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Perception of Internally Generated Noise in Hearing Amplification

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Abstract

Noise generated within hearing aid amplifiers is distracting and, if the level is high enough, may interfere with speech communication. For hearing aid specification and fitting, it is useful to know the acoustic levels at which internal amplifier noise becomes audible and at which it becomes objectionable. This paper reports, for eight subjects with moderate hearing losses, the perceived levels at which internal noise became both audible and objectionable, using a test amplifier with no acoustic input. For comparison purposes, five normal-hearing subjects were also tested. Two noise sources were tested. The first was a broadband noise that was shaped only by the receiver, used to simulate output stage noise. The second was a broadband noise shaped by the target National Acoustics Laboratory-Revised (NAL-R) frequency response for each subject's hearing loss, used to simulate input stage noise. For both types of noise, the overall levels and spectra of the noise are reported for each subject. The relationship between ⅓-octave measurements of the noise and the audiometric configuration of the subjects is explored. The internal level at which the noise was perceived to be audible could be related to ⅓-octave measurements of the noise through the audiometric configuration of each subject's hearing loss. The results for the frequency-shaped input-generated noise and for the output-generated noise were similar.

Key Words: Hearing aid, hearing loss, noise

The measurement and the understanding of acoustic noise levels in hearing aids have become more important with the advance of techniques and technology used for hearing aid integrated circuit design and manufacturing. Hearing aid amplifiers may have different noise characteristics, depending on the particular design and fabrication of the silicon circuit. An example of different noise levels and spectra generated by functionally equivalent hearing aid amplifiers is given in Agnew (1988).

Modern integrated circuits fabricated with complementary metal oxide semiconductor (CMOS) integrated circuit technology typically have 3 to 10 times higher noise than the same circuit architecture implemented with low-noise bipolar devices (Gregorian and Temes, 1986). With an increasing use of CMOS digital and analog circuitry in hearing aids in order to provide more advanced features and functionality, internal noise levels have become more of an issue for both manufacturers and users.

Internal amplifier noise generated within any audio system has always been looked upon as objectionable, since it adds undesired coloration to the reproduced sound. Thus, because it is not possible to realize a totally noiseless hearing aid amplifier in practice, it is useful to know at what level amplifier noise becomes audible, and at what level it becomes distracting or objectionable to the listener.

The problem of specifying reasonable levels of noise performance becomes more complex when considering that the end-user of a hearing aid is hearing impaired. Low levels of noise that are audible to a normal-hearing listener may be inaudible to a hard-of-hearing listener, if the levels are below his or her auditory threshold. However, as internal noise levels increase, they eventually exceed the listener's depressed hearing threshold and become audible. As the noise level increases further, it will become distracting and objectionable. For hard-of-hearing individuals, excessive noise in an assistive amplifying device may be more than just objectionable; it may be disruptive to the ability to understand

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desired speech communications. At high enough levels, the noise may interfere with speech reception, either by direct acoustic masking of the desired signal (Moore, 1986), or by the creation of undesired added intermodulation products in the perceived sound (Agnew, 1988; Teder, 1993).

Acoustic noise in a hearing aid is usually specified as the equivalent input noise (EIN) level or L_n (ANSI, 1987). This figure is the standard specification given on hearing aid data sheets and, for a linear hearing aid, is obtained from the formula:

$$L_n = L_2 - (L_{av} - 60).$$

L_2 is the sound pressure level (SPL) of the internal noise, in dB, measured in a 2-cc coupler. This level is measured by removing any input signal and measuring the output due to the inherent noise within the hearing aid. L_{av} is the mean SPL in the coupler measured with pure-tone input signals of 60 dB SPL at 1000, 1600, and 2500 Hz. Both measurements are made with the hearing aid gain control set to the reference test gain position. In this method of calculating L_n, the smaller the calculated figure in dB, the better the noise performance is assumed to be. A typical maximum-allowable figure used by many manufacturers is a noise figure of 30 dB, with the performance of many hearing aids being measured between 24 dB and 28 dB. This figure, however, may be deceiving in some cases. For example, because power hearing aids have very high gain, the calculated L_n may be quite low, though the absolute noise may be very high and a user may complain of poor noise performance.

