Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 37 No. 4, July/August 2000
Pages 473–481

# Fitting hearing aids with the Articulation Index: Impact on hearing aid effectiveness

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**Abstract**—Although most clinical tests focus on how much a particular hearing aid improves speech audibility under controlled conditions, it is unclear how these measures relate to hearing aid effectiveness, or the benefit perceived by the patient under everyday conditions. In this study, the relationship between audibility and hearing aid effectiveness was examined in a cohort of patients who obtained hearing aids through the Veteran's Administration. The measure of audibility was the Articulation Index, a common index of speech audibility. Measures of effectiveness included two hearing-specific surveys and self-reported ratings of global satisfaction and hearing aid use adherence. Results indicated that there were no systematic relationships between measurements of improved audibility and patient ratings of communication ability. Additionally, improved audibility was not related to overall satisfaction with the amplification characteristics of the hearing aid (fitting). However, improved audibility is related to hearing aid use adherence, with patients who achieve better audibility reporting that they use their hearing aids more frequently.

**This material is based on work supported by a grant from the Deafness Research Foundation and by a Department of Veterans Affairs, Veterans Health Administration, Health Services Research and Development Service Career Development Award #CD-98318.**

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**Key words:** *audibility, effectiveness, hearing aid*

## INTRODUCTION

Both physicians and audiologists are increasingly aware of a need to quantify the outcomes of hearing amplification. The evaluation of outcomes after a treatment can be thought of as either measures of efficacy or measures of effectiveness. Efficacy refers to the degree of benefit that a specific group of patients in an experimental setting receive for treatment under ideal conditions. Effectiveness reflects the benefit the typical patient receives in a community setting for treatment under ordinary conditions. Because the primary goal of hearing amplification is to increase the amount of speech information received by the patient (1–5), most clinical tests focus on how much a particular hearing aid improves speech audibility under controlled conditions. The greater the increase in audibility with the hearing aid, the more the patient's performance is expected to improve with amplification. However, it is unclear whether the measures used to assess audibility in the clinic can actually predict effective treatment when patients take the aids home and use them in a normal community setting.

A popular way to quantify audibility is to use an audibility index, which is a single number that expresses the amount of speech information available to the patient. The most common of these indices is the Articulation Index, or AI (6, 7). The AI is based on the amount of audible speech information in each of several frequency bands and on the importance of each band to speech recognition. The contribution of each band is summed, resulting in a calculated AI value that ranges from zero, indicating that speech is inaudible, to one, indicating that speech is fully audible. In other words, an AI of 0.5 would indicate that half of the available speech information is audible to the patient.

There has been a recent surge of interest in using the AI to evaluate hearing aid effectiveness (8), due in part to the availability of simple calculation methods appropriate for use in the clinic (9–12). The recent incorporation of such methods into clinical test equipment allows the audiologist to assess instantly the audibility for any set of measured amplification characteristics. For example, an audiologist might use the AI to select between three possible hearing aids (or between different hearing aid settings), ultimately choosing the hearing aid that provides the highest audibility for the patient. Several investigators have suggested that the hearing aid that produces the highest AI offers the best treatment choice for the patient (9–11). However, it is important to remember that what is considered "best" may depend on the choice of outcome variables (13).

Thus far, evaluations of the AI have focused on efficacy measurements (e.g., speech recognition) obtained in a controlled setting such as a sound-attenuated booth. For example, higher AIs are associated with better speech recognition scores (14–20). Because increased audibility is linked to improved speech recognition, and because improvements in speech recognition are desirable, it has been assumed that higher aided AIs should also lead to increased hearing aid effectiveness. For example, Cox and Alexander (21) noted that predictions of hearing aid benefit were most accurate when audibility was taken into account. However, every audiologist is familiar with patients who receive maximal audibility improvement, and corresponding improvements in speech recognition, and yet report their hearing aids provide little benefit. Ultimately, the extent to which improved audibility independently influences hearing aid effectiveness is unknown (11).

In the present study, the relationship between audibility and hearing aid effectiveness was examined in a cohort of patients who obtained hearing aids through the Veteran's Administration (VA). Measures of effectiveness included two hearing-specific surveys and self-reported ratings of global satisfaction and hearing aid adherence. The primary goal was to determine the direct relationship between improved audibility measured with the AI and the overall effectiveness of the hearing aid. Because a "shortcut" AI method was used to fit hearing aids, we also sought to determine whether simplified AI methods designed for use in the clinic provide the same information as the more traditional, and time-consuming AI calculation.

