Telephone Communication with In-the-Ear Hearing Aids Using Acoustic and Electromagnetic Coupling

Patrick N. Plyler*
Samuel B. Burchfield†
James W. Thein†

Abstract
The purpose of this study was to determine whether telephone communication was improved with electromagnetic coupling for in-the-ear hearing aid users with mild to moderate hearing losses. Each user adjusted his hearing aid gain to the level he determined to be best for telephone communication with each coupling method. Under these conditions, average word recognition scores in quiet and average high-frequency output levels measured at the tympanic membrane were not different for each coupling method. The ability to tolerate background noise was also studied. Background noise tolerance was not different for the two coupling methods. However, significantly greater levels of background noise were tolerated when telephone side-tone feedback was eliminated regardless of coupling method.

Key Words: Acoustic coupling, electromagnetic coupling, side-tone feedback

Abbreviations: ATI = audiometer-telephone interface, BTE = behind the ear, ITE = in the ear, REAR = real-ear aided response

One method of telephone communication for hearing aid users is to acoustically couple the telephone receiver to the hearing aid. However, acoustic coupling often results in problems such as acoustic feedback (Smith, 1974; Goldberg, 1975) and amplification of ambient noise in the listener’s environment (Stoker, 1981). The hearing aid telecoil was developed to provide hearing aid users with an alternative method of coupling to overcome the problems associated with acoustic coupling. With a hearing aid telecoil, acoustic feedback is avoided since the hearing aid is inductively coupled to the telephone by using the electromagnetic leakage produced by the telephone receiver (Smith, 1974). Several investigators have suggested that direct communication with the electromagnetic source can eliminate or greatly reduce interference from acoustic background noise (Stoker, 1981; Holmes, 1985; Beck and Nance, 1989).

Several studies regarding acoustic and electromagnetic coupling have been conducted using behind-the-ear (BTE) hearing aids. In these aids, telecoil orientation within the hearing aid casing is perpendicular to the telephone receiver, and telecoil size is sufficient to produce an inductive signal with adequate strength for electromagnetic coupling (Compton, 1994). Results of these studies indicate that (1) electromagnetic transduction results in reduced output levels and narrower frequency responses than electroacoustic transduction when measured using a fixed volume control setting (Tannahill, 1983; Holmes, 1985), (2) electromagnetic coupling results in similar or poorer word recognition in quiet when measured using a fixed volume control setting (Tannahill, 1983; Holmes, 1985), and (3) electromagnetic coupling improves word recognition in noise for moderate to severely hearing-impaired listeners (Stoker, 1981).
There is reason to believe that electromagnetic coupling with in-the-ear (ITE) hearing aids may be poorer than with BTE hearing aids because of design constraints. With ITE hearing aids, orientation of the telecoil varies and telecoil size may be reduced due to the irregular shapes of hearing aid shells and space limitations within the shell itself. Less than optimal telecoil orientation within the hearing aid shell or a reduction in telecoil size may result in insufficient inductive signal strength for electromagnetic coupling. The limitation of space within the ITE hearing aid shell may also prevent the inclusion of a telecoil preamplifier, which is used to increase electromagnetic signal strength (Compton, 1994). Mueller and Bryant (1991) found that hearing aid output levels and frequency responses for acoustic and electromagnetic coupling may be similar or considerably different for a given ITE hearing aid. Telephone communication with ITE hearing aids has not been studied.

**Experiment I: Performance in Quiet**

The first purpose of the present study was to determine whether ITE hearing aid performance during telephone communication in quiet was similar for acoustic and electromagnetic coupling. Performance was evaluated with the hearing aid gain control set by the subjects to a level deemed best for telephone communication for acoustic coupling and set separately for electromagnetic coupling. Subjects were allowed to set the hearing aid gain separately for each coupling method in order to reduce potential hearing aid amplification differences that may occur for a given ITE hearing aid (Mueller and Bryant, 1991). The measures of hearing aid performance were word recognition in quiet and high-frequency average acoustic output level measured at the tympanic membrane.