Rather than gathering data on EIN figures, the goal of the present study was to obtain measurements, in hearing aids, of the SPLs of noise that were perceived by hard-of-hearing listeners to be audible, and then the levels that were perceived to be objectionable. These data have not previously been available in the literature, but are desirable for hearing aid specification and fitting. The only other data found in the literature relating hearing aid noise to user perception described the noise in terms of equivalent input noise spectra and signal-to-noise ratio (Dillon and Macrae, 1984; Macrae and Dillon, 1986).

For the purposes of simplified noise analysis, a typical basic linear hearing aid can be partitioned into two functional stages: a preamplifier stage with a gain of A1 before the gain control, and an output amplifier stage with a gain of A2 after the gain control, as shown in Figure 1. Most circuits usually also contain a frequency-shaping stage, but, for simplification, this stage can be assumed to have a gain of 1 (and thus be ignored), and its noise contribution included with the preamplifier.

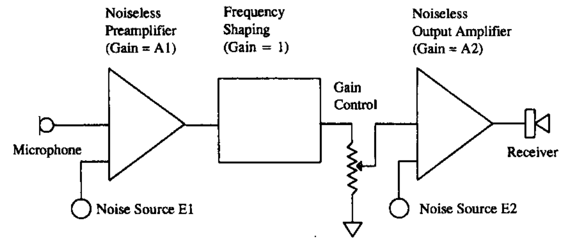

Figure 1 Block diagram of a typical hearing aid amplifier, showing functional stages.

From circuit analysis theory, the preamplifier and output amplifier stages can be considered as noiseless amplifiers with noise sources E1 and E2 attached to their respective inputs. For hearing aid psychoacoustic purposes, these sources of noise relate respectively to the noise perceived from the output transducer when the gain control is at the full-on position, and the noise perceived from the output transducer when the gain control is at the full-off position.

With the gain control at the full-on position, the noise appearing at the output of the hearing aid is the sum of the amplified input noise and the amplified output noise, or

$$\text{Noise}_{\text{VCfull-on}} = E1 * (A1 + A2) + (E2 * A2).$$

Likewise, with the gain control at the full-off position, the noise appearing at the output is

$$\text{Noise}_{\text{VCfull-off}} = E2 * A2.$$

At intermediate gain control positions, the output noise will consist of noise generated by the output stage, (E2 * A2), plus an amplified contribution from the input stage that is proportional to the setting of the gain control. For this study, no intermediate gain control positions were measured, and data were gathered only for the full-on and full-off positions. Anecdotal reports from hearing aid manufacturers' customer service departments have indicated that, if hearing aid wearers complain about excessive noise, it is usually at one of these gain control settings.

METHOD

Test Hearing Aid

A special hearing aid circuit, designed to generate noise for these perceptual tests, was constructed in a single test box with a jack at the output to connect to different receiver modules. The circuit scheme followed that of Figure 1, using a low-noise preamplifier with a variable noise source at its input, and an output stage with a variable noise source at its input.

In order to be able to test with inherent system noise levels below those currently achievable with off-the-shelf hearing aid amplifiers, the test system was constructed with Analog Devices OP-270 low-noise precision audio op-amps. The maximum peak acoustic gain achievable was 35 dB, which was adequate to fit all of the hearing losses of the test subjects. A highly flexible, continuously adjustable filtering stage was included in the signal path to set the frequency response of the test hearing aid to match the National Acoustics Laboratory-Revised (NAL-R) target frequency response for each subject.

To accurately control the level of the noise and to include the ability to test with noise levels much lower and higher than those currently available in hearing aid amplifiers, the test circuit was built with independent noise generators that could be used to accurately generate different levels of input and output noise. These generators were equivalent to noise sources E1 and E2 in Figure 1. The noise generators were designed with switched attenuators at their outputs, with a step size of 3 dB between minimum and maximum output. A switched attenuator was used, rather than a continuously variable control, in order to be able to exactly reproduce the subjects' individual settings for acoustic measurement following the psychoacoustic test session. Each noise generator attenuator also contained a bypass position, by which the noise generator could be completely disconnected from the circuit, thus making the test amplifier into a low-noise hearing aid.

