14.6 (5–40)	10.8 (4–15)	18.4 (2–42)	K-W = 5.2, NS

χ^2 = Chi-squared test; K-W = Kruskal-Wallis (test); NS = not significant; Wa = water noise; WN = broadband noise; WWN = notched broadband noise.
*Mean and range (except gender ratio).
Note: Mean values (all variables except gender ratio) and proportions (gender ratio) did not differ among the three groups (last column, test, Chi-squared test) [17].

reporting the tinnitus only, or predominantly, in one ear, the comparison tone was presented contralaterally, whereas if the intensity of the subject's tinnitus sensation was similar in both ears, the tone to be matched was presented bilaterally.

We used tonal stimulation in all tested subjects regardless of type of tinnitus (e.g., hissing rather than ringing tinnitus). Pure tones are commonly used for measuring the pitch of both noise-like and tonal tinnitus [10]. In our case, the use of pure tones facilitated the comparison of tinnitus pitch among subjects receiving different acoustic therapies and the tracking of its variation across time (see later). Of course, the perceptual quality of a tone stimulus seldom corresponds to subjects' tinnitus sensation. This may partly explain the high between-session variability of pitch-matching measurements often reported in the literature [11–13].

Conversely, in our study, an essential prerequisite for the correct application of the experimental acoustic therapy (notched broadband noise; see later) was the reliability (and repeatability) of the measurement of the tinnitus pitch. Therefore, we developed a novel method of pitch matching in an effort to provide a better assessment of this parameter as compared with current standard procedures (i.e., the two-alternatives, forced-choice method [2AFC]).

Our method was based on the classic pure tone–matching paradigm and consisted of two phases. In the first phase (termed *tonal selection*), we presented to a subject two pure-tone sweeps in the band 0.05–13 kHz in succession: an upward tone sweep (i.e., from low to high frequencies) followed by a downward tone sweep (i.e., from high to low frequencies). During each tone sweep, the subject was asked to manually adjust the amplitude knob of the switchboard so as to keep the tone loudness approximately similar to the loudness of the tinnitus. This was difficult for most patients; practice was required. Therefore, before testing the patients for the first time, they were instructed in how to use the apparatus and make the tinnitus pitch-tone comparisons. In addition, during testing, the sweep rate was kept slow by the operator (approximately 0.25 kHz/sec) to allow the subject to regulate with ease the stimulus amplitude for the equal-loudness adjustment of the tone signals.

During both the upward and downward sweeps, we stopped tone presentation every time the subject reported a match between the tone and the pitch of the tinnitus. In such cases, the frequency value of the matching tone was noted, and the tone sweep was resumed, starting from the frequency at which it had been interrupted. Usually subjects reported more than one tone as matching the pitch of their tinnitus during both the upward and downward sweeps. The frequency values identified by the subject in the two sweep tests were grouped and ordered from the lowest to the highest. The ordered sequence of tones (F_i, $i = 1,2,3 = \ldots n$) was used in the second phase of the method for a finer identification of the pitch.

The second phase (termed *sequential binary choice*) resembled the traditional 2AFC procedure. We asked subjects which of the previously identified tones were more similar to the pitch of their tinnitus. Tones were presented in pairs (i.e., F_i vs F_{i+1}), starting from the lower frequencies: We asked the subjects to choose which tone of the pair (i.e., F_i or F_{i+1}) was more similar to their tinnitus. It might happen that the patient was undecided about the two alternatives when these were of similar frequency. This occurred frequently, as many subjects identified matching tones of similar frequency during the upward and downward sweeps. In such cases, the operator continuously varied the knob of the tone generator within the narrow band delimited by the two frequency values to allow the subject to identify the tone best matching the tinnitus pitch. This value (i.e., F1, F2, or an intermediate one) was then compared with the subsequent tone (F3) of the ordered sequence of selected tones, and again the subjects were asked which of the two tones was most similar to their tinnitus. The procedure was repeated until the tone identified up to that point was compared with the highest tone (F*n*) of the sequence. The tone best matching the tinnitus pitch was assumed to be the tinnitus frequency (F*t*).

During this phase, a number of patients reported more than one tone as matching their tinnitus pitch. This could happen for several reasons: presence of different kinds of tinnitus, such as a ringing associated to hissing tinnitus, presence of multiple tinnitus spectral peaks [13], or octave confusion. In the latter case, subjects were asked to choose which one between the two tones (one having double the frequency of the other) best matched their tinnitus pitch. Whenever subjects were unable to rate two or more matching tones as substantially different from their tinnitus pitch, the frequency of these tones was noted (i.e., more than one value of F*t* was taken), and the tinnitus was labeled as "multi-pitched" as opposed to single-pitched tinnitus. We note that the distinction made here between single- and multi-pitched tinnitus was intended solely for the development of an appropriate tinnitus therapy; it may or may not have a relationship with the internal spectrum of the tinnitus. Hence, our results cannot be compared with those of studies trying to assess the form of the tinnitus spectrum [13]. Overall, the entire procedure for the determination of the tinnitus pitch or pitches lasted on average 30–40 minutes per subject, but it could be very short (i.e., about 15 minutes) or exceed 1 hour in relation to a number of factors (e.g., subject age, previous training experience, type of tinnitus). Cursory examination of pitch match position in relation to the patient's audiogram showed that the matches were frequencies above that at the beginning of the region of hearing loss on the audiogram. This observation agrees with results by earlier and recent studies on the relationship between tinnitus pitch and hearing loss [9].