**Experiment II: Noise Tolerance**

The second purpose of the present study was to determine the tolerance levels for background noise during telephone communication for acoustic and electromagnetic coupling. Subjects adjusted the level of the background noise to their maximum tolerance level while listening to speech transduced through the telephone. Maximum tolerance level was defined as the highest level of background noise each listener could tolerate without sacrificing the ability to comprehend the telephone-transduced speech. Tolerance of ambient background noise was also studied with and without the side-tone feedback system that enables the telephone user to monitor his or her own voice level. Deactivation of the side-tone feedback has been shown to improve telephone communication in noise for normal-hearing persons (Holmes et al, 1983). Comparisons of maximum tolerance levels were made to determine if tolerance of ambient noise was affected by method of coupling and by the use of side-tone feedback.

**METHODS**

**Subjects**

Eight experienced hearing aid users with bilateral sensorineural hearing loss served as the subjects. They ranged in age from 56 to 74 years. All were aided binaurally with ITE hearing aids prior to the onset of this study. Each ITE hearing aid was fit using probe microphone measurements and the National Acoustic Laboratories' prescriptive formula. Six subjects were fitted with linear circuitry and two subjects with compression circuitry (K-amp, WDRC AGCi). Vent sizes were 0.13 inches for five subjects, 0.022 inches for two subjects, and 0.095 inches for one subject. The ITE hearing aid equipped with a telecoil served as the test ear for each subject. No attempt was made to determine telecoil orientation within the hearing aid shell.

Mean pure-tone air-conduction thresholds for the test ears were computed using the data for subjects 1 to 7. Mean thresholds ranged from 32 to 70 dB HL (ANSI, 1989) for test frequencies 250 to 8000 Hz (Table 1). Subject 8 was considered separately because his loss was substantially greater. Bone-conduction thresholds were within 10 dB of the air-conduction thresholds. The ITE hearing aid equipped with a telecoil used in the study was evaluated prior to the experiment to ensure appropriate electroacoustic and electromagnetic hearing aid functioning (ANSI, 1987). During the experiment when behavioral and probe microphone measurements were made, the nontelecoil hearing aid remained in the nontest ear but was turned off. All qualification and experimental tests were conducted in a double-walled, sound-treated examination room (Industrial Acoustics) with ambient noise levels suitable for testing with ears uncovered (ANSI, 1991). Incandescent lighting was used to minimize ambient electromagnetic noise.
### Table 1 Age (Years) and Hearing Thresholds (dB HL) for Hearing-impaired Listeners

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Frequency (Hz)</th>
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<tbody>
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<td></td>
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<tr>
<td>1</td>
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<td>(55)</td>
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<tr>
<td>Mean</td>
<td>66</td>
<td>32</td>
</tr>
</tbody>
</table>

Subject 8 was not included in mean calculations.

### Equipment

Speech stimuli were generated using a compact disc player (Pioneer PD-103) through one channel of a diagnostic audiometer (Madsen OB 802) to a custom-made audiometer telephone interface (ATI, Mark VI), which modified the output of the audiometer to produce the approximate gain, frequency response, and electrical line noise of a typical telephone loop (Stoker, 1982). The output of the ATI was then routed to a 500 series telephone handset with a side-tone muting control. The 500 series telephone handset uses a U1 receiver with sufficient electromagnetic leakage for the electromagnetic coupling of hearing aids.

The subject was seated in the center of the examination room. Ambient noise was generated from a loudspeaker (Beovox S45) 1 meter from the subject at 0° azimuth. The stimulus-generating equipment and the side-tone muting control were located in the control room and were controlled by the experimenter (Fig. 1).

Speech stimulus levels were calibrated using the 1000-Hz calibration tone on the compact disc containing the speech materials. In accordance with previously reported calibration procedures for the ATI and 500 series telephone handsets, the level of the tone was set at 86 dB SPL in an NBS 9A coupler with the handset sealed to the coupler with Fun-Tac (Stoker, 1981, 1982). Measurements were made with a sound level meter (Quest. 1800) using a 1-inch condenser microphone (Quest. 4170) and an audiometric analyzer (Quest. AA-175). The output of the handset was calibrated before the experiment and rechecked during and at the end of the experiment.

