2012

Difference between the default telecoil (T-Coil) and programmed microphone frequency response in behind-the-ear (BTE) hearing aids

Daniel B. Putterman
Washington University School of Medicine in St. Louis

Michael Valente
Washington University School of Medicine in St. Louis

J Am Acad Audiol 23:366–378 (2012)

Difference between the Default Telecoil (T-Coil) and Programmed Microphone Frequency Response in Behind-the-Ear (BTE) Hearing Aids

DOI: 10.3766/jaaa.23.5.7

Daniel B. Putterman*
Michael Valente†

Abstract

Background: A telecoil (t-coil) is essential for hearing aid users when listening on the telephone because using the hearing aid microphone when communicating on the telephone can cause feedback due to telephone handset proximity to the hearing aid microphone. Clinicians may overlook the role of the t-coil due to a primary concern of matching the microphone frequency response to a valid prescriptive target. Little has been published to support the idea that the t-coil frequency response should match the microphone frequency response to provide "seamless" and perhaps optimal performance on the telephone. If the clinical goal were to match both frequency responses, it would be useful to know the relative differences, if any, that currently exist between these two transducers.

Purpose: The primary purpose of this study was to determine if statistically significant differences were present between the mean output (in dB SPL) of the programmed microphone program and the hearing aid manufacturer's default t-coil program as a function of discrete test frequencies. In addition, pilot data are presented on the feasibility of measuring the microphone and t-coil frequency response with real-ear measures using a digital speech-weighted noise.

Research Design: A repeated-measures design was utilized for a 2-cc coupler measurement condition. Independent variables were the transducer (microphone, t-coil) and 11 discrete test frequencies (15 discrete frequencies in the real-ear pilot condition).

Study Sample: The study sample was comprised of behind-the-ear (BTE) hearing aids from one manufacturer. Fifty-two hearing aids were measured in a coupler condition, 39 of which were measured in the real-ear pilot condition. Hearing aids were previously programmed and verified using real-ear measures to the NAL-NL1 (National Acoustic Laboratories—Non-linear 1) prescriptive target by a licensed audiologist.

Data Collection and Analysis: Hearing aid output was measured with a Fonix 7000 hearing aid analyzer (Frye Electronics, Inc.) in a HA-2 2-cc coupler condition using a pure-tone sweep at an input level of 60 dB SPL with the hearing aid in the microphone program and 31.6 mA/M in the t-coil program. A digital speech weighted noise input signal presented at additional input levels was used in the real-ear pilot condition. A mixed-model repeated-measures analysis of variance (ANOVA) and the Tukey Honestly Significant Difference (HSD) post hoc test were utilized to determine if significant differences were present in performance across treatment levels.

*Program in Audiology and Communication Sciences, Washington University in St. Louis School of Medicine, St. Louis, MO; †Division of Adult Audiology, Washington University in St. Louis School of Medicine, St. Louis, MO

Daniel B. Putterman, National Center for Rehabilitative Auditory Research (NCRAR), Portland VA Medical Center, Portland, OR 97239; Phone: 503-220-8262, ext. 57094; Fax: 503-721-1402; E-mail: Daniel.Putterman@va.gov

Portions of this manuscript were presented at the annual meeting of the American Auditory Society, March 2010, Scottsdale, AZ, and at AudiologyNOW!, April 2010, San Diego.

Frye Electronics, Inc., provided the FP40 telewand, footswitch, and demonstrator ear.

This publication was made possible by Grant Number TL1 RR024995 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. The contents of this article are solely the responsibility of the authors and do not necessarily represent the official view of NCRR or NIH.

Results: There was no significant difference between mean overall t-coil and microphone output averaged across 11 discrete frequencies ($F(1,102) = 0$, $p < 0.98$). A mixed-model repeated-measures ANOVA revealed a significant transducer by frequency interaction ($F(10,102) = 13.0$, $p < 0.0001$). Significant differences were present at 200 and 400 Hz where the mean t-coil output was less than the mean microphone output, and at 4000, 5000, and 6300 Hz where the mean t-coil output was greater than the mean microphone output.

Conclusions: The mean t-coil output was significantly lower than the mean microphone output at 400 Hz, a frequency that lies within the typical telephone bandwidth of 300–3300 Hz. This difference may partially help to explain why some patients often complain the t-coil fails to provide sufficient loudness for telephone communication.

Key Words: Electromagnetic (EM) field, hearing aid, telecoil (t-coil)

Abbreviations: ANSI = American National Standards Institute; BTE = behind the ear; digispeech = digital speech; EAM = external auditory meatus; EM = electromagnetic; FFC = far-field cancelling; HFA = high frequency average; HSD = Honestly Significant Difference; REAR = real-ear aided response; RSETS = relative simulated equivalent telephone sensitivity; SPLITS = sound pressure level of the inductive telephone simulator; t-coil = telecoil; TMFS = telephone magnetic field simulator

In 1936 Joseph Poliakoff patented a magnetic induction loop that transmitted electromagnetic (EM) signals to a nearby antenna. In the subsequent year, an induction coil acting as an antenna for EM signals was embedded in the British Multitone hearing aid for use on the telephone, representing the first documented use of the telecoil (t-coil) (Levitt, 2007). Sam Lybarger, however, is acknowledged for implementing t-coils in hearing aids in the United States in 1947, reporting that unintended EM leakage from a telephone receiver causes a field immediately adjacent to the t-coil embedded in the hearing aid. This EM field contains the source signal from the telephone receiver with the EM signal proportional to the intended electrical signal (Ross, 2005; Levitt, 2007). The EM signal is detected by the t-coil, a wire coiled about a permeable metal core, and transduced by the hearing aid into an acoustic signal (Yanz and Preves, 2003). Specifically, successful induction requires that the signal must pass through the metal core while an electric current flows through the coiled wire (Ross, 2005). The result is an enduring technology that provides several distinct advantages over the microphone when a hearing aid user uses the t-coil while communicating on the telephone.

