

Accuracy of Predicted Ear Canal Speech Levels Using the VIOLA Input/Output-Based Fitting Strategy

Robyn M. Cox and Gregory A. Flamme

Objective: The Visual Input/Output Locator Algorithm (VIOLA) is a software-assisted method for prescribing amplification targets and selecting a hearing aid to match the targets. Although the procedure calls for selection and fitting of hearing aids in terms of their pure-tone input/output functions in a coupler, it is assumed that a hearing aid that matches the coupler prescription targets will produce specific amplified speech levels in the patient's ear canal. This investigation evaluated the validity of that assumption.

Design: Six hearing aids were evaluated. They were representative of linear and compression processing as well as single- and 2-channel designs. The "subject" was a KEMAR manikin with realistic assumed hearing loss and loudness perception characteristics. Each hearing aid was configured to match the subject's VIOLA prescription as closely as possible. Predicted ear canal speech levels were determined using the prescription rules and modified by the differences between coupler prescription targets and coupler performance of the actual hearing aids. With the subject wearing each hearing aid coupled to an unvented earmold, continuous speech was presented in the sound field and measured, after amplification, in the ear canal. The match between observed and predicted levels of amplified speech indicated the validity of the VIOLA assumptions under examination.

Results: The match between predicted and observed levels was good for soft speech input levels. As speech input levels increased, the differences between observed and predicted levels also increased, with the largest differences seen for loud speech inputs. When differences were seen between observed and predicted levels, they were always in the direction of lower than predicted ear canal levels. The differences between observed and predicted levels were attributed to the effects of limiting, effects of compression ratio in wide range compression, the individual subject's field-to-microphone transfer function, and the subject's individual real-ear-to-coupler level difference.

Conclusions: Ear canal speech levels were reasonably close to predicted values, and the deviations from predicted levels were plausibly accounted for

by consideration of hearing aid performance. Thus, the approach used by the VIOLA procedure holds considerable promise for extending clinical control over the complex and interactive parameters of nonlinear hearing aids. The results of this study indicate that selection and fitting of hearing aids using the current VIOLA procedure usually will result in the generation of lower than predicted ear canal speech levels, especially for loud speech inputs. However, the accuracy of the procedure could be improved substantially by modification of the software to account for the effects of limiting and those of the compression ratio in systems with compression thresholds lower than the level of unamplified loud speech.

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The Visual Input/Output Locator Algorithm (VIOLA) is a software-assisted method for prescribing amplification targets and selecting a hearing aid to match the targets. The approach is suitable for either linear or nonlinear instruments. The goal of the procedure is to restore the loudness of typical speech input levels to those that are experienced by normal-hearing persons. The method relies on recreating the normal relationships between speech at three vocal efforts (soft, average, and loud) and the loudness of warble tones measured using the Contour test (Cox, Alexander, Taylor, & Gray, 1997).*

Figure 1 illustrates the theoretical basis of the VIOLA prescription. The upper panel depicts the relationship between speech stimuli and the loudness of warble tones for a group of normal-hearing listeners. One-third octave band levels at five test frequencies are shown for three speech input levels (solid lines). The shaded areas depict a loudness map generated using the Contour test procedure with warble tone stimuli. Note that the 1/3 octave band levels for soft speech fall in the lower part of the range of soft warble tones, the 1/3 octave band levels for average speech fall in the upper part of the

* The VIOLA procedure is incorporated as a component of the IHAFF protocol (Valente & Van Vliet, 1997). Software to implement the procedure also may be obtained by contacting the first author or through the Hearing Aid Research Laboratory home page at www.ausp.memphis.edu/harl.

University of Memphis (R.M.C., G.A.F.), and Department of Veterans Affairs Medical Center (R.M.C.), Memphis, Tennessee.

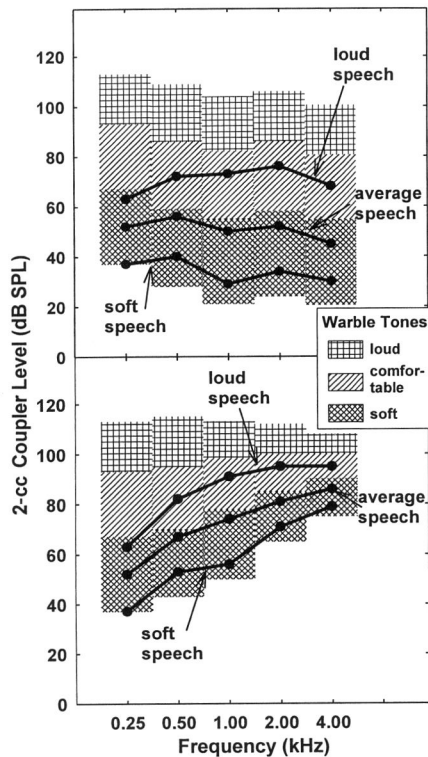


Figure 1. Theoretical basis of the Visual Input/Output Locator Algorithm prescription rationale. The upper panel shows the relationships, for normal-hearing listeners, between 1/3 octave band levels of speech at three vocal efforts (soft, average, and loud) and judgments of the loudness of warble tones derived from the Contour test. The lower panel illustrates the replication of these relationships for a hearing-impaired individual.