THE WINDOWED SOUND THERAPY

The experimental sound therapy consisted of auditory stimulation of patients with broadband noise containing a notch centered at the tinnitus frequency (i.e., the experimental treatment stimulus, windowed white noise [WWN]). WWN was constructed from a 10-minute sequence of white noise generated by the white noise generation function of a suitable software for sound analysis (AVISOFT; Avisoft Bioacoustics, Berlin, Germany). The noise sequence was band-passed from 50 Hz to 15 kHz and equalized to compensate for the low-frequency bias of the frequency response of the earphones used for sound stimulation (see later). Then, a band-stop filter centered at the patients' tinnitus frequency or frequencies was applied (i.e., a silent window was created) using the IIR filter function of AVISOFT. The width of the filter was set at the value of 2 × ERB (F*t*), where ERB represents the equivalent rectangular bandwidth (i.e., the width of the estimated critical band [14]) and where ERB (F*t*) is the value of ERB at the tinnitus frequency F*t*. For example, assuming an F*t* of 6,150 Hz, the width of the corresponding critical band is 688.5 Hz [$ERB = 24.7 \times (4.37 \times F+1)$, where F = frequency in kiloHertz] [14]. Hence, the width of the band-stop filter amounts to 1,377 Hz, being 5,462 Hz and 6,838 Hz, respectively, the lower and upper frequency extremes of the band, with the center frequency at 6,150 Hz.

We should note that any procedure of tinnitus pitch assessment is subject to many errors owing to, for example, differences in the ability of subjects to compare and discriminate among tones, the uniqueness of the tinnitus sensation, or the presence of different types of tinnitus. For these reasons, the width of the erased band of WWN was set prudently to a value double the width of the critical band of the tinnitus frequency.

The aim of WST was threefold: (1) avoiding auditory stimulation of the hair cells and the terminations of the cochlear nerve in the region of the tinnitus; (2) avoiding exacerbation of the tinnitus sensation by the subject, as determined by stimulation of the ear with frequencies similar to the tinnitus; and (3) decreasing the tinnitus perception of subjects through remote masking [15] from the noise frequencies outside the erased band.

To assess the effectiveness of the experimental therapy, two other types of acoustic stimulation (i.e., control therapies), represented by non-notched broadband noise (white noise [WN]) and by waterfall noise (Wa), were used. WN differed from WWN only in the lack of notch (i.e., it was a 10-minute sequence of equalized broadband noise from 50 Hz to 15 kHz; Fig. 1). Wa stimulation was an 8-minute sequence of stream noise recorded underwater with a hydrophone placed close to a stream cascade [16] (see Fig. 1). As compared to the waterfall noise recorded in air, the waterfall noise recorded underwater is characterized by greater energy content at lower frequencies and larger amplitude and frequency modulation [16]. In general, white noise–based acoustic stimulations, such as TRT, or those based on the listening of natural sounds (e.g., waterfall noise, sea noise) are known to provide some temporary relief to the tinnitus sufferer but no objective long-term reduction of the tinnitus sensation.

The experimental and control acoustic stimulations were presented to the subjects using a portable sound