## METHOD

### Study Population

Patients seen in the Audiology Clinic at the Seattle division of the VA Puget Sound Health Care System between Jan 1, 1997 and Apr 30, 1998 for hearing aid evaluation were included in this retrospective analysis. During this period, all patients routinely completed questionnaires that assessed their communication abilities and the impact of their hearing loss before and after hearing aid fitting. Patients who did not complete follow-up, who did not complete both pre- and post-fitting questionnaires, and whose audiometric information was incomplete or missing were excluded from our analysis.

The inception cohort of 115 patients included 114 males and one female, ranging in age from 39–88 y with a mean age of 65.5 y. Mean hearing thresholds (22) are shown in **Figure 1**. The majority of the participants (n=107) had sensorineural losses with no significant air-bone gaps in either ear. The remainder (n=8) had mixed losses and exhibited air-bone gaps of 15 to 30 dB at one or more test frequencies. Mean speech reception thresholds were 30.8 dB HL (SD=15.6) in the right ear and 30.2 dB HL (SD=12.5) in the left ear. Mean speech discrimination scores were 86.7 percent (SD=11.5) in the right ear and 87.8 percent (SD=10.8) in the left ear.

Only patients who received binaural amplification were included. Because the great majority of patients received either peak clipping or compression limiting aids, we excluded patients receiving wide-dynamic range compression hearing aids to avoid confounding effects from nonlinear speech processing. All hearing aids were analog, non-programmable systems without advanced speech-in-noise processing or directional microphones. Amplification characteristics are summarized in **Table 1**.

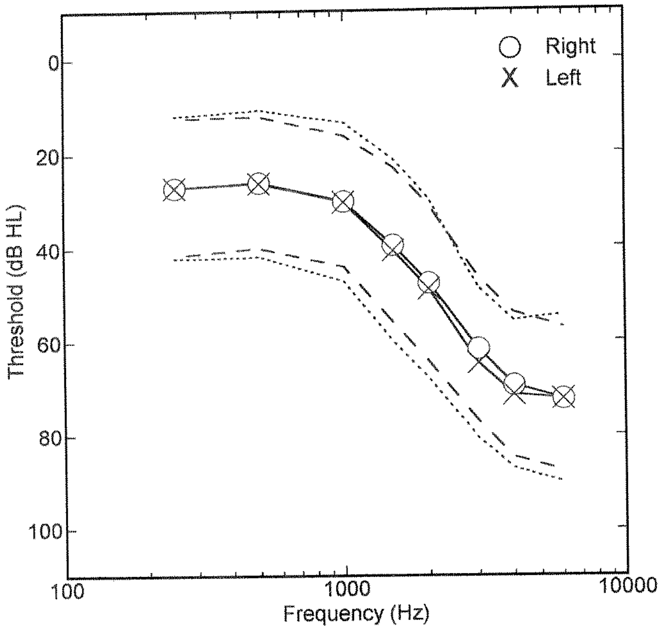


**Figure 1.**
Mean hearing thresholds (in dB HL) for right and left ears. Dashed lines show ±one standard deviation for the right ear; dotted lines show ± one standard deviation for the left ear.

**Table 1.**
Summary of amplification characteristics (n=115).

| | |
|---|---|
| **Output limiting** | |
| Peak clipping | 9 |
| Compression limiting | 106 |
| **Amplification history** | |
| New hearing aid wearer | 72 |
| Past hearing aid wearer | 20 |
| Current hearing aid wearer | 23 |
| **Hearing aid style** | |
| Behind-the-ear | 2 |
| In-the-ear | 69 |
| In-the-canal | 13 |
| Completely-in-the-canal | 31 |

## Hearing Aid Fitting Procedure

During the hearing aid fitting, the desired gain at each frequency was calculated for each participant using the National Acoustic Laboratories- Revised formula (NAL-R) prescriptive method (2). This formula prescribes a specific amount of amplification based on the hearing threshold at each frequency (target values). The frequency-gain response of the hearing aid was then adjusted to provide the best possible match to desired gain for a conversational-level (55 dB sound pressure level (SPL)) input signal. Following insertion of the aid, real-ear insertion gain [REIG] values for each patient were measured at the tympanic membrane using an Audioscan™ (Etymonic Design Inc., Dorchester, Ontario) probe-microphone system. Mean target and REIG values are shown in **Figure 2.** On average, measured REIG was within 1.5 dB of the fitting target up to 3000 Hz. The poorest match to target occurred at 4000 and 6000 Hz, where sufficient gain could not be achieved. This pattern is typical of conventional hearing aids, which are generally incapable of providing high gain at high frequencies.