range of soft warble tones, and the 1/3 octave band levels for loud speech fall near the middle of the range of comfortable warble tones (except for 250 Hz). The lower panel depicts the loudness map from the Contour test for a typical hearing-impaired listener as well as the location of the 1/3 octave band speech spectra that would be required to recreate the loudness relationships between speech and warble tones that were observed for normal hearers as depicted in the upper panel. For each frequency, the required amplification for each speech input level is the difference between the unamplified speech level in the upper panel and the amplified speech level in the lower panel. Thus, at each frequency, three target levels are computed, one for each speech input level. Further description of the procedure can be found in Cox, 1995.

Using the VIOLA approach, hearing aid selection follows a two-dimensional strategy, considering gain as a simultaneous function of frequency and input level. The software facilitates the selection process by providing templates for input/output (I/O) functions for two frequencies. Each template shows the

prescribed target levels at that frequency for the 1/3 octave bands of speech at the three input levels (soft, average, and loud). The dispenser evaluates potentially appropriate instruments by: 1) entering values for signal processing parameters (gain, compression, maximum output); 2) having the program display the I/O function produced using those parameter values and; 3) observing the closeness of the match between the I/O functions and the target levels at both test frequencies. The goal is to select a hearing aid configuration for which the I/O function at each test frequency passes close to the three targets and does not exceed the upper limit of the "loud" region for warble tones.

Inherent in the VIOLA procedure is the assumption that a hearing aid with the prescribed pure-tone I/O functions at test frequencies would produce amplified speech in the ear canal having the target long-term 1/3 octave band spectra for soft, average, and loud speech inputs. The purpose of this study was to evaluate the accuracy of that assumption for unvented hearing aid fittings.

METHOD

Target Ear Canal Levels for Amplified Speech

To use the VIOLA procedure clinically, it is not necessary to compute the target long-term 1/3 octave band spectrum in the ear canal for each speech input level. However, to allow comparison of observed and predicted ear canal speech levels in this study, the target ear canal spectra were needed. They were generated as follows: 1) The Contour test was administered to a hearing-impaired subject at six test frequencies to determine the levels of warble tones that corresponded to seven categories of loudness for that individual. Data were expressed in ear canal sound pressure levels. 2) Equations derived from normative data (see Cox, 1995) were applied to the Contour test data to determine the ear canal 1/3 octave band levels of speech necessary at each test frequency to reproduce the normal relationships between speech inputs and the loudness perception data obtained for warble tones. This procedure was used to generate target ear canal 1/3 octave band spectra for each of three speech input levels (soft, average, and loud).

In the VIOLA procedure it is theoretically possible to use I/O functions for up to six test frequencies for the purpose of selecting and fitting a hearing aid. However, in the practical application of the procedure, it is typical to use I/O functions for two test frequencies. In this study, we evaluated the extent to which hearing aids fitted using I/O functions for two frequencies (500 Hz and 3000 Hz) would pro-

TABLE 1. Puretone thresholds and warble tone loudness contours assumed for the KEMAR's test ear (dB HL).

Contour	Frequency in kHz					
	0.25	0.5	1.0	2.0	3.0	4.0
Threshold	45	45	45	60	70	65
Very soft	57	57	55	74	76	71
Soft	61	64	61	78	80	75
Comfortable/soft	66	67	65	80	83	78
Comfortable	68	71	69	84	87	82
Comfortable/loud	73	77	72	88	89	83
Loud, but OK	76	81	80	91	94	88
Uncomf. loud	80	92	88	94	96	92

duce the predicted spectra of amplified speech in the ear canal when the predicted spectra were based on loudness data from six test frequencies.

Subject

Table 1 gives threshold and loudness contour values for the test ear of the "subject." Although assumed to apply to the KEMAR manikin, these data are based on the results obtained from an individual with a moderate, gently sloping sensorineural hearing loss.

Stimuli

Continuous speech from the Connected Speech Test (CST) (Cox, Alexander, Gilmore, & Pusakulich, 1989) was presented to the experimental hearing aids at each of three levels, corresponding to soft, average, and loud vocal effort. In the VIOLA procedure, the overall long-term levels assumed for soft, average, and loud vocal effort are 50, 65, and 85 dB, respectively. The three speech levels also are defined in terms of their 1/3 octave band spectra in the unobstructed sound field (Cox, 1995). As vocal effort increases, the long-term speech spectrum changes in shape as well as in level (Pearsons, Bennett, & Fidell, Reference Note 2). For each speech level presented in this investigation, the speech spectrum of the talker for the CST was shaped to conform as closely as possible to the typical talker shape assumed in the VIOLA program. The shaped speech was then amplified to the overall level appropriate for that vocal effort. Figure 2 depicts the 1/3 octave band spectra of speech in the sound field (solid lines), representing soft, average, and loud vocal effort used in the study. The filled symbols depict the corresponding 1/3 octave band levels assumed in the VIOLA procedure. Because the symbols depicting assumed levels align very closely with the shaped CST speech spectra used in this study, we can be confident that any differences between ob-