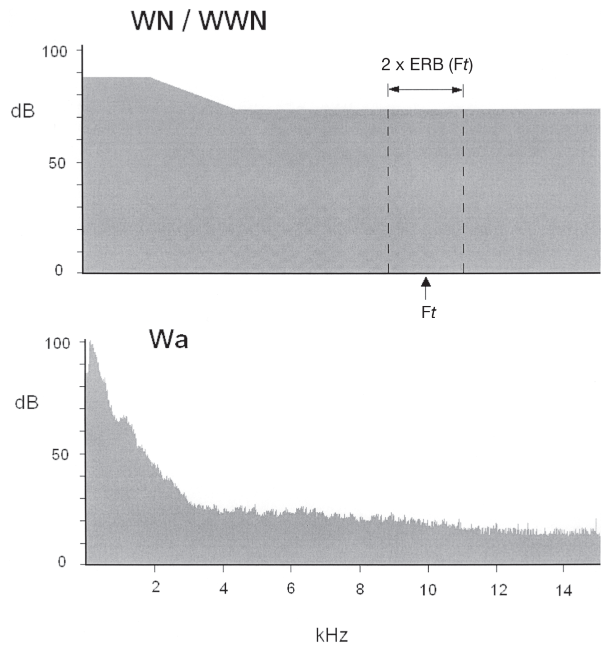

Figure 1. Spectral characterization of the three sound therapies with decibel values in relative units. The acoustic stimulation of the WN sound therapy was white noise in the frequency range 0.05–15 kHz equalized as shown in the figure to compensate for the poor low-frequency response of the earphones (see Methods section for details). The WWN sound therapy was obtained from WN using a band-stop filter with center frequency given by the value of F*t* (F*t* = 10 kHz, in the figure), the upper and lower limits of which were determined by the width of the ERB (F*t*), that is, the estimated critical band, at that frequency [ERB(10 kHz) = 1.1 kHz] [14] according to the formula shown in the figure (top spectrum). Therefore, the noise energy between the two broken lines is missing in the WWN sound therapy. In the Wa sound therapy, most energy is concentrated in the lower part of the spectrum (bottom spectrum = mean spectrum of the 8-minute sequence of waterfall noise; see Methods). (WN = broadband noise; WWN = notched broadband noise, top spectrum; Wa = water noise; bottom spectrum.)

reproduction device (CD reader) and a pair of clip-on, open-air earphones (GBC model KH-101; Kon.El.Co s.r.l. Milan, Italy) having a specific frequency response curve. The sound therapy consisted of the subjects' listening to the CD containing a given sound sequence (i.e., WWN, WN, or Wa) continually for a total listening time of 1.5–3 hr/day (preferably distributed equally among three different periods of the day: morning, afternoon, and evening) using the REPEAT function of the CD reader. Patients were also asked to regulate the listening volume to a level approximately matching the loudness of their tinnitus. In case of marked hearing loss in one ear, subjects were advised to regulate the listening volume using the ear of best hearing.

Experimental Design

The experimental design consisted of randomly assigning to each patient either the experimental sound therapy (WWN)* or one of the two control sound therapies (WN or Wa) following a double-blind procedure. (That is, the patients, the otolaryngologist, and the technicians measuring the tinnitus were unaware of which acoustic treatment each patient received.) In addition, each time a new patient entered the therapeutic program, care was taken to favor the assignment of the sound therapy that happened to be underrepresented until that moment (i.e., regardless of the patient and tinnitus characteristics). These procedures aimed at obtaining a balanced design with an approximately equal number of subjects treated with the experimental therapy and with the control therapies (WN or Wa) and, at the same time, avoiding any possible bias in the process of data collection owing to, for example, the differential treatment of patients by the experimenters because of the type of therapy assigned.

Variation of Tinnitus Parameters Over Time

We examined variation of the tinnitus parameters (F*t*, dB*t*) over time for each patient by repeating measurements, ideally after 1, 3, and 6 months from the start of the therapy, following the same procedures of the first visit. Indeed, the period elapsing between subsequent visits and the number of control visits varied greatly among subjects in relation to a number of unpredictable factors (e.g., patient's eagerness to cooperate, patient's commitments). When the loudness-matching test was performed on the same subject during a control visit, care was taken to use the same type of comparison stimulus (i.e., pure-tone or NBN stimulation) employed initially.

In addition, when the subject's tinnitus pitch was reassessed during a control visit, usually the observed value of F*t* was not exactly the same as the one measured in the previous visit. This was expected, as any procedure of pitch assessment is inherently imprecise for reasons already discussed. Furthermore, the tinnitus pitch may change over time. In such cases, the patient usually informed the experimenters about the change that occurred. Conversely, the key feature of the WWN therapy is the construction of a noise window around the tinnitus pitch, implying that the window features should track any observed change (real or supposed) of the value of F*t*. Thus, ideally, patients subjected to the WWN therapy should receive a new windowed noise sequence almost each time at every control visit. This is admittedly tedious and perhaps of little therapeutic significance when the re-measured value of F*t* is similar to the last one determined in the previous session.

Therefore, the following compromise criterion was adopted: A new, updated WWN acoustic sequence was constructed only when the re-measured value of F*t* fell outside the noise window previously determined. In this case, the patient was asked to return the old disk and listen to a new disk that contained the usual 8-minute sequence of equalized broadband noise recorded after a notch centered at the new tinnitus frequency or frequencies was created following the method explained earlier.

Analysis of Data

The initial group of participants consisted of 60 volunteers of both genders. However, 11 subjects withdrew participation immediately for reasons unrelated to the type of acoustic treatment being assigned (e.g., not enough time for listening, fear determined by the psychometric measurements). These noncompliant patients were not counted in the analysis, thereby reducing the sample to 49 patients. Six subjects felt annoyed by the therapy and refused to continue before the first control visit (see Results). For these subjects, only the initial tinnitus measurements are available. Thus, the overall number of subjects available for the comparative analysis of data was of 43 patients, of whom 20 were treated with WWN, 11 were treated with WN, and 12 were treated with Wa. To explore the efficacy of the WWN therapy further, three Wa subjects and one WN subject were chosen among the group of patients reporting no relief from the therapy and were asked to abandon the assigned therapy and to start with the WWN therapy. The control-to-experimental therapy shift occurred after 3–7 months from the beginning of the experiment. Of course, for these subjects, the tinnitus measurements considered for statistical analysis were those taken during the period during

* The same acronym is used interchangeably for indicating the type of sound stimulation and therapy.

which they listened to the first therapy (i.e., Wa or WN), unless otherwise specified.