One advantage, unlike the microphone, is that the t-coil will only detect EM signals and not any undesired nearby acoustic signals. This will provide the user with a more favorable listening situation for achieving improved speech recognition when using the telephone or assistive devices. A second advantage is that the t-coil allows the telephone receiver to be positioned in close proximity to the ear without producing feedback. Feedback will naturally occur due to the close proximity of the telephone receiver to the hearing aid microphone (Takahashi, 2005). A patient might decrease the hearing aid volume to eliminate feedback with the expense of a likelihood of decreased speech recognition. A third advantage is that using the microphone when communicating on the telephone can cause attenuation of low frequency energy as the user attempts to eliminate the feedback by distancing the hearing aid from the EM telephone receiver (Goldberg, 1975). In addition, the t-coil can receive EM signals from sources other than telephones such as a neck-loop or an inductive loop system installed in educational settings, clinics, homes, theaters, and places of worship. Inductive loop systems transmit an EM signal to the hearing aid via a wire that "loops" around a room. This arrangement provides a high signal-to-noise ratio (SNR), whereby the acoustic signal of interest can effectively circumvent distance and background noise as it is transmitted electromagnetically from the induction loop to the t-coil. In addition, t-coils and induction loops can provide connectivity to modern technologies (e.g., cellular telephones and portable music devices) that are of low cost and easy to use relative to other options (Beck and Fabry, 2011). Direct cell phone use with t-coils, however, can be problematic because cell phones use high frequency signals in the gigahertz range that can become amplified by metal and wire of short length (Victorian and Preves, 2004). Efforts are underway for cell phone manufacturers to specify EM interference as well as hearing aid manufacturers to specify hearing aid immunity to these signals. For example, the American National Standards Institute (ANSI) C63.19 2006 (ANSI, 2006) assists hearing aid users and clinicians to identify cell phones that are less likely to cause interference (Levitt et al, 2005). Unfortunately, the implementation of standards specific to t-coil use has historically been slow and limited.

For decades, electroacoustic measurement of the t-coil frequency response has received substantially less attention than the microphone frequency response

(Ross, 2005; Takahashi, 2005). In fact, ANSI S3.22-1976 (ANSI, 1976) only required a test-field strength of 10 mA/M and output measured at 1000 Hz (Teder, 2003). Twenty years later, ANSI S3.22-1996 (ANSI, 1996) mandated that t-coil performance be evaluated with a test-field strength of 31.6 mA/M. This can be accomplished in one test system using a test transducer called a telephone magnetic field simulator (TMFS), which is a handheld device designed to generate a 31.6 mA/M EM field, simulating the average EM leakage of a conventional telephone. Furthermore, the high frequency average (HFA) (1000, 1600, and 2500 Hz) in sound pressure level of the inductive telephone simulator (SPLITS) was compared to the HFA of the microphone response using a 60 dB SPL input signal with the volume control at reference test position (RTP) (Teder, 2003). Formerly known as the simulated telephone sensitivity (STS) in ANSI S3.22-1996, this difference between the microphone HFA and t-coil HFA has recently been renamed the relative simulated equivalent telephone sensitivity (RSETS) in ANSI S3.22-2003 (ANSI, 2003). The closer the RSETS is to 0 dB, the closer the t-coil frequency response matches the microphone frequency response at 1000, 1600, and 2500 Hz (Teder, 2003).

Prescriptive fits are typically based on the microphone frequency response to average conversational speech presented at an input level of 65 dB SPL at a distance of 1 m. This is conventionally deemed to be representative of "real-life" one-on-one listening. There is, however, no standardized protocol for verification of t-coil performance because the listening condition is more of a challenge to simulate (Yanz and Pehringer, 2003). Despite the fact that the conventional telephone's bandwidth is from 300 to 3300 Hz, telephones are not equal in terms of how much EM leakage is released from the handset (Kozma-Spytek, 2003; Yanz and Preves, 2003). This causes inconvenience whereby the hearing aid user must manually adjust the volume control of the hearing aid while in the t-coil program at the beginning of a telephone conversation. Also, the distance from the telephone receiver is only centimeters from the t-coil, which makes the appropriate input level for creating a prescribed target even more difficult to identify. Furthermore, not all hearing aid t-coil frequency responses are programmable, and of those that are, not all allow frequency specific adjustment of the gain of the frequency response. Even if clinicians had the ability to program the t-coil frequency response, it has not been determined whether the t-coil frequency response should be the same as the microphone frequency response when the bandwidth of the telephone is narrower than the bandwidth of average conversational speech arriving at the microphone (Rodriguez et al, 1993).

Previous studies have measured hearing aids in a test box with the volume control full on (Tannahill, 1983; Rodriguez et al, 1985). Rodriguez et al (1985) reported that, in general, the microphone transducer produced consistently higher gain (output) than the t-coil transducer irrespective of the frequency region of interest. These results necessitated verification measures to determine the magnitude of gain (output) arriving to the ear in the microphone and t-coil programs. Additional studies measured the real-ear insertion response (REIR) and real-ear aided response (REAR) for the microphone and t-coil programs using an Audiometer Telephone Interface (ATI) designed to match a conventional telephone in the t-coil (Rodriguez et al, 1991; Rodriguez et al, 1993). Again, the mean gain was higher for the microphone response at all frequencies lower than 4500 Hz, and there was a subjective preference for increased t-coil gain (specifically more low frequency gain and a flatter frequency response). Because the aforementioned studies reported that differences exist between these two listening conditions (i.e., microphone and t-coil) using coupler and real-ear measures, other investigators elected to analyze how different coupling modes would impact user performance in word recognition. These studies concluded that differences in word recognition between the microphone and t-coil were not statistically significant and the main variable affecting user performance was the particular telephone used in the study (Holmes, 1985; Upfold and Goodair, 1997; Plyler et al, 1998). These studies, however, may have been limited by hearing aids without effective feedback management and an inability to program the t-coil independent of the microphone program in order to investigate if an increase in t-coil gain would improve word recognition.

In summary, despite comparisons of the microphone and t-coil conditions using word recognition measures that include distance, real-ear measures, and coupler measures, the appropriate fit for the t-coil frequency response remains ambiguous. Teder (2003) reports that there is little evidence addressing what t-coil frequency response condition is most satisfactory for "real-life" telephone use. Specifically, should the t-coil frequency response be based on the microphone frequency response, and if so, should the overall gain of the t-coil be equal to the overall gain of the microphone? Most clinicians do not consider the role of the overall gain and frequency response of the t-coil because clinicians are primarily concerned with matching the microphone response to a valid prescriptive target. Further, during the hearing aid fitting it is probably typical for clinicians to upload the manufacturer's default t-coil setting. Moreover, if the patient then reports poor performance with the telephone, clinicians typically suggest an amplified telephone or counsel the patient on the importance of correct telephone receiver position. The clinician might also explain there is a poor history of telephone-to-hearing-aid compatibility, as well as poor reliability in the coupling success between and across telephones to hearing aids. None of these strategies, however, take into account that the cause of the poor t-coil performance could be an inappropriately programmed t-coil.