### Experimental Procedures

Experiments I (performance in quiet) and II (tolerance of noise) were performed in their entirety for one method of coupling at a time (acoustic or electromagnetic). This was done so that hearing aid performance could be measured at a single gain setting for each coupling method. Before each experiment was conducted, each subject adjusted the hearing aid gain to the level that he or she determined to be best for telephone communication, as is done in typical telephone use. This was done with the subjects listening through the telephone to an ongoing story—the competing message from the Synthetic Sentence Identification Test (Jerger et al, 1968). Each subject listened to the story, removed the telephone, adjusted the gain, and resituated the handset in the listening position.
next to the ITE hearing aid. Each subject made as many adjustments as needed to set the gain. When the gain was set for one method of coupling, the subject held the handset to the ITE hearing aid and did not remove it until all tests had been conducted for that method of coupling. The initial method of coupling was selected at random and the order of other test procedures was block randomized.

Experiment I: Performance in Quiet

In the first part of Experiment I, acoustic measurements were made to determine relative differences in speech levels at the tympanic membrane with acoustic and electromagnetic coupling. In the second part of Experiment I, word recognition in quiet was measured using each method of coupling.

The response characteristics of the ITE hearing aids were determined by routing a 60 dB SPL speech spectrum noise to the telephone handset and by measuring output levels at the tympanic membrane for each coupling method. Speech spectrum noise at 60 dB SPL was used because it approximated the signal used during typical probe microphone evaluations of hearing aid performance. Hearing aid output levels were measured with a probe microphone system (Audioscan, RM500) in 1/12-octave steps from 200 to 8000 Hz. The measure of hearing aid output used was the average output level of 1000, 1600, and 2500 Hz measured at the tympanic membrane. All measurements made at the tympanic membrane and stored in the Audioscan RM500 were downloaded to a personal computer using the Audioscan RM500 XDATA32 data extraction program. With this program, data stored in the Audioscan RM500 were converted into ASCII text files, which were stored as individual subject files in Microsoft Excel (5.0).

Word recognition in quiet was assessed by delivering a W-22 50 word list through the handset for each coupling method. Lists 1A and 2A were used and were selected randomly for each coupling method. Side-tone feedback was present as it is in normal telephone communication.

Experiment II: Tolerance of Noise

In the first part of Experiment II, acoustic measurements were made to determine the relative levels of background noise at the tympanic membrane with the two coupling methods with and without side-tone feedback. In the second part of Experiment II, maximum tolerance levels for babble were determined with the two coupling methods with and without side-tone feedback.

Relative levels of background noise reaching the tympanic membrane were determined using a speech spectrum noise presented through the loudspeaker and measured in the ear canal in 1/12-octave steps from 200 to 8000 Hz using the probe microphone system. Speech spectrum noise measures were made for each coupling condition with and without side-tone feedback. The speech spectrum noise was used to avoid the temporal waveform variations in multitalker babble, which resulted in unstable probe microphone measurements. The level of the speech spectrum noise was 60 dB SPL measured in the sound field at the location of the pinna. All probe microphone measurements were made at the tympanic membrane with the subject holding the telephone handset in the test position while no signal was delivered through the telephone handset.

To assess tolerance of background noise, the subject used the telephone in the presence of 12-speaker multitalker babble generated in the sound field by the loudspeaker. The multitalker babble was routed through the second channel of the audiometer to the loudspeaker located 1 meter from the subject at a 0° azimuth. The subject listened to the same ongoing story (Jerger et al, 1968) as in the procedure used to set the hearing aid gain and simultaneously adjusted the level of the multitalker babble from the loudspeaker in ±2-dB increments. The task of each subject was to determine his maximum tolerance level. To do this, each subject was instructed to adjust the multitalker babble to a level that was intolerable, then to a level that was barely noticeable, and finally to the highest level of multitalker babble each subject could tolerate without sacrificing the ability to comprehend the story. Maximum tolerance levels were determined for four conditions: acoustic and electromagnetic coupling with and without side-tone amplification. The initial side-tone condition was selected at random. Maximum tolerance levels were based on the average of two determinations. In all cases but three, the two determinations were within 2 dB of each other. In the three exceptional cases, the maximum tolerance levels differed by 4 dB. In those cases, an additional trial was run and the maximum tolerance level was based on the average of three determinations.
RESULTS