We determined the effectiveness of the experimental and control therapies in reducing subjects' tinnitus loudness by computing for each patient the absolute and percentage variation of the value of dBt measured during the last measurement session of the therapy (i.e., dBt_{final}), relative to the value measured at the first visit (i.e., dBt_0). Thus, the two measures indicated, respectively, by ΔdBt_{final} (= dBt_{final} – dBt_0) and PΔdBt_{final} (= ΔdBt_{final} / dB$t_0 \times 100$), were zero, or positive, when the tinnitus loudness was unchanged or increased during the treatment period, whereas a negative value indicated a decrease of tinnitus severity.

We should note that these measurements were determined for each subject regardless of the type of comparison stimulus employed for the loudness-matching tests (i.e., pure-tone or NBN stimulations). Conversely, the presence of two control treatments allowed the effectiveness of the WWN therapy to be established regardless of the type of comparison stimuli used for the measurement of tinnitus loudness.

The temporal variation of tinnitus loudness in the three groups of patients was examined by computing the values of ΔdBt using the patient's values of dBt measured during subsequent control visits. The number of control visits (and re-measurements of dBt) varied from one to seven per patient. For each visit, we noted the number of days (dd) elapsed from the date of the start of therapy (usually within 1 week from the first visit) and the date of the control visit. Then, the value of dBt computed at each control visit was assigned—on the basis of the value of dd (i.e., dBt_{1-2}, dBt_{3-6} , and dBt_{7-12})—to one of three temporal classes: 1–2 months, 3–6 months, and 7–12 months.

Thus, the variations of tinnitus loudness of patients with respect to dBt_0 were expressed as ΔdBt_{1-2}, ΔdBt_{3-6}, and ΔdBt_{7-12} on the basis of the value of dd. When subsequent visits of the patient fell within the same temporal class, only the value of dBt measured during the last visit within the class was considered for analysis. This was necessary to ensure that each patient contributed only one measurement value (if available) to the class mean value.

The between-session variability of tinnitus pitch matches (i.e., values of Ft) was assessed by computing for each patient the absolute difference ($|\Delta Ft| = |Ft_0 - Ft_c|$ [in kiloHertz]) between the value of Ft measured at the first visit (Ft_0) and that measured at the first control visit (Ft_c).

Statistical Analysis

We examined the presence of differences in the mean value of patients' characteristics (age, gender, maximum hearing loss, duration of tinnitus) and tinnitus parameters (i.e., Ft, ΔdBt_{final}, PΔdBt_{final}, PΔdBt_{1-2}, ΔdBt_{3-6}, and ΔdBt_{7-12}) among the three treatment groups (i.e., WN, Wa, WWN) using the nonparametric analysis of variance (Kruskal-Wallis test) [17]. If the difference among means was statistically significant, we used the multiple-comparisons procedure of the Kruskal-Wallis test to test the difference of mean value between pairs of treatments. (Other tests used are reported in the Results section.) We examined the between-session variability of the tinnitus pitch measurements by means of cumulative plots of the absolute differences (in kiloHertz).

RESULTS

Table 1 summarizes the characteristics of patients of each treatment group together with the clinical measurements of their tinnitus at their first visit. Patients of the three groups did not differ significantly regarding gender ratio, mean age, mean hearing loss, and mean value of tinnitus parameters. Of the 49 patients who started acoustic therapy, 2 in the WWN group, 3 in the WN group, and 1 in the Wa group withdrew before the first control visit. If these subjects are included in the total count of patients treated, the number voluntarily withdrawing from the therapy in the WWN, WN, and Wa groups amounted to three, four, and seven, respectively, the highest percentage being in the WN group (about 30% of subjects) and the lowest being in the WWN group (about 15% of subjects; Fig. 2). We did not attempt the chi-squared analysis of the proportion of those who withdrew in the three groups owing to the low number of those who withdrew, expected in each group under the null hypothesis. Finally, 7 of the 20 patients treated

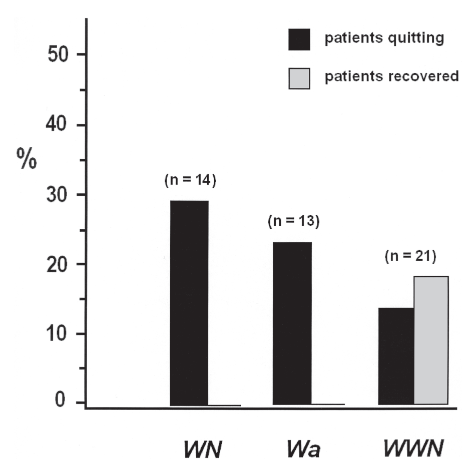

Figure 2. Frequency of quitters and patients recovered in the three sound therapy groups. (WN = broadband noise; WWN = notched broadband noise; Wa = water noise.)

with WWN were given one (n = 5) or two (n = 2) updated WWN treatments during the study period (see Methods for details).