Due to the lack of t-coil consideration, little has been published to support the idea that the t-coil frequency response should match the microphone frequency response to provide improved performance on the telephone. Until these data become available it seems reasonable to assume that the t-coil frequency response should match the microphone frequency response. If the audiologist's goal were to match both frequency responses, it would be useful to know the relative differences that may exist between these transducers.

The primary purpose of this study was to address differences in the mean frequency response between the programmed microphone and default t-coil hearing aid settings through coupler measures of programmed behind-the-ear (BTE) hearing aids. The following null hypotheses were developed for the coupler test condition:

1. There will be no significant difference in the measured output (in dB SPL) of the frequency response between microphone and t-coil transducers averaged across 11 test frequencies.
2. There will be no significant difference in measured output (in dB SPL) of the two-factor interaction of transducers and frequencies.

METHODS

Hearing Aids

Fifty-two BTE hearing aids were measured in a 2-cc coupler condition. All hearing aids were recently returned from repair to the Adult Audiology Clinic at the Center for Advanced Medicine at Washington University in St. Louis School of Medicine. Each hearing aid had the ability for the investigators to select the microphone and t-coil programs through the programming software. For all hearing aids, the microphone frequency response was programmed to the NAL-NL1 (National Acoustic Laboratories—Non-linear 1) (Dillon, 1999) prescriptive target for the patient's hearing loss using an input level of 65 dB SPL. T-coil settings were not adjusted and thereby left to the manufacturer default setting. Prior to analysis, each hearing aid was temporarily programmed via the manufacturer's NOAH-integrated software module so that the patient's previously programmed microphone and the default t-coil frequency response were set to programs one (programmed microphone) and two (default t-coil) respectively. The current manufacturer NOAH software module was used to make these programming changes.

Equipment

All performance measures were completed using a Fonix 7000 hearing aid analyzer (Frye Electronics, Inc.) situated inside a double-walled sound suite absent of EM interference. Coupler measures were completed to determine possible differences between the programmed microphone and default t-coil frequency response. A pure-tone sweep was used to measure the frequency response of the programmed microphone and default t-coil in the 2-cc coupler in accordance with ANSI S3.22-2003. By default, the source input level for ANSI S3.22-2003 is 60 dB SPL. The equivalent EM drive of the test-field strength of the TMFS that the Fonix 7000 is equipped with is 31.6 mA/M, and this was used to measure the frequency response of the default t-coil.

The swept pure-tone signal presents one frequency at a time from 200 to 8000 Hz. The output (in dB SPL) of the frequency response was measured at 11 discrete frequencies (200, 400, 500, 800, 1000, 1600, 2000, 2500, 4000, 5000, and 6300 Hz). The output using a pure-tone sweep could only be viewed in "graphic" mode (right side in Fig. 1). This limited the investigators to visually examine the measured output (to the nearest dB SPL tick on the ordinate) based on the intersection of the vertical lines that denote the 11 frequencies previously listed and the horizontal line denoting dB SPL. To control for this possible confounding variable, the investigators were careful to consistently read the measured output of each "graphic" in the same manner for all pure-tone measures. In Figure 1, the curve labeled "O" is the OSPL90 curve, the curve labeled "S" is the SPLITS curve representing the frequency response of the t-coil, and the curve labeled "R" is the frequency response of the microphone.

For accurate coupler measures of the microphone frequency response, the coupler test microphone was leveled at the test point of the test box prior to each measurement to calibrate the test microphone and the test box loudspeaker. Then the test BTE hearing aid was connected to an HA-2 coupler by the earhook via 25 mm of #13 tubing with the microphone of the hearing aid placed appropriately at the test point and facing the right side of the test box where the loudspeaker is housed. The hearing aid was placed in the test box connected to the HA-2 coupler, the test box lid was closed and sealed, and the hearing aid was programmed to Program 1 (programmed microphone mode). The frequency response was measured using the pure-tone sweep ("R" in Fig. 2).

For the t-coil condition, the hearing aid was removed from the test chamber while remaining coupled to the HA-2 coupler, programmed to Program 2 (default t-coil), and held upright in the investigator's hand. In the other hand, the TMFS shipped and designed for

Freq Hz	SPL dB	Freq Hz	SPL dB	Freq Hz	SPL dB	Freq Hz	SPL dB
		2100	82.7	4100	82.4	6100	74.2
200	37.0	2200	82.6	4200	82.0	6200	73.8
300	36.7	2300	83.2	4300	80.7	6300	73.2
400	38.6	2400	83.4	4400	79.8	6400	72.1
500	41.2	2500	84.0	4500	78.6	6500	71.2
600	46.3	2600	83.6	4600	78.3	6600	70.5
700	54.5	2700	83.4	4700	77.7	6700	68.6
800	65.8	2800	82.1	4800	77.6	6800	67.4
900	78.9	2900	82.2	4900	77.1	6900	66.0
1000	86.4	3000	81.0	5000	77.5	7000	65.0
1100	89.0	3100	79.8	5100	77.7	7100	63.2
1200	88.6	3200	79.0	5200	77.4	7200	60.9
1300	88.9	3300	78.5	5300	77.6	7300	58.6
1400	89.3	3400	78.1	5400	77.0	7400	57.0
1500	89.7	3500	78.2	5500	76.8	7500	54.9
1600	86.8	3600	78.8	5600	76.4	7600	52.3
1700	84.1	3700	80.1	5700	76.2	7700	50.1
1800	81.6	3800	81.1	5800	75.5	7800	49.0
1900	81.7	3900	81.3	5900	75.3	7900	48.5
2000	81.7	4000	82.2	6000	74.8	8000	47.3

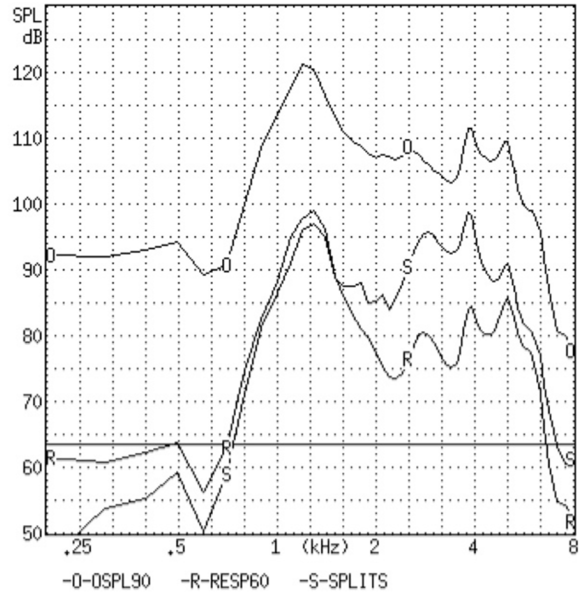

Figure 1. The "graphic" mode *(right),* which was the only viewing option available for the ANSI S3.22-2003 pure-tone coupler condition, and the "data" mode *(left)* available for the experimental digispeech real-ear measures condition.