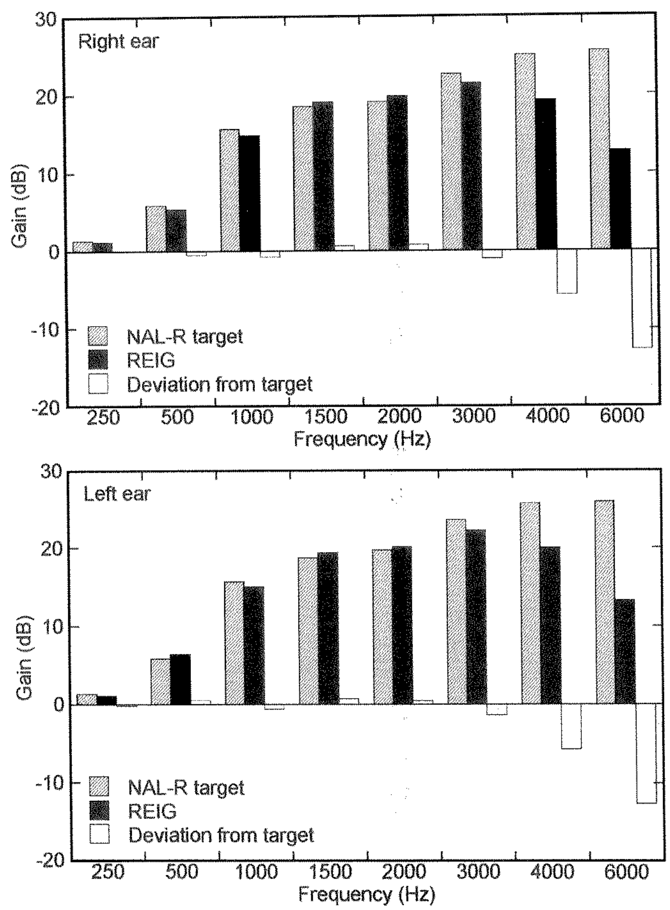


**Figure 2.**
Mean target gain values (hatched bars) and measured REIG values (solid bars) as a function of frequency. The deviation from target at each frequency is shown by the open bars; positive values indicate that more gain than the target was provided and negative values indicate that gain fell short of target gain.

## Articulation Index Measurements

During the hearing aid fitting, target, unaided, and aided audibility index values were obtained using the

Audioscan AI function. The AI value provided by the Audioscan is based on the $A_0(4)$ version of the AI developed by Pavlovic (23, 24). With this simplified version of the AI, the speech spectrum is represented as a shaded area on the audiogram. The shaded area exceeding the aided threshold represents the audible speech range. The AI is calculated by adding up the number of dB by which the speech peaks exceed threshold at each frequency, with the restriction that the speech range at any frequency will not exceed 30 dB. In the Audioscan calculation, the level of the input signal has been increased 10 dB relative to that suggested by Pavlovic (23). The adjustment is similar to that proposed by Byrne (8) to more accurately reflect conversational speech levels for a hearing aid wearer.

## Data Collection

Data from audiology records were extracted onto standardized forms by extractors unaware of hearing aid outcomes. Baseline data such as gender, age, prior hearing aid experience, pure-tone thresholds, speech recognition scores, speech reception thresholds, and baseline (pre-fitting) questionnaire scores were included. Hearing aid fitting data included target and insertion gain, as well as hearing aid features such as size, programmability, and circuit type. Post-fit questionnaire data were also collected. Additional, follow-up data were available from returned quality improvement questionnaires mailed to patients approximately 1 y after their fitting, which included:

- self-ratings of satisfaction (10-point response scale to the question "How satisfied have you been with your hearing aid?"),
- descriptions of adherence (h/d and d/wk the hearing aid was worn) and reasons for non-adherence, and
- a completed psychometric survey instrument called Satisfaction with Amplification in Daily Life (25).

The questionnaires are described in more detail below.