The average time elapsed from the beginning of the acoustic therapy and the last tinnitus measurement was similar in the three groups of patients: 148 dd (± 20), 145 dd (± 25), and 127 dd (± 16), respectively, for the WN, Wa, and WWN groups. Results of the Kruskal-Wallis test showed that the mean time elapsed did not differ significantly among groups (H = 0.42, not significant [NS]; n = 43).

Figure 3 reports mean values of ΔdBt_{final} and $P\Delta dBt_{final}$ for the three groups. Tinnitus loudness decreased (on average) in all groups. However, in the WWN group, the decrease was large (about –12 dB, corresponding to approximately a 75% decrease), whereas in the two other groups, the decrease was negligible (around –2 dB, corresponding to approximately a 10% decrease). In addition, four patients of the WWN group (approximately 20% of subjects) but none of the two other groups recovered from tinnitus (i.e., the tinnitus was no longer perceived by the patients; see Fig. 2).

Results of the Kruskal-Wallis test showed that the mean value of both ΔdBt_{final} and $P\Delta dBt_{final}$ differed significantly among the three groups (ΔdBt_{final}, H = 15.6, $p < .001$; $P\Delta dBt_{final}$, H = 14.4, $p < .001$, n = 43). Results of the multiple comparison tests showed that the mean value of both ΔdBt_{final} and $P\Delta dBt_{final}$ was significantly larger in the WWN group than in the two other groups (WWN vs. WN, $p < .05$; WWN vs. Wa, $p < .05$; n = 43, both measurements), whereas no significant difference was found in the mean value of the two measurements between WN and Wa groups (WN vs. Wa, NS; n = 43, both measurements).

Figure 4 shows the variation of tinnitus loudness with time elapsed from the start of therapy for three patients taken as an example (one for each type of therapy) and for one subject initially receiving the Wa therapy and later re-treated with the WWN therapy (see further discussion later). In the WWN-treated patient, tinnitus intensity decreased by 12 dB after only 1 month of therapy and by 15 dB at the end of the observation period (after 7 months). By contrast, in two patients receiving the control therapies, tinnitus intensity was initially increased by about 5 dB, showing only minor fluctuations during subsequent control visits. Figure 5 reports the variation of the mean value of ΔdBt, with time elapsed from the start of the therapy, for the three groups of patients. After 1–2 months, tinnitus loudness decreased markedly in patients of the WWN group (mean value of ΔdBt_{1-2}, –6.7 dB) but increased slightly in patients of the two other groups (mean value of ΔdBt_{1-2}, +2.0 dB, WN; +0.6 dB, Wa). In the ensuing months, average loudness tended to decrease with time in all groups.

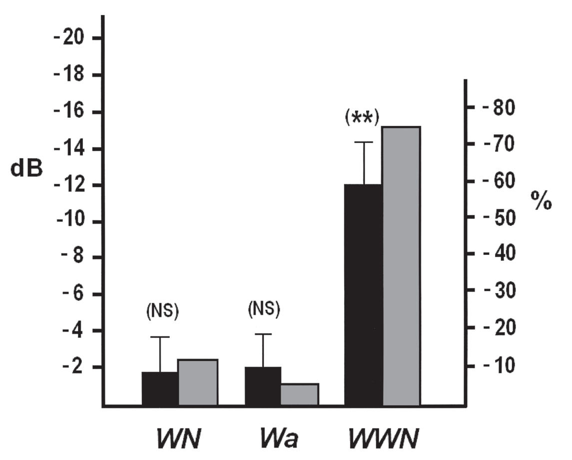

Figure 3. Mean values of ΔdBt_{final} (+1 SE), and $P\Delta dBt_{final}$, of the three sound therapy groups. Note that the number of cases in which ΔdBt_{final} was less than 0 (i.e., tinnitus severity decreased) differed statistically from chance only in the WWN group (binomial test) [17]. For further details, see the Results section. (**$p < .01$; WN = broadband noise; WWN = notched broadband noise; Wa = water noise.)