use with Fonix 7000 was manipulated adjacent to the hearing aid case until the "sweet spot" was found. The "sweet spot" was detected by observing the maximum output (i.e., maximum output measured while observing the HFA-SPLITS value shown in Figure 2, which is 74.7 dB in this example) that could be observed on the hearing aid analyzer computer screen. When this was achieved, the pure-tone sweep was started to generate the t-coil frequency response ("S" curve in Fig. 2). The analyzer automatically calculated the pure-tone RSETS value (in dB) by subtracting the programmed microphone HFA (1000, 1600, 2500 Hz) from the default t-coil HFA (i.e., −2.6 dB in this example). This RSETS value was recorded in addition to visually estimating the output at discrete frequencies of both transducers in "graphic" display (as was previously described).

RESULTS

Hearing aid output (in dB SPL) was measured using a pure-tone sweep (200–8000 Hz in 100 Hz increments) at an input level of 60 dB SPL with the hearing aid configured to the programmed microphone and an input level of 31.6 mA/M using the TMFS shipped with the Fonix 7000 when measuring the t-coil. Independent variables included (1) transducer (microphone and t-coil) and (2) frequency (11 discrete test frequencies and the HFA).

Transducer Main Effect

The mean (and ±1 SD) overall output (output averaged across the 11 discrete test frequencies) measured for the programmed microphone and default t-coil is reported in Figure 3. The mean overall output for the programmed microphone was 77.1 dB SPL (SD = 12.7 dB SPL), whereas the mean overall output for the default t-coil was 77.0 dB SPL (SD = 13.6 dB SPL). A mixed-model repeated-measures analysis of variance (ANOVA) revealed no significant difference between transducers ($F(1,102) = 0$, $p < 0.98$).

Transducer by Frequency Interaction

The mean (and ±1 SD) output (in dB SPL) of the programmed microphone and default t-coil was compared at the 11 discrete test frequencies and for the HFA as reported in Figure 4. A mixed-model repeated-measures ANOVA revealed a significant transducer by frequency interaction ($F(10,102) = 13.0$, $p < 0.0001$). Figure 5 reports the mean difference (and ±1 SD) between the microphone and t-coil conditions at the 11 discrete test frequencies and for the HFA calculated from Figure 4. If the height of the bar is 0 dB, then the performance of the microphone and t-coil was equal. If the height of the bar is greater than 0 dB, then the mean measured output of the microphone was greater than the mean measured output of the t-coil. On the other hand, if the height of the bar is less than 0 dB, then the mean measured output of the microphone was less than the mean measured output of the t-coil. Reported in Figure 5 are post hoc analyses using the Tukey Honestly Significant Difference (HSD) test, which revealed that significant differences were present at 200 Hz (Delta = 15.2 dB, SD = 8.5 dB; $p < 0.001$) and 400 Hz (Delta = 6.0 dB, SD = 7.7 dB; $p < 0.05$) where the t-coil output was greater than the microphone, and at 4000 Hz (Delta = −5.9 dB, SD = 9.6 dB; $p < 0.01$), 5000 Hz (Delta = −5.7 dB, SD = 9.1 dB;

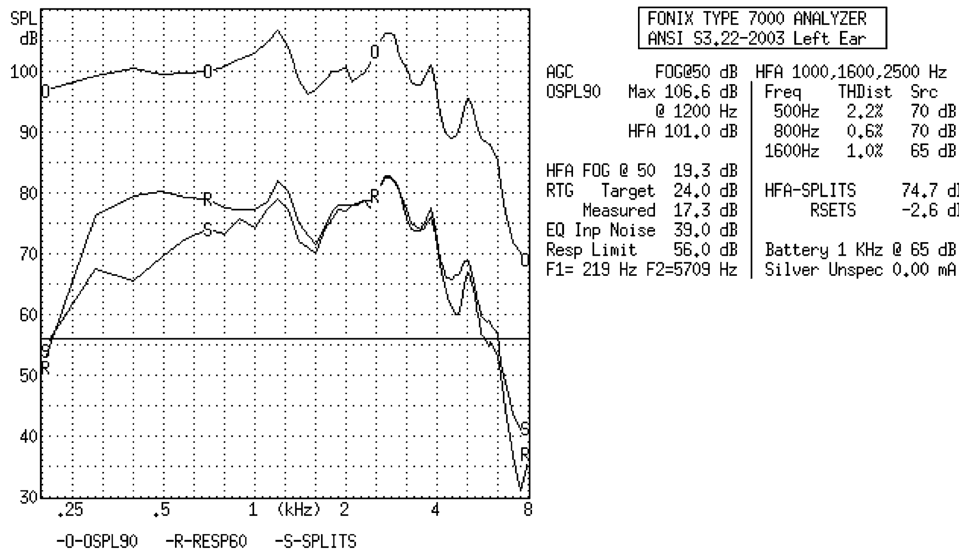

Figure 2. The "graphic" mode view of the measured coupler frequency responses (in dB SPL) of the programmed microphone (Curve R) and default t-coil (Curve S) to a pure-tone sweep signal via ANSI S3.22-2003. Curve 0 represents the OSPL90 microphone frequency response. Note in this case that the RSETS is −2.6 dB, which means that the HFA for the t-coil is 2.6 dB lower than the HFA for the microphone.

$p < 0.01$), and 6300 Hz (Delta = −7.4 dB, SD = 9.7; $p < 0.001$) where the microphone output was greater than the t-coil. The mean output for 500–2500 Hz discrete test frequencies was statistically equivalent between the two transducers. A paired t-test comparing the mean output for the HFA (1000, 1600, and 2500 Hz) revealed no significant difference between the two transducers ($p < 0.10$).