Experiment 1: Performance in Quiet

Probe Microphone Measurements of Acoustic and Electromagnetic Output

An experimental procedure was used to assess the relative response characteristics of the ITE hearing aids. In this procedure, a speech spectrum noise input of 60 dB SPL was delivered from a telephone handset to an ITE hearing aid with the gain control adjusted to the level deemed best for telephone communication by the subject. This was done for each coupling method. The real-ear aided response (REAR) was measured over the frequency range 200 to 8000 Hz for each coupling method.

Seven of the eight subjects were able to place the telephone receiver flush with the pinna without acoustic feedback problems following the hearing aid gain adjustment procedure for each coupling method. Subject 8, who had the greatest hearing loss, encountered acoustic feedback with acoustic coupling. To overcome this problem, he held the posterior portion of the receiver flush to the posterior portion of the pinna while the anterior portion of the receiver was held at a 45° angle, creating about a 2-inch gap between the anterior portion of the receiver and the anterior portion of the pinna. For this reason, this subject's data were not included in the group data and were analyzed separately.

REARS measured using the experimental procedure were averaged for the seven hearing aids for each coupling method. In Figure 2, the mean REAR is shown for acoustic and electromagnetic coupling. On average, REARS were similar for each coupling method. The mean difference in high-frequency average output levels was 2 dB, which was not significant (t[6] = .58, p = .58).

Although mean REARs were similar, substantial REAR differences did occur for subjects 2 and 5 and are shown in Figures 3 and 4. In Figure 3, REARs were similar for frequencies higher...
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than 2100 Hz; however, electromagnetic coupling resulted in greater output levels for frequencies lower than 2100 Hz. In contrast, REARs in Figure 4 were similar for frequencies lower than 500 Hz; however, acoustic coupling resulted in greater output levels for frequencies higher than 500 Hz. These cases illustrate that there may be differences in hearing aids that cause the users to prefer one method of coupling over another for a particular hearing aid.

**Word Recognition**

Hearing aid performance for the two coupling methods was also evaluated by measuring the ability to understand speech in quiet using the telephone with the hearing aid volume set by the user. The mean percent correct word recognition scores were 75.1 percent (range = 34–90%) for acoustic coupling and 76.3 percent (range = 52–90%) for electromagnetic coupling. The word recognition ability in quiet was not significantly different for the two coupling methods (t [61] = –0.2, p = .85). These findings are in agreement with previous research conducted using BTE hearing aids. It was found that word recognition in quiet for electromagnetic coupling was similar to that for acoustic coupling (Tannahill, 1983; Holmes, 1985).

We attempted to determine whether individual differences in word recognition were related to the high-frequency output levels of the speech spectrum noise measured at the tympanic membrane. However, that relation was not found to be significant (r = .33, p = .42).

**Experiment II: Tolerance of Noise**

**Tolerance of Background Noise**

To evaluate tolerance of background noise, the subject used the telephone in the presence of 12-speaker multitalker babble generated in the sound field by the loudspeaker. The maximum tolerance levels for each condition are shown in Table 2. On average, the tolerance of multitalker babble was greatest when the side-tone feedback was muted.

A two-factor, repeated-measures analysis of variance was performed to evaluate the effects of coupling method and side-tone feedback. The results of the maximum tolerance levels were not different for acoustic and electromagnetic coupling (F = .003, p = .96), indicating that subjects tolerated similar levels of multitalker babble for each method of coupling. The results were different, however, with and without side-tone feedback (F = 6.69, p = .04), indicating that subjects were able to tolerate significantly higher levels of multitalker babble when the side-tone feedback was muted. On average, the maximum tolerance levels were 2.4 dB higher (54.9 dB SPL vs 57.3 dB SPL) when the side-tone feedback was deactivated. The interaction between coupling method and side tone was not significant.