## Data Classification

*Articulation Index.*

Nine AI values were obtained for each patient. Aided and unaided AIs were obtained for each ear, representing the speech information available with and without amplification, respectively. Because in binaural listening the patient's performance would be most influenced by the better ear, we also noted the best aided AI between ears for each patient. To assess the improvement in available speech information with amplification, we calculated the difference in AI between the aided and unaided condition for each ear. This value will be referred to as the AI increase. Finally, the target AI value for each ear represents the AI that would have occurred if an exact match to the prescribed NAL-R target gain had been obtained.

*Hearing Aid Effectiveness.*

To obtain the patient's assessment of the change in their listening ability with hearing aids, all patients completed the Abbreviated Profile of Hearing Aid Benefit (APHAB) (26) two times: once for unaided listening prior to being fit with amplification, and again, for aided listening at their 1 mo follow-up visit. The APHAB includes 24 items, divided into four subscales. The ease of communication (EC) subscale assesses ability to communicate in quiet situations. The reverberation (RV) and background noise (BN) subscales assess ability to communicate in reverberant or noisy situations. Discomfort from loud sounds is measured in the aversive sounds (AV) subscale. Benefit is calculated as the aided score minus the unaided score. We have expressed improved, perceived performance with a positive score. An overall benefit score and four subscale benefit scores were obtained for each patient.

Because satisfaction and benefit depend somewhat on the survey instrument chosen, we also analyzed another outcome measure: Satisfaction with Amplification in Daily Life (SADL). SADL questionnaire scores (25) were obtained from a quality assessment survey of all patients approximately 1 y after fitting. The SADL consists of four subscales: positive effect; service and cost; negative features; and personal image. Typical positive effect questions include "Are you convinced that obtaining hearing aids was in your best interest?", while negative effect questions include "Are you bothered by an inability to turn your hearing aids up loud enough without getting feedback?". In addition, we asked patients to assess global satisfaction with their hearing aid 1 y after fitting. They were asked the question "How satisfied have you been with your hearing aid?", using a rating scale marked in integer increments from zero (least satisfied) to ten (highly satisfied).

*Adherence.*

Respondents were asked to indicate whether they still used their aid (regularly, occasionally, no), and to quantify their average hearing aid use in number of d/wk and in number of h/d. Patients were also asked to detail reasons for non-adherence.

### Data Analysis

Data from extraction forms were transferred to computer code with double-entry verification. Bivariate statistical analyses were performed with the Statistical Analysis Software system (version 6.12, SAS Institute, Inc, Cary, NC). Multiple linear regression was used to identify variables that independently predicted satisfaction and benefit.

## RESULTS

### Audibility

Mean unaided, target, aided, and improvement in AI scores are shown in **Table 2**. On average, patients improved by approximately 0.30 with amplification, or a predicted improvement in intelligibility of about 20 percent (27). The aided AI was slightly lower than the target AI, primarily because insufficient gain was provided, relative to target, above 3 kHz (**Figure 2**). Because the majority of patients had symmetrical hearing losses, the difference in AI between ears was very small, 0.01 or less on average.

We found excellent correlation between the clinical "shortcut" AI assessment used in this study and the traditional AI (**Figure 3**). Pearson correlation coefficients were high for both the right ear ($r=0.89$, $p<0.0001$) and the left ear ($r=0.86$, $p<0.0001$). The correspondence in AI values is similar to that found by Humes and Riker (18) for a comparison of two different clinical versions of the AI.

**Table 2.**
Mean articulation index (AI) values obtained for unaided, target gain, and aided listening conditions.

| Condition | AI(RE) | | AI(LE) |
|---|---|---|---|
| **Unaided** | 0.56 | | 0.56 |
| **Target** | 0.88 | | 0.87 |
| **Aided** | 0.85 | | 0.84 |
| **Increase** | 0.29 | | 0.28 |
| **Best aided** | | 0.88 | |

RE=right ear; LE=left ear.