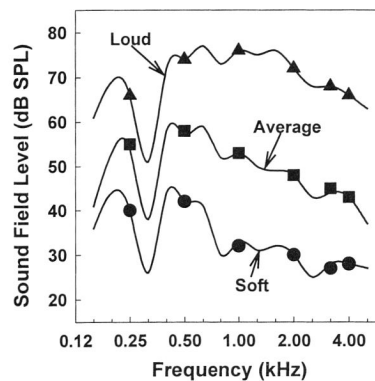


Figure 2. Solid lines illustrate the 1/3 octave band spectra of speech used in the study to represent soft, average, and loud vocal effort. Filled symbols depict the 1/3 octave band levels assumed in the Visual Input/Output Locator Algorithm procedure for each vocal effort.

served and predicted ear canal levels for amplified speech were not due to inaccuracies in the speech input spectra.

It should be noted that vowels and consonants produced with loud vocal effort are somewhat different in intensity relationships from the same units spoken with average vocal effort (Tschopp, Kaser, & Kunert, 1992). These differences in individual speech units were not reproduced in our simulation of loud vocal effort. The effect, if any, of this discrepancy is not known.

Hearing Aids

Four different hearing aid models were configured to produce six hearing aid test conditions. They were chosen to exemplify single-channel and 2-channel designs as well as linear and wide dynamic range compression (WDRC) processing. In addition, one instrument was tested in both long release time and short release time modes to evaluate the effect, if any, of this variable. Table 2 summarizes the six test conditions.

The hearing aid conditions were chosen to represent differing processing strategies. They were not necessarily expected to allow a good match to the VIOLA targets. It is well known, for example, that

TABLE 2. Hearing aid conditions tested.

Hearing Aid Condition	Processing	Channels
1. Widex, Quattro Q8®	Linear, compression limiting	1
2. Qualitone, TKA	WDRC, TILL K-amp®	1
3. Qualitone, TKA	WDRC, FFR K-amp®	1
4. Resound, BT2®	WDRC	2
5. 3M™, 8200	WDRC, short release	2
6. 3M™, 8200	WDRC, long release	2

WDRC = wide dynamic range compression; TILL = treble increase at low levels; FFR = flat frequency response.

hearing aids with linear processing and a fixed volume control setting often can over-amplify loud speech and under-amplify soft speech.

Procedure

The general approach to data collection was as follows:

1. Obtain basic prefitting data: The audiogram and corresponding contour data obtained from an actual hearing aid candidate were assumed to have been obtained from a KEMAR manikin. The data were expressed in ear canal levels (to obtain target speech spectra), in 2-cc coupler levels (to enter into the VIOLA software to generate targets for I/O functions), and in hearing levels (dB HL) for descriptive purposes (see Table 1). The real-ear-to-coupler level difference (RECD) reported by Revitt (1994) was used to convert between ear canal and coupler levels. (In retrospect, it would have been slightly more accurate to use the RECD reported by Killion and Revitt [1993] because it assumes measurements at the ear drum. This would have resulted in a 1 dB lower coupler level at 3000 Hz.)

2. Generate prescription target values: The Contour data were entered into the VIOLA program, which used them to obtain prescribed target values for I/O functions at 500 Hz and 3000 Hz for a monaural Behind-The-Ear hearing aid in an unvented fitting.

3. Match the targets using hearing aid specifications: Using data obtained from the specifications for one of the tested hearing aid conditions, hearing aid parameter values were entered to generate I/O functions at the two test frequencies. The I/O functions were evaluated, and the parameter values were modified until the VIOLA-prescribed target values were matched as well as possible. The goal of the matching procedure was to select a combination of the hearing aid's fitting parameters that would result in I/O functions at the test frequencies that passed through each target dot and did not exceed the upper limit of the "loud" region on the VIOLA graph.

4. Optimize the match and measure hearing aid I/O functions: After selection of best-match parameter values using hearing aid specifications and the VIOLA program, the actual hearing aid was attached to an HA-1 coupler using an earmold comprising a compressible foam plug threaded with a 3 mm Libby horn trimmed at the hearing aid end to fit KEMAR. The hearing aid controls were adjusted as prescribed in the VIOLA procedure, and I/O functions were measured in a test box at 500 and 3000 Hz. These I/O functions were compared with the VIOLA prescription targets. If it was possible to

achieve a better match to the target values by further adjustments of the hearing aid controls, these adjustments were made and final I/O functions were recorded.