Measurements of speech spectrum noise presented in the sound field were made at the tympanic membrane for the four noise-tolerance conditions in an attempt to explain the

**Table 2** Individual Subject Maximum Background Noise Tolerance Levels for Two Methods of Coupling (Acoustic and Electromagnetic) and for Side-tone Feedback (On or Muted)

<table>
<thead>
<tr>
<th>Subject</th>
<th>AC On</th>
<th>AC Muted</th>
<th>EM On</th>
<th>EM Muted</th>
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<tr>
<td>Mean</td>
<td>54.7</td>
<td>57.4</td>
<td>55.1</td>
<td>57.1</td>
</tr>
</tbody>
</table>

Subject 8 was not included in mean calculations.

**Figure 5** Simulated spectra of background noise with side-tone feedback. Mean responses for seven aided subjects to a 60 dB SPL speech spectrum noise delivered from the loudspeaker and measured at the tympanic membrane.
result of the noise tolerance testing. For each subject, the speech spectrum noise presented was 60 dB SPL at the pinna; it was not the multitalker babble presented at maximum tolerance levels in the behavioral section of the study. As mentioned previously, multitalker babble could not be accurately measured using the probe microphone system due to temporal waveform variations. The average speech spectrum noise levels for acoustic and electromagnetic coupling with side-tone feedback either on or muted are displayed in Figures 5 and 6 and in a different form in Figures 7 and 8. The noise level reaching the tympanic membrane was determined by calculating the high-frequency average noise level of 1000, 1600, and 2500 Hz for each condition.

The speech spectrum noise levels reaching the tympanic membrane as a function of frequency measured when side-tone feedback was operative are displayed in Figure 5. High-frequency average noise levels were not different (t[61] = 0.15, p = .89) for acoustic and electromagnetic coupling, indicating that the side-tone amplification system transduced ambient acoustic noise equally regardless of the method of coupling. Therefore, when side-tone feedback was present, as it is for normal telephone use, noise tolerance levels (see Table 2) were similar for acoustic and electromagnetic coupling.

The effects of deactivating the side-tone feedback on speech spectrum noise levels reaching the tympanic membrane for acoustic and electromagnetic coupling are shown in Figures 7 and 8, respectively. For the lower frequencies (up to about 740–900 Hz), deactivating side-tone feedback had no effect on the noise level.
reaching the tympanic membrane for either method of coupling. This finding indicates that transduction of noise to the tympanic membrane in this frequency range is a result of direct acoustic stimulation through the hearing aid vent and/or case. Thus, noise levels at the tympanic membrane in this frequency range are independent of the side-tone feedback system and depend on the attenuative properties of the hearing aid and the venting used.

For the mid- and high-frequency regions (beyond 740–900 Hz), the noise reaching the tympanic membrane is attenuated significantly by deactivating side-tone feedback. With acoustic coupling, the high-frequency average noise level was reduced by 11 dB. With the electromagnetic coupling, the high-frequency average noise level was decreased by 18 dB. These speech spectrum noise reductions were significant for acoustic ($t \{6\} = 3.51, p = .01$) and for electromagnetic coupling ($t \{6\} = 3.51, p = .01$).

**DISCUSSION**

**Hearing Aid Users with Mild to Moderate Hearing Loss**

Seven subjects in the present study had mild to moderate hearing loss and did not experience acoustic feedback when using the telephone with acoustic coupling. For these subjects, hearing aid performance in quiet was equivalent with acoustic and electromagnetic coupling.

The results of the present study differ from those conducted with BTE hearing aids, in part because of the method used to compare acoustic and electromagnetic coupling. Studies using BTE hearing aids were conducted with the hearing aid volume control set to the same position for acoustic and electromagnetic coupling. Under these conditions, electromagnetic coupling resulted in reduced output levels, narrower frequency responses, and similar or poorer word recognition in quiet than acoustic coupling (Tannahill, 1983; Holmes, 1985). In the present study, in which subjects were allowed to set the hearing aid volume control separately for each coupling method, subjects increased the hearing aid gain for electromagnetic coupling and decreased the gain for acoustic coupling. This readjustment allowed subjects to compensate for differences in amplification reported in studies that used a fixed volume control setting. With this readjustment, hearing aid response characteristics and word recognition in quiet were similar for acoustic and electromagnetic coupling because hearing aid response differences were overcome.