DISCUSSION AND CONCLUSION

Coupler Measures

This study compared the measured output of the programmed microphone frequency response to the default t-coil frequency response in the coupler condition using the pure-tone sweep signal. It is of note that post hoc statistically significant frequency-specific differences for coupler measures were found at 200, 400, 4000, 5000, and 6300 Hz. Figure 5 illustrates how this is possible despite the lack of significant difference in overall output between the transducers, since the mean microphone output was greater in the low frequencies (200 and 400 Hz), yet the mean t-coil output was greater in the high frequencies (4000, 5000, and 6300 Hz). Thus the low and high frequency differences between the two transducers negated each other when the overall output of each transducer was calculated.

The relationship between the mean programmed microphone and default t-coil frequency response

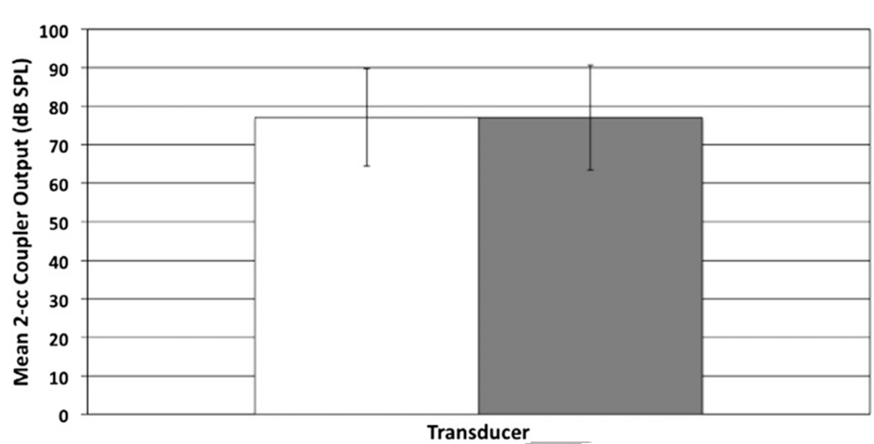

Figure 3. The mean coupler output (in dB SPL) of 52 test hearing aids averaged across 11 discrete test frequencies when programmed to the microphone (empty bar) and t-coil (shaded bar) using a 60 dB SPL (and 31.6 mA/M) pure-tone sweep. The error bars represent ±1 SD.

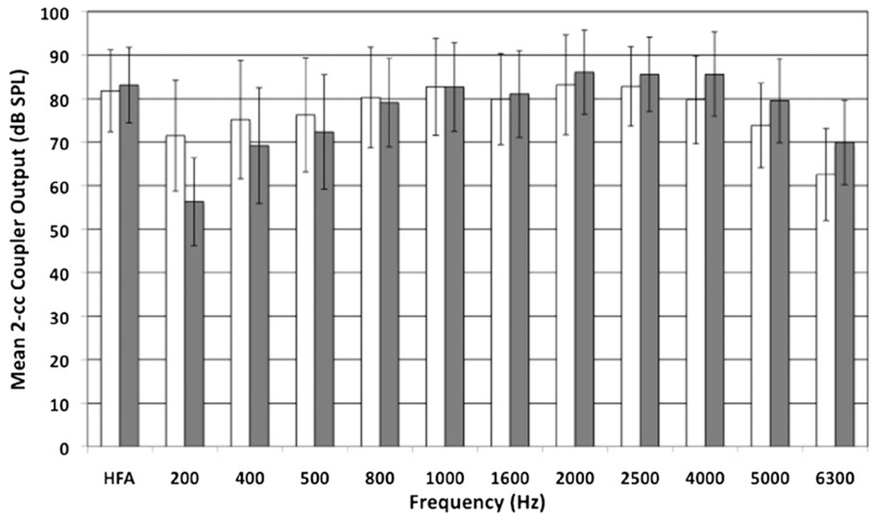

Figure 4. The mean coupler output (in dB SPL) of the microphone (empty bars) and t-coil (shaded bars) output of 52 test hearing aids for 11 discrete test frequencies using a 60 dB SPL (and 31.6 mA/M) pure-tone sweep. The HFA is included at the far left. The error bars represent ±1 SD.

shown in Figure 5 is remarkably similar to single hearing aid data (not shown) from a publication by Ross (2006), who suggested that a t-coil with a pre-amplifier could allow the t-coil frequency response to nearly match the microphone frequency response. Consistent with Figure 5, the Ross (2006) figure demonstrates some reduction in the t-coil frequency response in the low frequencies and an increase in the high frequencies when compared to the programmed microphone frequency response. Recall that a typical telephone bandwidth is 300 to 3300 Hz (Yanz and Preves, 2003). Importantly, when the telephone bandwidth is taken into consideration then the only significant differences reported from coupler results influential to telephone communication are the low frequency differences (specifically 200 to 400 Hz), where the mean default t-coil output was lower than the mean programmed microphone output by 6 dB. While the t-coil response was also 3.9 dB lower at 500 Hz, this was not found to be a statistically significant difference. Figure 2 provides an example of how a difference in low frequency amplification between transducers may be overlooked using coupler measures. Note that there is clear low frequency attenuation of the t-coil frequency response compared to the microphone response, yet the RSETS value is nearly zero (−2.6 dB) because it is calculated as the difference between the HFA (1000, 1600, and 2500 Hz) of each transducer. A reasonable question to ask is

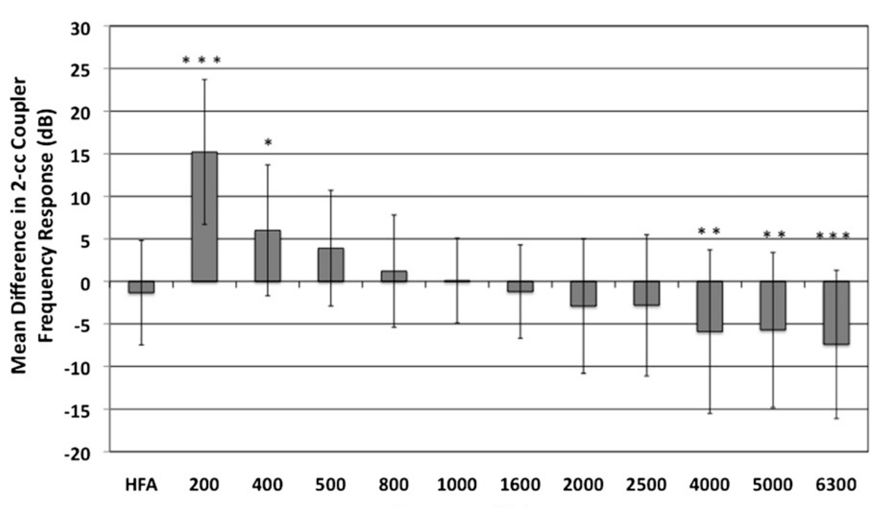

Figure 5. The mean difference (delta) in coupler output (in dB SPL) between the microphone and t-coil output of 52 test hearing aids for 11 discrete test frequencies using a 60 dB SPL (and 31.6 mA/M) pure-tone sweep. $^{***}p \leq 0.001$; $^{**}p \leq 0.01$; $^{*}p \leq 0.05$. The HFA is included at the far left. The error bars represent ±1 SD.

whether this magnitude of low frequency attenuation of the t-coil frequency response can be problematic for the listener.