5. Fit the hearing aid to KEMAR: The fully configured hearing aid then was fitted using the same compressible foam earmold to the ear of a KEMAR manikin, equipped with an ear-simulator coupler and ½ inch pressure-calibrated microphone. The manikin was located in the approximate center of a sound-treated audiometric test room. None of the extraneous noises was high enough to affect the data: ambient noise 1/3 octave band levels were less than 10 dB SPL in the range from 250 to 5000 Hz, and equivalent input noises for the tested hearing aids ranged from 20 to 25 dB SPL.

6. Present speech in the sound field and measure amplified spectrum in the ear canal: Continuous speech was presented at one of the three speech input levels (soft, average, or loud) from a small loudspeaker located at a zero-degree azimuth 1.0 m from the manikin. The long-term 1/3 octave band spectrum of amplified speech in the ear canal was measured at the manikin's simulated eardrum.

7. Compare measured spectrum with predicted spectrum: The measured 1/3 octave band spectrum of amplified speech in the ear canal was compared with the predicted values at the two test frequencies for that speech input level. The predicted values were derived from the ear canal target levels computed using the prescription rules, modified by the error in the match between the VIOLA I/O function prescription target levels and the I/O function actually produced by the experimental hearing aid when tested in an HA-2 coupler (an example of the determination of predicted level is given below). This comparison between measured and predicted spectra revealed the extent to which this particular hearing aid produced the amplified speech levels in the ear canal that were called for by the assumptions of the VIOLA procedure.

8. Repeat for other speech levels: Steps 6 and 7 were repeated for each of the two other speech input levels.

9. Repeat with the next hearing aid condition: Steps 3 through 8 were repeated using each different hearing aid condition.

RESULTS

Match of I/O Functions to VIOLA Targets

Figure 3 illustrates the final I/O templates from the VIOLA program for each hearing aid condition. This figure shows the extent to which each tested condition actually matched the coupler prescription targets. Note the following:

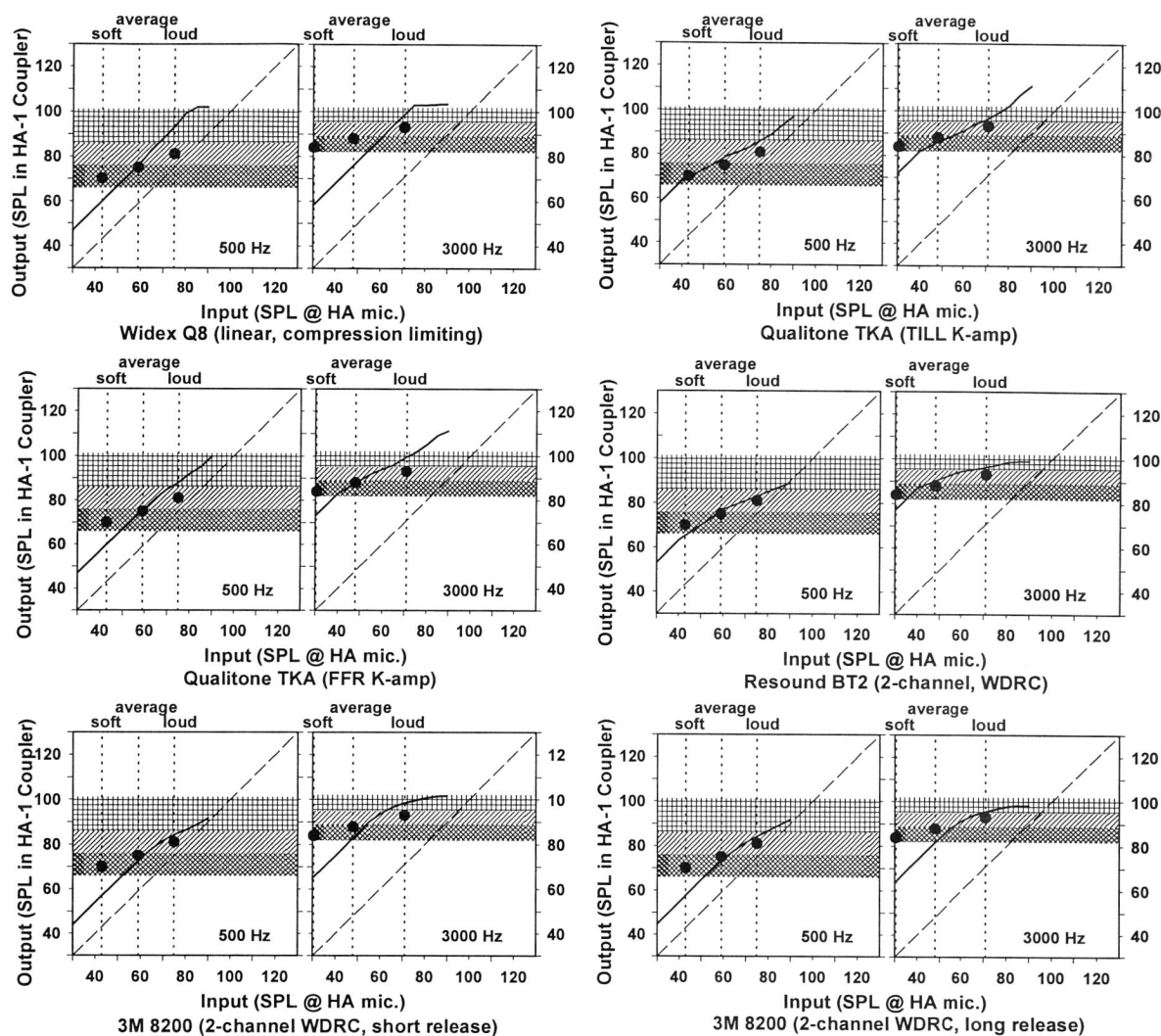


Figure 3. Final input/output templates from the Visual Input/Output Locator Algorithm program for each hearing aid condition. Data are provided for 500 Hz (left panel) and 3000 Hz (right panel). Each panel shows loudness judgments by the subject (shaded areas), assumed 1/3 octave band input levels of soft, average, and loud speech (dotted lines), target levels derived from the prescription (filled circles), and the hearing aid input/output function (solid line).

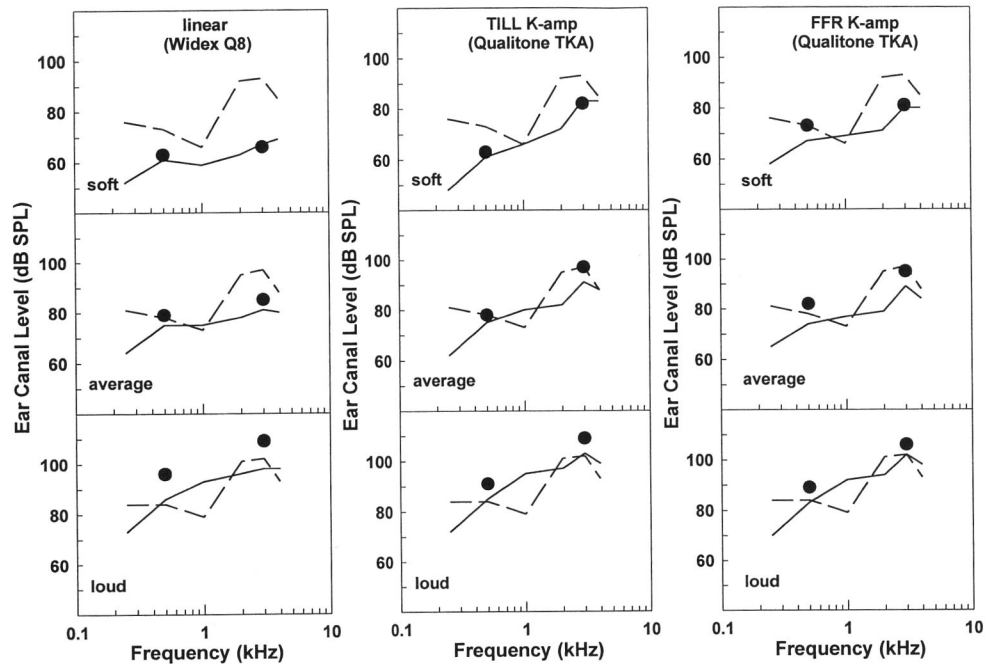
- The horizontal shaded regions depict the subject’s judgments of soft (bottom band), average (middle band), and loud (top band) warble tones from the Contour test, expressed in HA-1 coupler levels.
- The vertical dotted lines denote the 1/3 octave band levels of speech at the test frequency for soft, average, and loud vocal efforts. These levels reflect the input to the hearing aid’s microphone in the sound field. Because of head baffle effects, they vary to some extent depending on the style of hearing aid selected in the prescription program.
- The filled circle on each dotted line shows the target output level in the HA-1 coupler for that speech input level at the test frequency.
- The diagonal dashed line indicates the zero coupler gain locus.
- The vertical distance between each target circle

and the zero gain line indicates the 2-cc coupler gain needed for that speech input level.

- The solid lines in each panel show the I/O functions at 500 Hz (left) and 3000 Hz (right) after optimization of the match between the VIOLA targets and the hearing aid’s I/O performance measured in the test box.

In each I/O template, the differences between the filled circles (prescription target levels) and the I/O function (achieved levels) give the predicted deviations of amplified speech from prescription target values in the real ear. For example, from the data for the Widex Q8 (upper left panel in Fig. 3), we predicted that, at 500 Hz, the real ear level produced by the Widex hearing aid would be 10 dB lower than the prescription target for soft speech, 1 dB higher

Figure 4. Results for the three 1-channel instrument conditions. Each panel shows the prescription target 1/3 octave band ear canal spectrum for amplified speech (dashed line), the predicted ear canal levels of amplified speech at two frequencies (filled circles), and the 1/3 octave band spectrum of amplified speech actually measured in the ear canal (solid line).



for average speech, and 13 dB higher for loud speech. To determine the predicted ear canal speech levels after amplification in this hearing aid condition, these differences were added to the ear canal 1/3 octave band prescription target level for each speech input level.