The output transducers were Knowles model EP4107 hearing aid receivers, built into custom in-the-ear hearing aid modules fabricated to fit each subject tested. Though not strictly required for noise measurements, since acoustic amplification was not performed except to verify the target NAL-R setting for each subject, an electret microphone was connected to the input of the test circuit, in order to place a known fixed source impedance on the input of the circuit. In order to lower the input noise below that available using conventional hearing aid microphones, the microphone used in the test amplifier was a low-noise electret pencil microphone intended for high-quality audio recording.

Subject Selection

Eight hearing-impaired individuals, who were experienced hearing aid wearers, were selected as subjects. The ages of the subjects ranged from 58 to 79, with a mean age of 69. General selection criteria included a normal tympanogram, normal otoscopic examination, and a moderate hearing loss, particularly in the high frequencies. Individual audiograms for the eight test subjects are shown in Figure 2.

Subjects with moderate sensorineural hearing losses were selected as being representative of a common hearing loss group who might object to internal noise in hearing aids, and who could benefit from a reduction of internal hearing aid noise. Mild hearing losses were excluded from this study because they were assumed to be close to normal-hearing individuals in their perception of audible noise levels. Subjects with severe hearing losses were also excluded, since their losses are usually such that internal noise in hearing aids is not audible to them.

For comparison with the hearing-impaired results, five normal-hearing subjects (less than 15 dB loss at all audiometric frequencies) were also selected. Unfortunately, when testing this normal-hearing group, all subjects reported hearing the noise at the lowest possible setting of the attenuators. This meant that their hearing was so good that their just-audible setting could not be effectively measured with this test circuit. Therefore, testing could not be completed for this group of subjects, and all data that will be presented are for the group of hearing-impaired subjects.

Test and Presentation Method

To provide acoustic isolation, each subject was seated in a double-walled audiometric test booth during the entire test session.

Following audiometric testing, the NAL-R target frequency response was calculated and set on the test hearing aid. Testing was initiated with both the input and output noise generator attenuators set to the bypass position. Conformance to target response was checked and adjusted in the filtering stage, if necessary, using real-ear measurement equipment.

Four test conditions were explored:

1. With the hearing aid gain control turned to the full-on position, the frequency response controls set to the NAL-R target gain position, the output noise attenuator set to the