It has been suggested that low frequencies should not be amplified in the t-coil position because the t-coil can be sensitive to low frequency interference (i.e., EM noise), which is then amplified in conjunction with the signal of interest (Ross, 2006). Without amplifying the low frequencies, however, patients often complain the t-coil fails to provide sufficient loudness for telephone communication. In addition, low frequency information below 300 Hz has already been removed from the telephone bandwidth. If the hearing aid user has hearing aids with a volume control, the patient may still remain inconvenienced by the need to increase the volume during a telephone conversation. Ideally, the transition from the microphone to the t-coil position should be seamless (i.e., the programs should have equal loudness). Moreover, much of the concern related to amplifying the low frequencies in the t-coil position may be reduced in part by the development of commercially available far-field cancelling (FFC) t-coils (Marshall, 2005). If FFC t-coils are incorporated into new hearing aids, then extraneous EM signals that are not in the near field (i.e., within inches of the t-coil) of the hearing aid will no longer contribute to interference of the low frequencies.

Modern T-Coil Applications

In MarkeTrak VIII (Kochkin, 2010), consumers were asked to rate 19 listening situations related to how "critical" these listening situations were to the consumer. At 64%, telephone communication was rated the third most important, behind only one-on-one communication (75%) and communication in small groups (65%). Moreover, t-coils have applications that extend beyond conventional telephone communication (hearing assistance technology that requires an induction loop for a room or an induction neck-loop). This means that there is an even greater responsibility on the part of clinicians to begin to consider how to appropriately program the t-coil mode. Advances in t-coil technology will be crucial as many current limitations can diminish the ability of the t-coil to transfer a clear and sufficiently amplified signal to the hearing aid user.

One recent development in hearing aid technology allows bilateral hearing aid users to hear the telephone signal received by one hearing aid in both hearing aids. Regardless of which hearing aid the telephone handset is held to, the designated hearing aid transmits the signal wirelessly to the other hearing aid for binaural listening on the telephone. To date, it does not appear that there have been any research studies on the efficacy and/or effectiveness of this novel technology. Despite advancements in t-coil design and flexibility, t-coil utilization is not always straightforward for the clinician. For example, not all manufacturers allow the same flexibility of gain manipulation in the hearing aid t-coil program. Some manufacturers restrict the audiologist by only allowing the ability to increase and decrease the overall gain of the t-coil, but the shape of the frequency response remains fixed. The extent to which the t-coil gain can be programmed by the audiologist can vary within the product line available from a single manufacturer. Some products allow the clinician to pair the t-coil frequency response to an acoustic program, whereby adjusting the frequency response of the acoustic setting will be emulated in the t-coil program. Other manufacturers, however, allow audiologists to increase and decrease gain across the frequency response of the hearing aid similarly to any of the microphone programs.

Further Research

The investigators were interested to determine if real-ear measures, using a "speechlike" signal, rather than a pure tone signal, might be feasible to measure differences in the performance between the microphone and t-coil in hearing aids. To this end, 39 of the 52 hearing aids from this study were measured using real-ear measures in a pilot investigation. The output (in dB SPL) was measured at 15 discrete frequencies (200, 300, 400, 500, 600, 800, 1000, 1200, 1600, 2000, 2500, 3200, 4000, 5000, and 6300 Hz) for real-ear measures using the digital speech (digispeech) ANSI speech-shaped noise. Digispeech is randomly interrupted to evaluate the electroacoustic characteristics of digital hearing aids. Unlike the pure-tone sweep, the signal frequencies of digispeech are measured simultaneously, and the analyzer individually adjusts the amplitude and phase at each frequency based on reference microphone placement (Frye, 2002). The use of digispeech bypasses an undesirable "blooming" artifact that can occur with the pure-tone sweep (Frye, 2002). Blooming (i.e., excessive low frequency gain/output) occurs for compression hearing aids because the circuit will focus amplification entirely on the input frequency of the sweep signal that is currently presented to the hearing aid. Measuring the electroacoustic performance of hearing aids using digispeech could provide a measured frequency response that is more indicative of a "real-world" speech signal. For real-ear measures, a left "demonstrator" ear (Frye Electronics, Inc.) mounted on a tripod was utilized to mimic the external auditory meatus (EAM). A narrow hole was drilled into the anterior face of the silicon block (i.e., 0° azimuth) into the medial portion of the EAM to within 5 mm from where the EAM terminates. A probe tube was then connected to the probe microphone, and the probe tube was fed through the hole. The probe tube was permanently affixed with glue so the tip of the probe tube rested where the bored hole intersected the medial EAM. An ear hanger housing the reference and probe microphone was then placed on the pinna of the demonstrator ear. The test BTE hearing aid was connected to an earmold fit specifically to the concha of the demonstrator ear, and the test BTE hearing aid was positioned on the demonstrator ear so that the front and rear microphones were level on a horizontal plane (Fig. 6). The demonstrator ear tripod was positioned with the demonstrator ear at an equal height (and centered) with respect to the real-ear loudspeaker. The distance from the opening of the EAM in the concha of the demonstrator ear to the loudspeaker was 22 in, consistent with the length of a short NOAHLink programming cable.

Prior to measuring the frequency response of the programmed microphone, the reference and probe microphones were enabled, and the sound field was leveled to calibrate the loudspeaker with the reference microphone. After leveling, the test BTE hearing aid was positioned on the demonstrator ear, the earmold was inserted into the ear canal, and the BTE hearing aid was set to Program 1 (programmed microphone). The digispeech signal was presented at 70 dB SPL and the REAR measured. The programmed microphone REAR was visualized in the "graphic" mode by the investigators to ensure stability. Then the measured REAR was recorded at each of the 15 discrete frequencies by switching "graphic" display to "data" display (left side of Fig. 1) and the values recorded and placed into a spreadsheet.