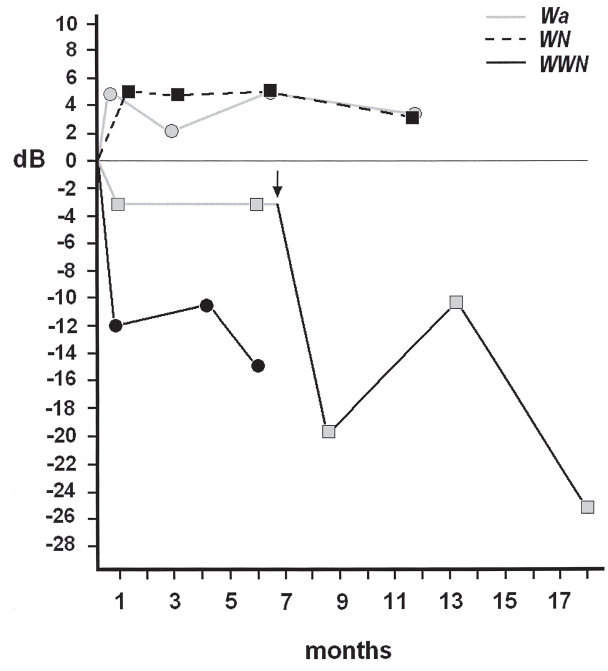

Figure 4. Variation of tinnitus loudness over time in four patients (indicated with a different symbol) taken as an example. Three patients received a different type of sound therapy (i.e., WWN, Wa, or WN), whereas one patient initially receiving the Wa therapy shifted to the WWN therapy about 3 months (*arrow*) after the first visit. Decibel units on the *y*-axis are values of ΔdBt computed using dBt measurements in subsequent control visits of the same subject (date on the *x*-axis). ΔdBt values are expressed relative to the decibel measurement at the first visit. See Methods for further details. (WN = broadband noise; WWN = notched broadband noise; Wa = water noise.)

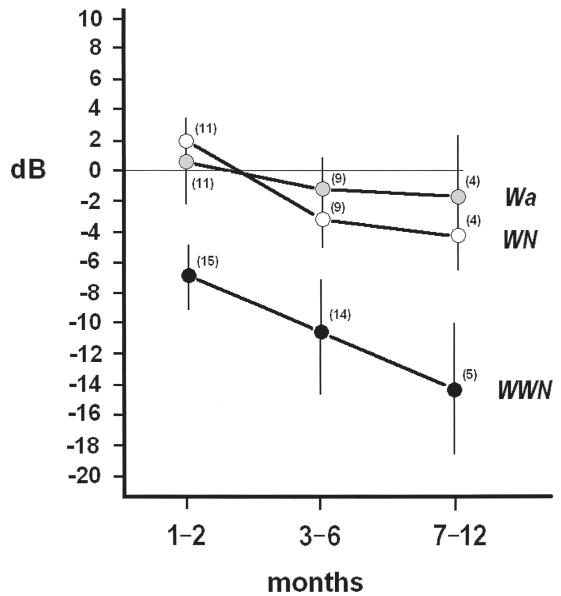

Figure 5. Mean variation of tinnitus loudness over time in the three sound therapy groups. Decibel units on the *y*-axis are mean values (± 1 SE) of ΔdBt computed for three subsequent temporal classes using dBt measurements in subsequent control visits of the same patient. See Methods for details. (WN = broadband noise; WWN = notched broadband noise; Wa = water noise.)

The mean decibel attenuation between 3 and 6 months of therapy was less than 1 dB in patients of the Wa group and 4–5 dB in those in the WN and WWN groups. The mean attenuation between 7 and 12 months was less than 1 dB in patients of both the WN and Wa groups and 3 dB in those of the WWN group. Results of the Kruskal-Wallis test showed that the mean value of both ΔdBt_{1-2} and ΔdBt_{3-6} differed significantly among the three groups (ΔdBt_{1-2}, H = 7.9, $p < .02$, n = 33; ΔdBt_{3-6}, H = 7.2, $p < .05$, n = 19). Results of the multiple comparison tests showed that the mean value of both ΔdBt_{1-2} and ΔdBt_{3-6} was significantly larger in the WWN group than in the two other groups (ΔdBt_{1-2}, $p_{\text{WWN vs. WN}} < .05$, $p_{\text{WWN vs. Wa}} < .05$; n = 33; ΔdBt_{3-6}, $p_{\text{WWN vs. WN}} < .05$, $p_{\text{WWN vs. Wa}} < .05$; n = 19), whereas no significant difference was found in the mean value of the two measurements between WN and Wa groups (ΔdBt_{1-2}, $p_{\text{WN vs. Wa}}$ = NS, n = 33; ΔdBt_{3-6}, $p_{\text{WN vs. Wa}}$ = NS; n =19). The statistical comparison of ΔdBt_{7-12} among groups was not attempted because of the low data sample (n = 13; see Fig. 5).

In the four patients re-treated with the WWN therapy, the value of dBt measured at the last control visit was compared to that measured at the control visit preceding the change of therapy. Results showed a remarkable reduction of tinnitus loudness in the three patients who were initially given the Wa therapy (one of them recovered from tinnitus; see Fig. 4 for an example) and no change of tinnitus loudness in the subject who was initially assigned to the WN therapy.