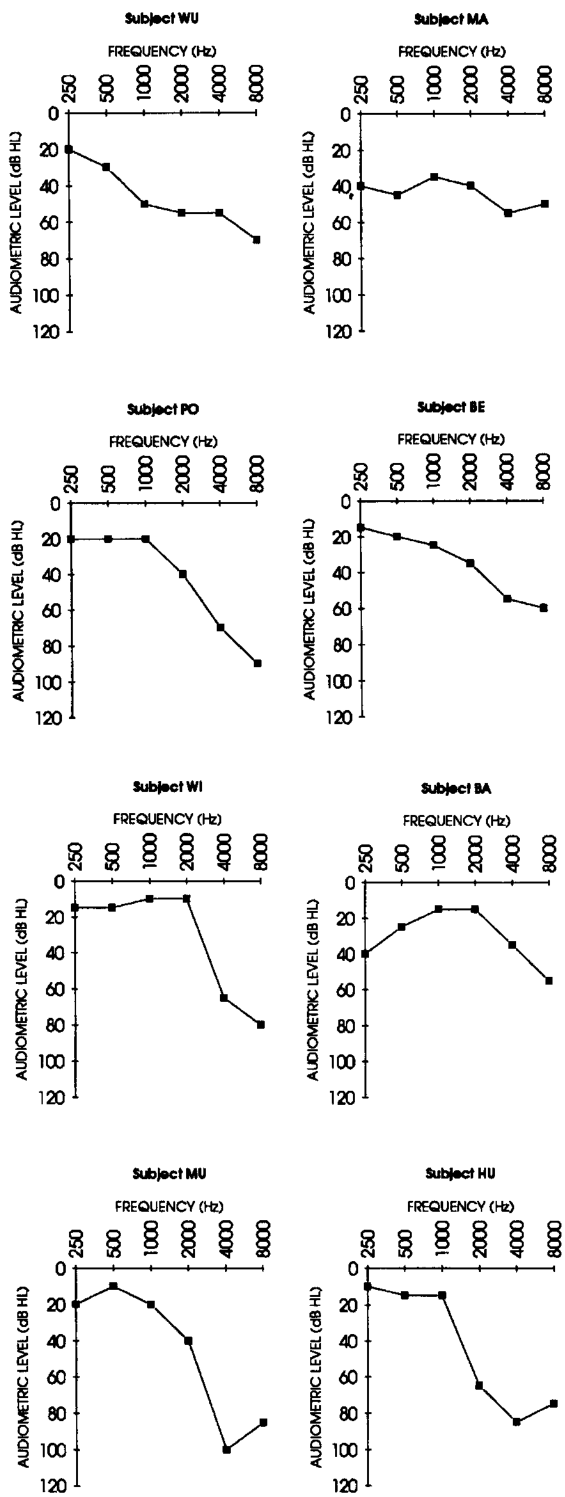

Figure 2 Individual audiograms of experimental subjects.

bypass position, and no acoustic input, the subject was instructed to advance the input noise attenuator to the position where he or she could just hear the input noise. This setting was recorded as the input noise audible setting.

2. The input noise attenuator was then advanced to the position where the subject felt that the noise would be objectionable to listen to for a continuous period of time. This setting was recorded as the input noise objectionable setting.
3. The input noise attenuator was returned to the bypass position and the gain control was set to the full-off position. The subject then advanced the output noise attenuator to the position where he or she could just hear the output noise. This setting was recorded as the output noise audible setting.
4. The output noise attenuator was then advanced to the position where the subject felt that the noise would be objectionable to listen to for a continuous period of time. This setting was recorded as the output noise objectionable setting.

This same testing was performed with the normal-hearing subjects. For the input noise testing, each normal-hearing subject was tested with a randomly selected hearing-impaired subject's NAL-R target gain setting. For output noise testing, the frequency response setting was not applicable.

Following psychoacoustic testing, the levels and spectra of the input and output noise were measured at the setting of each subject's perceived audible and objectionable levels, using a Bruel & Kjaer 2032 dual-channel signal analyzer connected to a type 2619 preamplifier and 4134 ½″ microphone with an attached Knowles Zwislocki coupler. The receiver modules were sealed in the coupler at a uniform depth of 1 cm, in order to closely approximate the insertion depth in the subjects' ears. While this was not a direct measure of the SPL generated in each subject's ear canal, this method was chosen as a standard and repeatable method, under the assumption that these data would eventually be used for both design and manufacturing quality-control purposes. Although a 2-cc coupler is normally used for hearing aid testing and quality control measurements (ANSI, 1973), the conversion back and forth to a Zwislocki coupler is a mathematical extrapolation (Killion and Monser, 1980; Killion and Revit, 1993).

RESULTS

Figure 2 shows the individual audiograms for the eight subjects, by individual. Figure 3 was a first attempt to relate the measured noise spectra from the audible noise settings to each subject's audiometric data. Each subject's audiometric hearing loss data points were converted to SPL values and were then superimposed on the noise spectra plotted in SPL for the perceived input and output noise levels.

Figure 4 was a second attempt to relate the measured noise spectra from the audible noise settings to each subject's audiometric data. Figure 4 is similar to Figure 3, but, for the Figure 4 graphs, the noise spectra were plotted in ⅓-octave values centered at the audiometric frequencies. The individual audiometric data points were then superimposed on these graphs, as in Figure 3.

Table 1 lists the ⅓-octave data values for input and output noise that were used to construct Figure 4, along with the mean value calculated for each frequency and the difference between the input and output noise figures. The mean values are plotted for both input noise and output noise in Figure 5.

Tables 2 and 3 list the measured broadband SPL values for the audible and the objectionable settings for each subject, for both input noise and output noise.