To measure the t-coil frequency response, the TMFS from an FP40 hearing aid analyzer (manufactured by Frye Electronics, Inc.) was used to generate a test field strength of 56.2 mA/M (George Frye, pers. comm.). Unlike the default telewand typically provided with the Fonix 7000 for coupler measures, the FP40 telewand is capable of producing an appropriate magnetic drive for the t-coil when completing real-ear measures. Unfortunately, consultation after completing data collection and analysis revealed that the loudspeaker input level for the microphone condition should have been 65 dB SPL (instead of 70 dB SPL) to be equal to the 56.2 mA/M input level to the telecoil provided by the TMFS telewand used in this part of the study. However, these investigators believe that significant value remains in reporting the results of the real-ear measures as it is hoped that the data in the following section might serve as a catalyst for manufacturers of coupler and real-ear equipment to consider providing the necessary tools to allow for real-ear measures of t-coil performance using a speechlike signal. Moreover, perhaps the data in the following section will serve, in part, to prompt those responsible for creating and revising ANSI standards to consider the feasibility of promoting the use of a speechlike signal for measuring t-coil performance for coupler and real-ear measures.

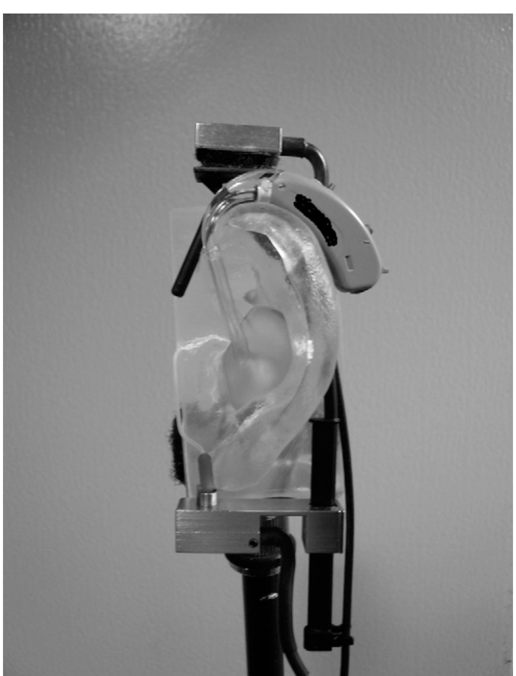

Figure 6. A sagittal view of the demonstrator ear with real-ear apparatus, custom earmold, and test hearing aid. The hearing aid is situated with front and rear hearing aid microphones oriented atop the pinna on a horizontal (level) plane. The reference microphone is placed medial to the hearing aid and adjacent to the front microphone.

When measuring the t-coil frequency response the reference microphone was turned off, and the test BTE hearing aid was then programmed to Program 2 (default t-coil). A foot switch was used to direct the digispeech signal through the TMFS rather than through the loudspeaker. With the signal turned on, the TMFS was manipulated adjacent to the hearing aid case until the "sweet spot" (most robust frequency response) was observed on the monitor. The sweet spot was detected by slowly manipulating the TMFS about the hearing aid case while observing the maximum output that could be measured in the "graphic" mode (bottom curve in Fig. 7). In Figure 7 the "RMS out" is 101.2 dB SPL for curve 1.

Once the sweet spot was detected, the "graphic" display was switched to "data" display to document the output at each of the 15 discrete test frequencies. By saving the t-coil frequency response as Curve 1 and the programmed microphone frequency response as Curve 2, the software of the Fonix 7000 calculates the difference between the two curves (Curve 6 in the top graph in Fig. 7). In this case, a value >0 dB gain reveals the output was greater for the microphone, a value of 0 dB means the output of the two transducers was equal, and a value <0 dB gain means the output for the t-coil was greater than the microphone. Finally, the investigators calculated the real-ear RSETS value as the difference between the HFA (1000, 1600, and 2500 Hz) of the programmed microphone and default t-coil output.

As mentioned earlier, hearing aid output (dB SPL) was measured using the digispeech ANSI speech-shaped composite signal presented at 70 dB SPL when

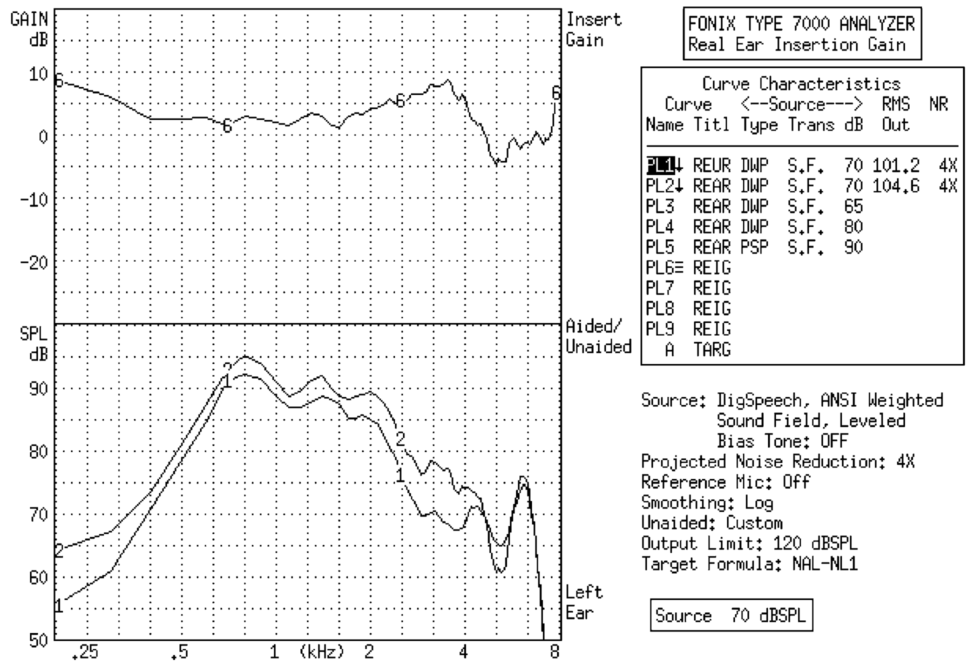

Figure 7. The "graphic" mode view of measured real-ear frequency responses (in dB SPL) of the programmed microphone (Curve 2) and default t-coil (Curve 1) with the digispeech input signal set to 70 dB SPL *(bottom graph)*. The gain curve *(top graph)* represents the difference (in dB) between Curves 1 and 2.

measuring the programmed microphone and 56.2 mA/M using the TMFS shipped with the Frye FP40 when testing the default t-coil. Independent variables included (1) transducer (microphone; t-coil), and (2) frequency (15 discrete test frequencies).