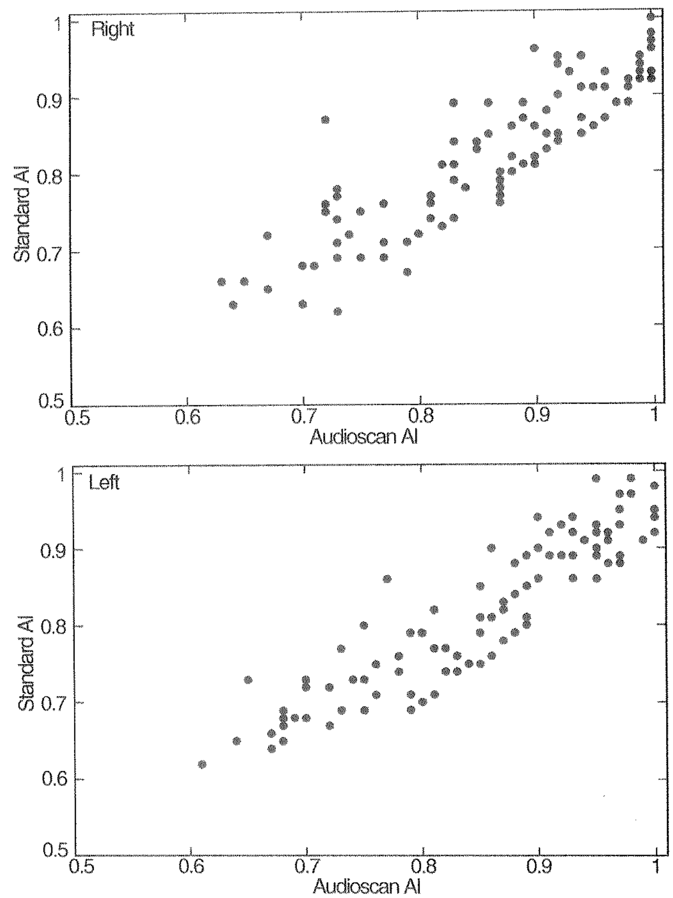


**Figure 3.**
Comparison of standard AI calculations to those provided by the Audioscan clinical AI function. Right ear results are shown in the top panel and left ear results in the lower panel.

### Hearing Aid Effectiveness

Mean APHAB benefit scores are shown in **Table 3**. The benefit scale represents the decrease in percent of problems experienced. For example, a benefit of 25 on the EC subscale indicates that patients experienced 25 percent fewer problems while wearing their hearing aid than they did without the hearing aid. On average, patients reported their hearing aids improved communication when listening in quiet situations (EC subscale), with background noise (BN scale), and with reverberation (RV scale). The negative AV scale indicates that the percentage of problems due to loudness discomfort increased. These benefit scores are similar to those reported by Cox (28) for a similar population of patients fit with linear hearing aids.

**Table 3.**
Mean benefit scores and (standard errors) for APHAB and SADL questionnaires.

| | |
|---|---|
| **APHAB** | |
| Ease of communication (EC) | 28.4(2.4) |
| Background noise (BN) | 16.5(3.0) |
| Reverberation (RV) | 26.9(2.1) |
| Aversiveness (AV) | -14.9(3.3) |
| **SADL** | |
| Positive effect | 5.3(0.15) |
| Service and cost | 5.5(0.15) |
| Negative features | 4.4(1.4) |
| Personal image | 5.6(1.0) |
| Overall SADL score | 5.1(0.9) |

Mean results for the SADL are also shown in **Table 3**. Most patients were highly satisfied, overall, and for positive effects of amplification. Mean satisfaction ratings for all subscales fall within the normative range for this test (25).

Global satisfaction ratings are shown in **Table 4**. The majority of patients were highly satisfied with their hearing aids, selecting an 8, 9 or 10 on the rating scale. **Table 4** also contains patient reports of h/d and d/wk the hearing aids were worn. To explore the reasons surrounding nonadherence, patients were also asked to report the reasons they did not wear the hearing aids. Although the most common explanation was "just forgetting", the next three most common reasons were physical discomfort from wearing the aid, difficulties with manipulation, and inconvenience of the device.

**Table 4.**
Responses to global satisfaction and adherence ratings.

| **Rating** | **Percent** |
|---|---|
| 0-2 | 3.0 |
| 3-4 | 9.2 |
| 5-6 | 12.2 |
| 7-8 | 39.8 |
| 9-10 | 35.7 |
| **Days** | **Percent** |
| 0-1 | 5.1 |
| 2-3 | 8.2 |
| 4-5 | 11.2 |
| 6-7 | 75.5 |
| **Hours** | **Percent** |
| 0-4 | 19.5 |
| 5-8 | 15.1 |
| 9-12 | 21.6 |
| 13-16 | 34.5 |
| 17-20 | 7.5 |
| 21-24 | 1.8 |

Percent=percent of patients; Days=days of hearing aid use; Hours=hours per day of hearing aid use.