Tolerance of background noise was assessed by having the subject use the telephone in the presence of multitalker babble generated in the sound field for each method of coupling with and without side-tone feedback. Measurements of speech spectrum noise, made to estimate the levels of noise at the tympanic membrane for the four noise conditions, were used to explain the results of the behavioral testing.

When telephone communication is attempted in background noise, the results of the present study indicate that, on average, the level of noise that can be tolerated is the same with acoustic or electromagnetic coupling if side-tone feedback is present as it is in normal telephone use. Switching to the telecoil did not result in additional noise suppression, nor did it improve tolerance of multitalker babble. It is important to note that these findings were obtained with the seven subjects with mild to moderate hearing losses who pressed the telephone receiver to the side of the head and formed an acoustic seal between the receiver and the pinna.

When side-tone feedback was deactivated, speech spectrum noise levels measured at the tympanic membrane were significantly reduced for frequencies above 900 Hz for each coupling method and tolerance of multitalker babble increased. These results were in agreement with studies conducted on normal-hearing subjects, indicating that telephone communication in noise was improved by deactivating the side-tone feedback (Holmes et al, 1983).

**Hearing Aid Users with Greater than Moderate Hearing Loss**

In the present study, subject 8 was the only individual with a moderately severe to profound hearing loss. Although he had to break the acoustic seal between the telephone receiver and the pinna to prevent acoustic feedback for acoustic coupling, he was able to set the volume control to a level he deemed best for telephone communication. Results of word recognition in quiet for subject 8 were 42 percent for electromagnetic coupling and 22 percent for acoustic coupling. These results indicated that, although subject 8 was able to acoustically couple despite the acoustic feedback, telephone communication in quiet was significantly better with electromagnetic coupling.
The spectra of the background noise near the tympanic membrane of subject 8 are displayed in Figure 9. Speech spectrum noise levels reaching the tympanic membrane for acoustic coupling with the poor telephone-receiver-to-pinna seal (the upper two functions) were much higher than the noise levels for electromagnetic coupling. As a result, subject 8 tolerated 18 dB less multitalker babble with acoustic coupling as compared to electromagnetic coupling. The results for subject 8 demonstrate that when acoustic feedback prevents a listener from forming a seal between the telephone receiver and the pinna, electromagnetic coupling is vastly superior to acoustic coupling and that muting the side-tone feedback provides additional improvement in noise suppression.

**CLINICAL IMPLICATIONS**

The present study was undertaken to obtain practical information for ITE hearing aid users who wished to purchase telecoils for their hearing aids or to evaluate the telecoil after the hearing aid had been purchased. Two categories of telecoil users were identified. Users with mild to moderate hearing loss who do not experience acoustic feedback for acoustic coupling can expect the following when comparing acoustic and electromagnetic coupling:

1. No significant difference in telephone communication in quiet.
2. No significant difference in telephone communication in noise when the side-tone feedback system is active.
3. Significant improvement in telephone communication in noise when the side-tone feedback system is deactivated.

Telecoil users with moderately severe to profound hearing loss who do experience acoustic feedback for acoustic coupling can expect the following when comparing acoustic and electromagnetic coupling:

1. Significant improvement in telephone communication in quiet and in noise with electromagnetic coupling.
2. Muting the side-tone feedback may improve communication or may have no effect.

Audiologists should order hearing aids with enough reserve gain that the volume control setting can be increased during telecoil use. To ensure that the reserve gain is adequate and that the telecoil is functioning properly, hearing aid performance should be evaluated behaviorally using acoustic and electromagnetic coupling as a part of the hearing aid orientation.

Telecoil users should be informed that the volume control may be used during electromagnetic coupling just as it is during everyday use. They also need to be instructed on how to compare telecoil performance to performance with acoustic coupling, on how to obtain an acoustic seal between the pinna and the telephone handset, and on how to deactivate the side-tone feedback by covering the telephone microphone with the palm of the hand or by using a mute button if available on the telephone being used.

**REFERENCES**