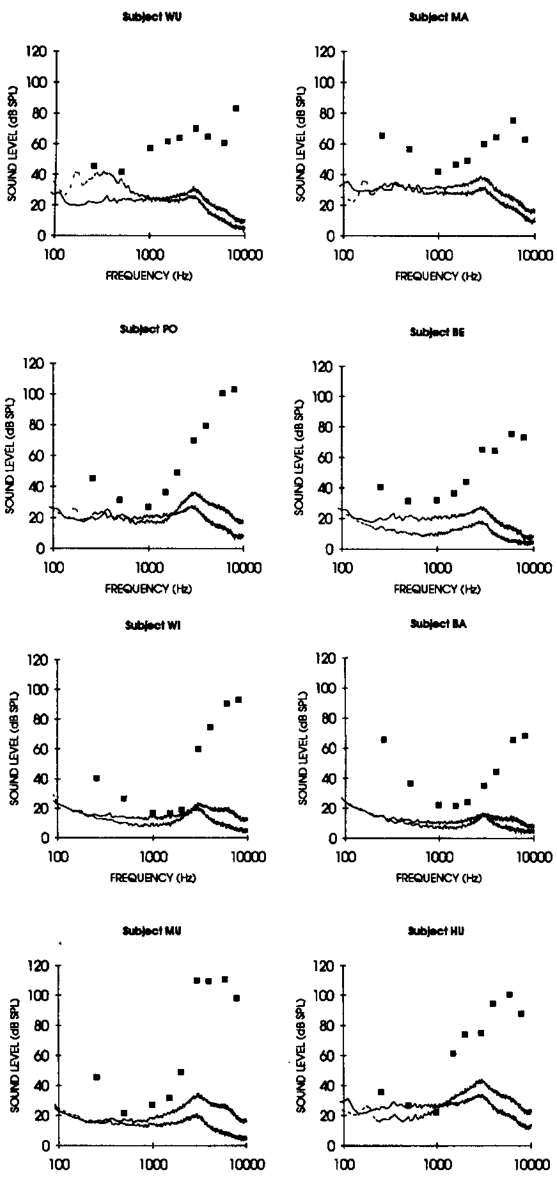

Figure 3 SPL graphs combining audiometric data (squares), input-generated noise data (dashed line), and output-generated noise data (solid line).

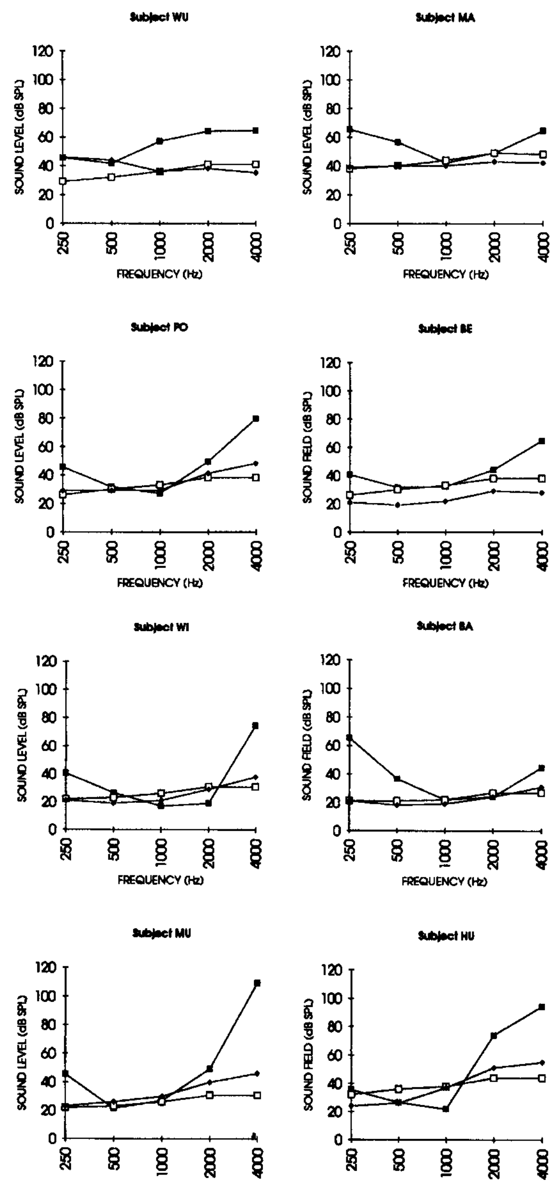

Figure 4 SPL graphs combining audiometric data (solid squares), input-generated noise converted to ⅓ octaves (open squares), and output-generated noise converted to ⅓ octaves (diamonds).