### Relationship Between Improved Audibility and Hearing Aid Effectiveness

The primary question of interest was whether patients who received greater improvements in audibility, and thus a larger improvement in speech recognition, would report greater hearing aid effectiveness. To examine the relationship between improved audibility and patient-rated communication improvements, Pearson product-moment correlations between the AI and APHAB benefit scores are shown in **Table 5**. Because larger increases in audibility are presumed to correlate with improvements in speech understanding, it is somewhat surprising that there is no strong relationship between the patients' self-rated hearing abilities and speech audibility. Patients who receive greater audibility are as likely to report poor communication ability as patients who achieve poorer, aided audibility (and, based on previous work (14), lower speech-recognition scores).

The exception is self-rated ability to understand speech in background noise, measured using the BN subscale of the APHAB, which is negatively correlated with the best aided AI. In other words, patients who achieve higher speech audibility with hearing aids report they are less able to understand speech in background noise. This is probably because all patients were fit with linear hearing aids that amplified both speech and noise. Those with higher speech audibility would presumably have noted greater amplification of the noise and perceived that as increased difficulty in noisy situations.

Hearing aid effectiveness incorporates a number of factors that may not be tied directly to speech intelligibility. For example, listeners asked to choose an amplification system based on sound quality do not necessarily choose the system that maximizes speech intelligibility (29–32). Patients also report that comfort and convenience are priorities. Accordingly, we examined the relationship between improved AI and patient satisfaction, measured with both the SADL score as well as the global satisfaction rating. Pearson product-moment correlations between these measures are shown in **Table 6**. Again, there is no clear trend; patients who achieve high audibility, and hence higher speech recognition, are as likely to be dissatisfied as patients who achieve lower audibility.

**Table 5.**
Pearson product-moment correlations between mobility and APHAB scores.

| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **1. Aided AI (RE)** | 1.00 | 0.54* | 0.93* | -0.30* | -0.34* | -0.04 | -0.00 | -0.11 |
| **2. Aided AI (LE)** | -- | 1.00 | 0.93* | -0.51* | -0.36* | -0.09 | -0.19 | -0.07 |
| **3. Aided AI (best)** | -- | -- | 1.00 | -0.31* | -0.36* | -0.10 | -0.05 | -0.23* |
| **4. AI increase (RE)** | -- | -- | -- | 1.00 | 0.72* | -0.12 | -0.05 | -0.03 |
| **5. AI increase (LE)** | -- | -- | -- | -- | 1.00 | 0.06 | -0.12 | 0.04 |
| **6. APHAB global** | -- | -- | -- | -- | -- | 1.00 | 0.61* | 0.76* |
| **7. APHAB EC** | -- | -- | -- | -- | -- | -- | 1.00 | 0.34* |
| **8. APHAB BN** | -- | -- | -- | -- | -- | -- | -- | 1.00 |

AI=articulation index; RE=right ear; LE=left ear; *=significant at $p<0.05$.

**Table 6.**
Pearson product-moment correlations between audibility and satisfaction.

| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| **1. Aided AI (RE)** | 1.00 | 0.54* | 0.84* | -0.30* | -0.34* | -0.11 | -0.05 |
| **2. Aided AI (LE)** | -- | 1.00 | 0.78* | -0.51* | -0.36* | -0.11 | 0.02 |
| **3. Aided AI (best)** | -- | -- | 1.00 | -0.32* | -0.34* | -0.12 | -0.05 |
| **4. AI increase (RE)** | -- | -- | -- | 1.00 | 0.72* | 0.14 | 0.07 |
| **5. AI increase (LE)** | -- | -- | -- | -- | 1.00 | 0.13 | 0.13 |
| **6. SADL benefit score** | -- | -- | -- | -- | -- | 1.00 | 0.10 |
| **7. Global rating** | -- | -- | -- | -- | -- | -- | 1.00 |

AI=articulation index; RE=right ear; LE=left ear; Global rating=Global satisfaction rating; *=significant at $p<0.05$.

We also examined the effect of speech audibility on hearing aid adherence, measured in h/d and d/wk of hearing aid use (**Table 7**). Perhaps surprisingly, in view of the nonsignificant correlations described above, there is a moderate relationship between adherence and audibility. Patients who achieve higher AIs are more likely to use their hearing aid on a consistent basis and for longer periods. This is an important issue, because subjects who use their hearing aid consistently are more likely to adjust to use of amplification than subjects who use their hearing aid sporadically (33, 34).