Finally, the analysis of variation of the tinnitus pitch measurements between the first visit and the first control visit (i.e., after 1–2 months of use of the sound therapy) showed that the mean absolute frequency difference (i.e., values of $|\Delta Ft|$, in kiloHertz) was 1.1 kHz (n = 41). Furthermore, about two-thirds of the differences were below 1 kHz, and approximately one-half of the differences were below 0.6 kHz.

DISCUSSION AND CONCLUSIONS

Experimental Evidence of the Effectiveness of WST

The traditional sound therapies for the treatment of tinnitus are based on the auditory stimulation of patients through the use of pleasant sounds (e.g., noise of water) or broadband noise, presumably including frequencies that are similar to the patient's tinnitus (TRT) [5]. These acoustic stimulations are standard for each subject; they are not personalized in relation to the tinnitus frequency that characterizes the subjective tinnitus.

Our method for the treatment of subjective tinnitus differs substantially from previous methods (but see Goldstein et el. [4] for an exception) because tinnitus sufferers were instructed to listen (at least) 2 hours daily to a broadband noise soundtrack (WWN treatment) not containing the patients' tinnitus frequency (i.e., a narrowband silent window centered at the tinnitus frequency is created in the noise spectrum). Thus, our sound therapy (WST) was tailored to the frequency characteristics of patients' tinnitus. We tested the effectiveness of the therapy using two types of control sound treatments: non-notched noise (WN) or waterfall noise recorded underwater (Wa). Thus, sound stimulation of patients of the two control groups was not personalized on the basis of frequency characteristics of patient's tinnitus.

The examination of the percentage of those withdrawing (i.e., subjects abandoning the therapeutic program too early) in the two control groups showed that the likelihood of withdrawing was higher in patients in the WN group and lower in those in the Wa group. These findings are in agreement with those of a recent study by Henry et al. [3] showing that auditory stimulation with natural sounds provided greater reduction in tinnitus annoyance than broadband noise stimulations. However, the WWN group had the lowest percentage of those who withdrew (around 15% of subjects compared to 28% in the WN group and 23% in the Wa group) among the three treatment groups, suggesting that WST was the sound therapy best tolerated by patients (presumably owing to the lack of annoyance caused by the stimulation of the patient with frequencies similar to that of the tinnitus).

Indeed, the most striking result of our study was the marked decrease of tinnitus loudness observed in patients after approximately 4–5 months of daily listening to the WWN sound stimulation but not seen in those listening to either the WN or the Wa sound stimulations for an equivalent amount of time. Furthermore, patient's estimation of tinnitus loudness showed a clear negative relationship with the time of WST application; loudness decreased by approximately 1 dB per month of application of the therapy (see Fig. 5). Thus, WST determined an objective and significant reduction of patient's tinnitus loudness and, hence, it appeared to be an effective sound therapy for the treatment of tinnitus.

The presence of subjects without residual tinnitus in the WWN group but not in the two control groups further strengthens this conclusion. These findings also suggest that sound therapies based on stimulation of patients via pleasant sounds (e.g., waterfall noise) or generic broadband noise (TRT) are ineffective for the objective reduction of tinnitus loudness. (Possibly the self-reported beneficial effect of TRT is due to the habituation phenomenon.) Of course, owing to the small sample size of our treatment groups, these conclusions are preliminary and can be validated only by further experimental evidence after more data are collected (including the use of other types of natural or custom sounds).

Apart from the beneficial effects on tinnitus loudness perception, another remarkable aspect of this study was the development of a novel tinnitus pitch-matching procedure using binary comparison of tones selected by the patient in a previous test on the basis of their resemblance to tinnitus. This procedure yielded pitch estimates characterized by low between-session variability (mean absolute difference of 1.1 kHz between the tinnitus pitch measured at the initial visit and at the first control visit after 1–2 months). These differences were much lower than those reported in other studies using different pitch-matching procedures (e.g., 2.2–3.2 kHz) [13,18, 19]. Thus, apparently our method yielded better pitch estimates as compared to the current standard procedures (e.g., the 2AFC), a necessary condition for a correct application of WST. Possible sources of between-session variability of pitch matches are, for example, the multi-pitched nature of many tinnitus percepts [13], the change of tinnitus pitch with time after application of the sound therapy [10] (Lugli et al., unpublished data), or judgment errors by patients. Though the reliability of the method of pitch assessment proposed here awaits further testing before being asserted, our findings nonetheless point to the type of pitch-matching procedure adopted as a major factor responsible for the unreliability of pitch estimates documented in the tinnitus literature [18].