Match Between Measured and Predicted Ear Canal Speech Levels

Figures 4 and 5 depict the ear canal level measurements for the six hearing aid conditions. Figure 4 shows data for the three 1-channel instrument conditions. Figure 5 shows the corresponding data for the three 2-channel instrument conditions. Note the following:

- The figures give data for soft (top panel), average (middle panel), and loud (bottom panel) speech level inputs for each hearing aid.
- Each dashed line depicts the 1/3 octave band ear canal target spectrum for speech after amplification (based on six test frequencies). This line is derived from the prescription and is the same for all hearing aid conditions for a given speech input level.
- The filled circles show the predicted levels of amplified speech in the ear canal in that hearing aid condition for the two test frequencies used in the VIOLA program. Each circle was derived from the prescribed ear canal target level plus the difference between the VIOLA HA-1 coupler target and the HA-1 coupler I/O function for the actual hearing aid (as described above).
- Each solid line portrays the 1/3 octave band levels

of amplified speech actually measured in the ear canal at six frequencies.

DISCUSSION

Figure 3 shows the extent to which the different hearing aid conditions could be configured to match the prescription targets determined by the VIOLA method for this particular set of individual data. The results follow expected patterns. All six conditions were adjustable to achieve a close match to the target for average speech at 500 Hz. The extent of match for other low-frequency targets and for all high-frequency targets varied across hearing aids. The linear instrument undershot the soft speech target and overshot the loud speech target at both test frequencies. In addition, because of limitations in frequency response shaping, average speech was under-amplified at 3000 Hz in the linear condition.

All of the WDRC conditions achieved a fairly close match to the targets for average speech at both test frequencies. The match for soft and loud target levels varied across compression hearing aids, with the best overall matches achieved by the Resound instrument and the Qualitone FFR K-amp. Note that these results apply to this particular combination of threshold and loudness data and would not necessarily generalize to fittings with these hearing aids for other individuals.

Figures 4 and 5 contain the data that answer the questions of this investigation. From these figures we can determine the extent to which amplified speech in the ear canal could be predicted from the

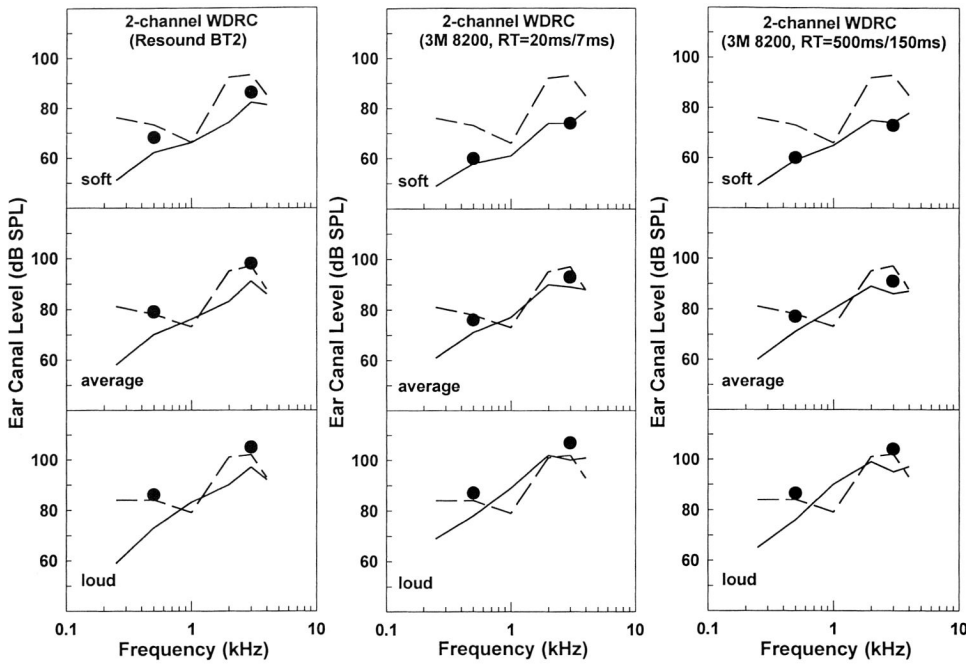


Figure 5. Results for the three 2-channel instrument conditions. See Figure 4 legend. WDRC = wide dynamic range compression.

VIOLA fitting strategy based on pure-tone I/O functions. In evaluating the results for each hearing aid condition depicted in Figures 4 and 5, keep in mind that if the measured ear canal speech levels (solid lines) coincide with the predicted levels (filled circles), the tested assumptions of the VIOLA method have been shown to be valid for that hearing aid condition and that speech input level.

Taken together, the results depicted in Figures 3, 4, and 5 support the following observations:

1. When a predicted level occurred on a linear portion of the hearing aid's I/O function, and the hearing aid was operating well below limiting, the ear canal levels of amplified speech were quite similar to the predicted values. This can be seen for soft speech for the Widex Q8, the 3M 8200 (both conditions), the TILL K-amp, and the FFR K-amp (at 3000 Hz). The mean error across these conditions is -1.7 dB at 500 Hz and +0.3 dB at 3000 Hz.