## DISCUSSION

This study was designed to explore use of simplified articulation index fitting methods to evaluate hearing aid fitting success in a population of veterans. Results of the

**Table 7.**
Spearman's rho correlations between audibility and adherence.

| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| **1. Aided AI (RE)** | 1.00 | 0.54* | 0.84* | -0.30* | -0.34* | -0.12 | -0.20 |
| **2. Aided AI (LE)** | -- | 1.00 | 0.78* | -0.51* | -0.36* | -0.25* | -0.21* |
| **3. Aided AI (best)** | -- | -- | 1.00 | -0.32* | -0.34* | -0.21* | -0.22* |
| **4. AI increase (RE)** | -- | -- | -- | 1.00 | 0.72* | 0.28* | 0.27* |
| **5. AI increase (LE)** | -- | -- | -- | -- | 1.00 | 0.33* | 0.22* |
| **6. Hours** | -- | -- | -- | -- | -- | 1.00 | 0.65* |
| **7. Days** | -- | -- | -- | -- | -- | 0.64* | 1.00 |

AI=articulation index; RE=right ear; LE=left ear; Hours=hours per day; Days=days per week; rating; *=significant at p<0.05.

study demonstrated that such "shortcut" methods offer a less time-consuming way to obtain audibility measures in the clinic. A more complex question is how use of these methods to measure hearing aid outcomes in the clinic relates to patient perceptions. Results of this study indicated that there was no systematic relationship between measurements of improved audibility and patient ratings of their communication ability in everyday situations.

Additionally, improved audibility was not related to overall satisfaction with the hearing aid fitting (i.e., the amplification characteristics of the hearing aid). However, improved audibility was related to hearing aid adherence, with patients who achieve greater improvement in audibility reporting that they used their hearing aids more frequently.

Because previous work conducted under laboratory conditions has shown that audibility outcomes are strongly related to measured speech understanding (14), the lack of relationship between audibility and satisfaction is surprising. It is tempting to conclude that patients do not weigh improved speech understanding heavily when evaluating the effect of their hearing aids. However, several factors may affect use of hearing aids in everyday listening situations that are not present in a more controlled test environment.

First, to understand fully the relationship between audibility and hearing aid satisfaction, it is necessary to consider the influence of the volume control. The extent to which the hearing aid improves audibility in the clinic is evaluated at an optimal volume setting for each listener, adjusted by the audiologist. However, a patient who normally wears their hearing aid at a lower volume setting would experience a lower audibility index in everyday situations. Cox and Alexander (35) compared patient-preferred volume settings to prescribed settings in quiet, noisy and reverberant listening environments. They noted that on average, preferred volume settings were approximately the same as those prescribed at the hearing aid fitting. However, because patients may select different volume settings with changes in the listening environment (35) it is possible that changes in volume setting influenced the results shown here.

A second concern is adequate loudness limiting. Studebaker (36) cautions that loudness comfort should be considered when selecting hearing aid characteristics based on audibility. If those patients who received greater audibility also experienced loudness discomfort, they would be likely to report dissatisfaction with their hearing aids. In this study, however, output limiting was consistently set to prevent loudness discomfort for each patient. It is, therefore, unlikely that loudness discomfort influenced results.

Finally, although the AI is strongly related to speech in quiet, the relationship is less robust for speech in noise (18). The majority of everyday communication situations involve some degree of background noise, possibly weakening the relationship with audibility. Additionally, we do not know what criteria listeners rely on when rating their communication ability. For example, subjects show a clear preference for some types of speech amplification over others, even when the systems provide equivalent intelligibility (37).

The suggestion that higher audibility may affect hearing aid adherence is particularly interesting. One possible conclusion is that although patients may not rate their communication ability highly, they are actually receiving benefit from their hearing aids. Future research that focuses on patient rating criteria can lead to a greater understanding of hearing aid effectiveness.

## ACKNOWLEDGEMENTS

The authors would like to thank Robbi Bishop and Virginia Kitch for their assistance with data collection. The research reported here was supported by the Deafness Research Foundation (P. Souza) and by a Department of Veterans Affairs, Veterans Health Administration, Health Services Research and Development Service Career Development Award #CD-98318 (B. Yueh).

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Submitted for publication December 15, 1999. Accepted in revised form February 23, 2000.