Potential Criticisms

A potential methodological criticism that should be addressed in this study is the lack of control by experimenters over the patients' motivation or willingness to carefully follow the procedures established by the therapeutic listening program. This could weaken the conclusions of our study if the patient's "at-home" listening behavior had been affected by the type of acoustic therapy they received. Indeed, analysis of the percentage of those withdrawing from each treatment group indicates that the WN therapy is the least tolerated, whereas the WWN therapy is the best tolerated by patients. Therefore, to the extent that these differences might correspond to a different listening behavior by patients in relation to the sound therapy they received, the decrease of tinnitus severity observed among the group of patients receiving the WWN therapy could partly be explained by their (supposed) higher tolerance and stamina in motivation to listen to the therapy as compared to patients receiving the control therapies. However, the following observations tend to indicate this was unlikely the case.

First, both the Wa and WN therapies were equally ineffective in reducing tinnitus loudness, despite the greater tolerability and pleasantness of the first therapy according to the patients' judgment. Second, tinnitus loudness did not decrease significantly with months of application of the sound therapy by patients of the two control groups. Third, in a few patients reporting subjective beneficial effects by the Wa therapy, the measure of the tinnitus loudness did not vary appreciably over the study period. Likewise, other patients treated with the WWN and reporting no subjective improvement of their tinnitus sensation showed in fact a decrease of tinnitus loudness measured over time. The presence of a discrepancy between the patient's tinnitus sensation (e.g., the perceived loudness of tinnitus, the severity of tinnitus) and the objective measurement of tinnitus loudness is a phenomenon widely documented in the tinnitus literature [10,20]. These facts do not support a supposed presence of marked differences in the at-home use of the therapy by patients of different treatment groups. Hence, the lack of direct control by the experimenters over the patient's at-home listening behavior was unlikely to be a factor potentially affecting the main conclusion of this study about the effectiveness of the WST therapy in the treatment of tinnitus.

Another point of criticism concerns the results of the loudness-matching test: Loudness match levels (11–18 dB, on average) were higher than those obtained in other studies measuring tinnitus loudness with pitch-matching tones (2–3 dB), being similar to those obtained using comparison tones outside the tinnitus region (10–15 dB) [1]. This discrepancy, however, may be easily explained by considering the rough clinical procedure used in our study for finding pitch matches suitable for the loudness-matching test.

Traditionally, tinnitus loudness is estimated using a pitch match obtained following a rigorous matching procedure (e.g., the 2AFC). In our study, the pitch-matching test conducted during audiological evaluation was aimed solely at obtaining a matching tone only approximately resembling the tinnitus frequency, the tinnitus pitch being accurately measured in a separate experimental test (see under Methods).

Theoretical Aspects of WST

The key element of the WST was the auditory stimulation of tinnitus sufferers with masking noise presumably not comprising the tinnitus frequencies, often suggested to be responsible for the exacerbation of the symptom. Jastreboff and Jastreboff [21] stressed the importance of ensuring that the sound-enriched environment provided with the TRT should not contain sounds causing annoyance and exacerbation of the tinnitus sensation. The purpose of TRT is the reduction of the alarm reaction associated with the tinnitus sensation by altering the connections between the limbic and autonomic nervous systems (responsible for the alarm reaction) and the auditory system [5]. Therefore, the observed effectiveness of the WST in reducing tinnitus loudness appears consistent with the neurophysiological model of tinnitus underlying TRT [5].

However, other findings in our study suggest that this might not be the complete story. The auditory stimulation of patients with waterfall noise recorded underwater (Wa therapy) did not contain significant energy in the frequency range above 3–4 kHz (where hearing loss usually occurs and most tinnitus sensations pitch) and, furthermore, appeared to be better tolerated as compared to the stimulation with white noise (WN sound therapy). Yet, both control therapies were equally ineffective in reducing tinnitus. One possibility is that Wa stimulation had poor masking effects on tinnitus in most patients, implying that the alarm reactions induced by tinnitus persisted in Wa-treated subjects. However, the observation that many of these subjects experienced tinnitus relief by listening to the water noise soundtrack (Lugli et al., unpublished data) does not support this interpretation.

An alternative explanation for the decreased tinnitus loudness in patients treated with WST might involve a change in the neural reorganization in the tinnitus region induced by stimulation with noise around, but not inside, the tinnitus pitch region. For instance, it has been hypothesized the overrepresentation of the edge frequencies before the hearing loss region is responsible for the tinnitus sensation [1]. Conversely, tinnitus pitch is often located inside the hearing loss region toward the audiogram's edge frequencies, a phenomenon having strong analogy with the one described for the occurrence of the Zwicker tone using notched noise [22]. Thus, a conceivable hypothesis is that a stimulation of the edge frequencies, but not the tinnitus region, by the noise frequencies just below the notched region has occurred during the listening of the WWN sound treatment. In addition, activation of the mechanism underlying the Zwicker tone must have occurred in patients listening to the WWN treatment, although none of them reported such an aftereffect, presumably because of the pitch similarity between the Zwicker tone and the tinnitus percepts. One or both of these phenomena might have determined a reorganization of the neural activity of the edge frequencies resulting in the observed long-term reduction of the tinnitus percept in such patients.

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