2. When a predicted level occurred on a nonlinear portion of the hearing aid's I/O function (as shown in Fig. 3), the observed amplified speech level was lower than the predicted value. This outcome might be explainable in terms of the probable levels actually stimulating a hearing aid during speech. When speech is presented to the hearing aid, the bandwidth and spectrum of the input signal vary widely depending on the individual phonemes and almost always encompass more than a single 1/3 octave. As a result, the actual input level to the hearing aid typically would be higher than the 1/3 octave band level at a single frequency that is used in the VIOLA procedure. When this input is above the compress-

ion threshold, a higher input level would result in lower gain, which would lead to a lower than predicted ear canal level in individual 1/3 octave bands. If this explanation is valid, the size of the effect should be proportional to the compression ratio, with higher ratios producing more deviation from predicted values. To explore this hypothesis, we examined the relationship between prediction errors and compression ratios. The result is illustrated in Figure 6. The figure includes a data point for each speech input level for each of the five compression conditions and for each of the two test frequencies. Linear regression analysis yielded the solid line for each frequency, which shows the overall relationship between compression ratio and prediction errors. The correlation coefficients were 0.91 for 500 Hz and 0.75 for 3000 Hz. This outcome supported our hypothesis of a fairly strong relationship be-

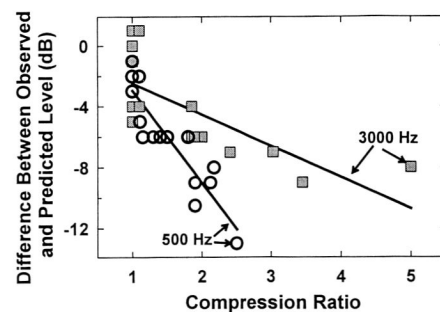


Figure 6. Each symbol gives the relationship between prediction error and compression ratio for one combination of hearing aid, frequency, and speech input level. The linear regression lines are illustrated for each test frequency.

tween compression ratios and amount by which amplified levels undershot predicted levels in compression hearing aids.

3. There are two additional noteworthy features of the data in Figure 6. First, the relationship between compression ratio and prediction errors was different at the two frequencies, with a given compression ratio resulting in a greater prediction error at 500 Hz than at 3000 Hz. This outcome may be due to different time/intensity characteristics of the speech signal at the two frequencies. Second, in conditions where processing was essentially linear (compression ratio close to 1.0), there was still an overall trend for the observed levels to be slightly less than the predicted levels. The regression equations indicate that the typical error associated with a compression ratio of 1.0 would be -3.0 dB at 500 Hz and -2.4 dB at 3000 Hz.

4. The under-amplification of average and loud speech processed by the Widex Q8 hearing aid was somewhat greater than expected. This instrument was a linear processor with compression limiting. Figure 3 shows that pure-tone levels equivalent to average speech were well below the OSPL90 (ANSI, 1996) values, and those for loud speech were 4 to 8 dB below OSPL90. Accepted thinking would suggest that under these circumstances the effects of compression limiting would be negligible for average speech and noticeable for loud speech. This is consistent with the work of Dillon (Reference Note 1), showing the extent to which limiting reduces broadband signals relative to the maximum output measured in the standard manner using pure tones. Dillon's theoretical approach would predict limiting effects for speech amplified by the Widex hearing aid in this study to be 0 dB for average speech and 7.5 dB for loud speech. We would expect this effect to be manifested as ear canal levels that were 0 dB and 7.5 dB lower than predicted for average and loud speech, respectively. Instead, we observed that the amplified level of average speech was 4 dB lower than predicted and that of loud speech was 10.5 dB lower than predicted. Thus, for both average and loud speech, the observed ear canal levels were about 3 to 4 dB less than expected even after accounting for the effects of limiting.

5. Comparison of results obtained with the two 3M hearing aids (Fig. 5) reveals that varying the release time did not affect the match between predicted and observed levels. Long time constants did not result in more or less error than short time constants. This outcome is consistent with the report by Bentler and Nelson (1997), indicating that similar variations in release time did not result in a systematic effect on performance with or preference for a hearing aid condition.

6. Errors between observed and predicted levels were about the same for single-channel WDRC systems and 2-channel WDRC systems. Note, however, that this result might not apply to other single-channel instruments or to all hearing loss configurations.

Figures 4 and 5 show that the VIOLA procedure is fairly accurate in predicting ear canal amplified speech levels for unvented hearing aid fittings, especially for soft and average speech inputs. When differences occurred between predicted and observed values, the errors always revealed lower than predicted amplified speech levels. After accounting for the effects of limiting (the Widex hearing aid) and wide range compression (the other five hearing aids), a persistent negative error of 2 to 4 dB was seen. Several variables were examined in an attempt to determine the source of this error. They included: 1) the sound field-to-microphone transfer function, 2) any earmold leakage, and 3) the RECD for the ear simulator coupler.