Table 1 ⅓-octave Values in dB SPL for Input and Output Noise

Input Noise					
	Frequency (Hz)				
Subject	*250*	*500*	*1000*	*2000*	*4000*
WU	46	44	36	38	35
MA	39	40	40	43	42
PO	29	29	29	41	48
BE	21	19	22	29	28
WI	21	19	21	29	38
BA	21	18	19	24	31
MU	23	26	30	40	46
HU	24	26	37	51	55
Mean	28	28	29	37	40
Output Noise					
WU	29	32	36	41	41
MA	38	40	44	49	48
PO	26	30	33	38	38
BE	26	30	33	38	38
WI	22	23	26	31	31
BA	21	21	22	27	27
MU	22	23	26	31	31
HU	32	26	38	44	44
Mean	27	29	32	37	37
Difference (dB)	1	1	3	0	3

DISCUSSION

Figure 3 was plotted in anticipation of finding some consistent relationship between the spectra of the noise and the subject's audiometric thresholds. However, as is seen, the noise

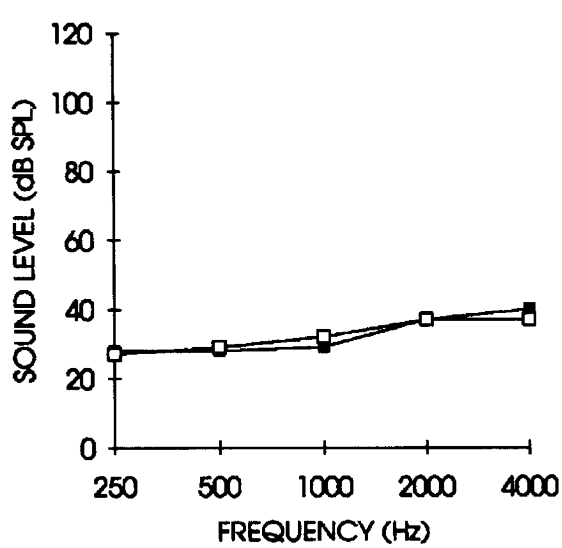

Figure 5 SPL graphs comparing mean input noise spectrum (solid squares) and output noise spectrum (open squares) from Table 1.

Table 2 Sound Levels for Noise Perceived to Be Audible

Subject	*Minimum Audiometric Loss (dB HL)*	*Input Noise (dB SPL)*	*Output Noise (dB SPL)*
WU	41.5	51.7	49.1
MA	42	51.7	57.0
PO	27	54.2	46.1
BE	32	37.0	46.1
WI	17	43.7	39.4
BA	22	38.0	35.9
MU	22	52.3	39.4
HU	22	61.1	52.3
Mean	28	48.7	45.7

plots were typically 5 dB to 10 dB below the audiometric threshold at the lowest point of the audiometric curve for subjects MA, PO, BE, BA, and MU. This would mean that the noise spectra were below the subjects' hearing thresholds, which did not make intuitive sense. Two other subjects varied from just intersecting the audiometric threshold (subject WI) to the audiometric threshold being below the noise spectrum (subject HU). Subject WU was problematic since the low-frequency portions of the noise spectra were widely different, unlike the other subjects, indicating a possible measurement error. Thus, a definite and understandable relationship between the noise level and spectra and the audiometric losses was not observed.

It was interesting, however, that the spectra of the input noise shaped by the NAL-R target settings were, in most cases, not much different from the spectra of the output noise that were shaped only by the inherent frequency response of the receiver. Except for subjects HU and WU, the portions of the spectra that were different were well below the subjects' audiometric thresholds.

Table 3 Sound Levels for Noise Perceived to Be Objectionable

Subject	*Minimum Audiometric Loss (dB HL)*	*Input Noise (dB SPL)*	*Output Noise (dB SPL)*
WU	41.5	65.3	58.9
MA	42	58.0	62.0
PO	27	61.2	52.3
BE	32	45.2	57.0
WI	17	43.7	43.3
BA	22	47.8	49.1
MU	22	74.2	58.9
HU	22	71.0	58.9
Mean	28	58.3	55.1

A second attempt to correlate noise with the audiometric thresholds is plotted in Figure 4, where the noise is plotted in ⅓-octave values centered at the audiometric frequencies. One-third octave analysis is consistent with the frequency analyzing power of the peripheral auditory system, since critical bands are roughly ⅓-octave in width over a fairly wide frequency range (Moore, 1982), though this approximation of critical bands by ⅓-octave filters is only acceptable above about 300 Hz (Zwicker and Fastl, 1990).