It was found that the actual sound field-to-microphone transfer function for the KEMAR manikin wearing a Behind-The-Ear hearing aid was about 1 dB less at 500 Hz and 2 dB less at 3000 Hz than assumed by the VIOLA software. Thus, the dotted lines depicting speech input levels on the VIOLA graphs were slightly too high. The result is to prescribe slightly less gain than actually is needed to meet the real ear goals. In addition, a post hoc measurement revealed that the RECD for the ear simulator coupler used in the study was 1 dB less at both VIOLA test frequencies than the average RECD reported by Revitt (1994) and used in the transformations between ear canal and coupler levels. The effect of this discrepancy would be to predict ear canal levels about 1 dB too high relative to coupler levels.

Taken together, the small deviations from expected values for field-to-microphone transfer function and RECD probably explain the consistent several dB by which observed ear canal levels were less than expected after accounting for limiting and compression effects. The RECD error was specific to this investigation and does not have implications for the overall accuracy of the computations used in the VIOLA method. The difference between the individual field-to-microphone transfer function and the average transfer function assumed by the software was not specific to this study and can be expected to occur with all applications because most individuals will vary to some extent from the average values. The size of this error usually will be quite small and will vary with the individual hearing aid wearer.

On principle, a hearing aid fitting should allow the hearing-impaired listener to make maximum

use of his or her residual dynamic range. If amplified levels in the ear canal are less than desired, it is unlikely that the fitting will promote full utilization of residual hearing. Thus, it is important to address the fact that ear canal levels were less than predicted under several conditions using the VIOLA procedure. On the other hand, the fact that ear canal levels did not exceed predicted levels under any condition is somewhat reassuring from a clinical point of view because it indicates that, when fitted using this method based on I/O functions, patients are not likely to be exposed to ear canal speech levels that are higher than expected. Recent work by Stelmachowicz, Kopun, Mace, and Lewis (1996) is pertinent to this issue. These authors demonstrated that when hearing aids are selected on the basis of traditional pure-tone sweep frequency gain data, ear canal levels of amplified speech often can be considerably greater than expected.

The accuracy of the VIOLA procedure could be improved by incorporating two features into the software. Addition of these features to the VIOLA software would probably remove most of the prediction errors seen in this investigation.

First, the procedure could be modified to account for the error expected with any compression ratio so that adjustments could be made to provide a better match to predicted levels in the ear canal. Based on the current data, the following regression equations would be used:

$$\text{Error}_{500} = 3.1 - 6.1(\text{Compression Ratio})$$

$$\text{Error}_{3000} = -0.4 - 2(\text{Compression Ratio})$$

More data would be needed to verify these equations and to add equations for other test frequencies.

Second, the effects of limiting (either peak clipping or compression) could be predicted using the approach developed by Dillon (Reference Note 1). It should be kept in mind, of course, that the perceptual effects of peak clipping and compression limiting would be different because of the greater distortion introduced by peak clipping.

FINAL COMMENTS

This investigation sought to evaluate the accuracy with which the VIOLA procedure for hearing aid fitting predicts the ear canal level of amplified speech. The method was investigated for hearing aids in unvented fittings on a single hypothetical subject implemented using a KEMAR manikin. Six different hearing aids were examined at three different speech input levels. It was determined that the levels of amplified speech in the ear canal were quite similar to the predicted levels and that all of the observed errors were in a negative direction (i.e.,

a lower speech level than predicted). These errors were largely accounted for by consideration of the effects of wide range compression, the effects of limiting, and the actual sound field-to-microphone transfer function. Based on the results of this investigation, the VIOLA procedure can be refined to improve the accuracy of predictions of amplified speech levels in the ear canal for unvented hearing aid fittings.

Dispensers should note that amplified levels in the ear canal can be influenced by the use of ear mold venting, with the frequency and direction of effects depending on the dimensions and design of the vent. These effects will have an independent impact on the match between predicted and observed levels in the ear canal for any hearing aid fitting strategy, including the VIOLA method. Estimates of the effects of venting can be found in several sources (e.g., Dillon, 1991; Tecca, 1991), but precise data on a particular vent must be measured on an individual basis. If the VIOLA procedure is used to predict ear canal levels of amplified speech in a clinical situation, the effects of any vent in the earmold also should be taken into account.

It is important to keep in mind that this investigation was not designed to evaluate the efficacy of the prescriptive method used by VIOLA (illustrated in Fig. 1). The outcomes of this study indicate that ear canal levels of amplified speech in an unvented hearing aid fitting can be predicted rather well from pure-tone I/O functions and a consideration of the limiting and compression characteristics of the hearing aids. The effectiveness of the method used to generate prescriptive targets for the I/O functions is an independent issue and must be evaluated using other methods.

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Address for correspondence: Robyn M. Cox, Ph.D., Hearing Aid Research Laboratory, 807 Jefferson Ave., Memphis, TN 38105.

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