In Figure 4, the relationship between the noise and the audiometric threshold becomes more obvious and, with hindsight, should not be particularly surprising. The noise power density for white noise is independent of frequency and the total noise power in a band of frequencies is the number of frequencies multiplied by the noise power density. It is well known from masking experiments that when the width of a band of frequencies equals the critical bandwidth, the total noise power of a masker in that band will equal the power of a tone at the central frequency of the band at threshold (Fletcher, 1940). Thus, for subjects WU, MA, PO, BE, BA, and MU, it is not surprising that the lowest point of the audiometric curve touches the curve for the noise spectrum. For all subjects except BE, the spectrum for the input noise and output noise were almost the same. For subject BE, the output noise spectrum was about 10 dB lower overall than the input noise spectrum. For subjects WI and HU, the audiometric threshold dipped about 5 dB below the graphs for the noise spectra.

For at least six of the eight subjects, then, it seems reasonable to say that the noise becomes audible where the ⅓-octave noise level is tangent to the audiometric curve plotted in SPL. This generalization also makes intuitive sense, in that it seems reasonable that the noise should become audible when the noise level is increased to the level at which it matches the individual subject's minimum audiometric loss.

There are two possible explanations for the differences observed with WI and HU. One is that their interpretation of the instruction "audible" may have been different than for other subjects. A higher SPL may have been required to achieve their perception of audible. A second possible explanation may be found in the measurement accuracy of the audiometric thresholds, which were taken in standard clinical 5-dB steps, and may have led to a lack of precision in the threshold measurements.

From these data, it can be seen that it would be useful for clinicians to have hearing aid manufacturers routinely supply ⅓-octave noise data for their hearing aids. These data could then be compared to the subject's audiogram to determine, before fitting the hearing aid, if the noise might fall into the user's audible area and perhaps generate complaints about audible noise.

As a start in this direction, ⅓-octave noise measurements, made with a 2-cc coupler and the gain control set to the reference test gain position, have been adopted by the International Electrotechnical Commission as an optional measurement for hearing aid characterization (IEC, 1983), and a similar optional measurement has been proposed for the forthcoming version of the ANSI hearing aid standard (ANSI, 1994). Discussion of the use of these ⅓-octave noise measurements is contained in Macrae and Dillon (1986).

As can be seen in Figure 4, the plots obtained for input and output noise were fairly similar. To further investigate the difference between input and output spectra, the mean values of the input and output noise are plotted in Figure 5, with data derived from Table 1. As can be seen, the curves look very similar and are relatively flat. From this observation, it seems reasonable to consider for qualitative analysis that they can be treated as the same spectrum.

Table 2 gives the overall sound levels perceived to be audible for input and output noise, along with the value for the minimum audiometric loss from the subject's audiogram. There does not seem to be any particular relationship between any of these figures. Table 3 gives the overall sound levels perceived to be objectionable. Again, there does not seem to be any particular relationship between any of the columns in the table.

Though it may be misleading to draw conclusions from the mean data presented in Table 2 since each subject has individual variations, it can perhaps be said, as a crude generalization, that a hearing aid with noise levels of about 45 to 50 dB SPL of inherent noise will start to become audible to subjects with a mild to moderate sloping sensorineural hearing loss.

Similarly, from Table 3, a hearing aid with noise levels of about 55 to 60 dB SPL of inherent noise, or about 10 dB higher than audible, will start to become objectionable to some subjects with a mild to moderate sloping sensorineural hearing loss.

CONCLUSIONS

The primary conclusion that can be drawn from this study is that hearing aid noise will become audible where the internal noise of the hearing aid, measured in ⅓-octaves, intersects the subject's audiogram plotted in SPL. Whether the noise is input or output generated does not seem to be important — only the level of the noise presented to the listener. A secondary conclusion is that noise levels of about 10 dB above the audible level will probably start to become objectionable to the listener.

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