The mean (and ±1 SD) overall output (output averaged across the 15 discrete test frequencies) measured for the programmed microphone and default t-coil is reported in Figure 8. The mean overall output for the programmed microphone was 77.8 dB SPL (SD = 12.9 dB SPL), whereas the mean overall output for the default t-coil was 70.0 dB SPL (SD = 16.8 dB SPL). A mixed-model repeated-measures ANOVA revealed that the mean difference of 7.8 dB was statistically significant ($F(1,76) = 18.8$, $p < 0.0001$). Please remember that if the correct input level of 65 dB SPL had been used instead of the 70 dB SPL that was used for the microphone measures, then the mean overall output for the programmed microphone would have likely been closer to 72.8 dB SPL, and the resulting mean difference of 2.8 dB would have probably not been statistically significant.

The mean (and ±1 SD) output (in dB SPL) of the programmed microphone and default t-coil was compared at the 15 discrete test frequencies and for the HFA as reported in Figure 9. A mixed-model repeated-

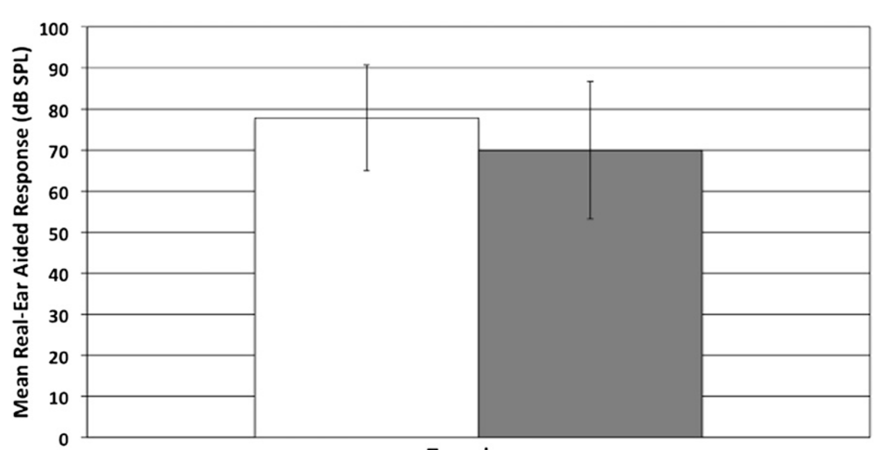

Figure 8. The mean REAR (in dB SPL) of 39 test hearing aids averaged across 15 discrete test frequencies when programmed to the microphone (empty bar) and t-coil (shaded bar). The error bars represent ±1 SD.

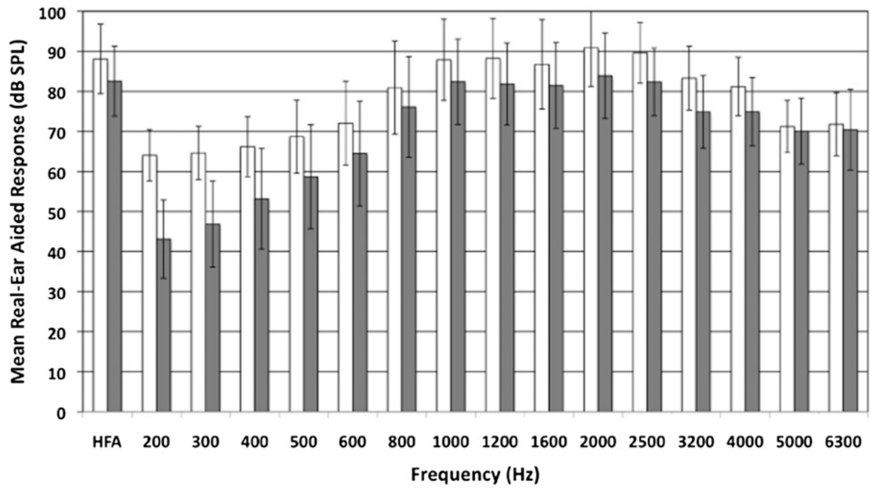

Figure 9. The mean REAR (in dB SPL) of the microphone (empty bars) and t-coil (shaded bars) output of 39 test hearing aids for 15 discrete test frequencies with the digispeech input signal set to 70 dB SPL. The HFA is included at the far left. The error bars represent ±1 SD.

measures ANOVA revealed a significant transducer by frequency interaction ($F(14,76) = 31.1$, $p < 0.0001$). Again, if the correct input level of 65 dB SPL had been used instead of the 70 dB SPL that was used for the microphone measures, then the mean overall output for the programmed microphone would have likely been reduced by approximately 5 dB, and several of the resulting mean differences across the 15 test frequencies may not have been statistically significant.

Reported in Figure 10 are the post hoc analyses using the Tukey HSD test, which revealed that the mean default t-coil output was significantly lower than the mean programmed microphone output at 200 Hz (Delta = 20.9 dB, SD = 6.4 dB), 300 Hz (Delta = 17.5 dB, SD = 6.5 dB), 400 Hz (Delta = 12.6 dB, SD = 7.1 dB), 500 Hz (Delta = 9.7 dB, SD = 5.7 dB), 600 Hz (Delta = 7.4 dB, SD = 5.0 dB), 1000 Hz (Delta = 5.0 dB, SD = 3.4 dB), 1200 Hz (Delta = 5.7 dB, SD = 3.7 dB), 1600 Hz (Delta = 4.9 dB, SD = 4.0 dB), 2000 Hz (Delta = 6.6 dB, SD = 4.0 dB), 3200 Hz (Delta = 7.7 dB, SD = 4.5 dB), and 4000 Hz (Delta = 6.0 dB, SD = 5.4 dB). The mean output for 800, 5000, and 6300 Hz discrete test frequencies was statistically equivalent between the two transducers. A paired *t*-test comparing the mean output for the HFA (1000, 1600, and 2500 Hz) revealed a significant difference between the two transducers ($p < 0.0001$). Once again, an input level of 65 dB SPL had been used in lieu of 70 dB SPL for the microphone measures, then the mean overall output for the programmed microphone at each of the 15 discrete test frequencies would have been reduced by approximately 5 dB, and the resulting mean differences (other than at 200, 300, 400, and 500 Hz) would not in all likelihood have been statistically significant.

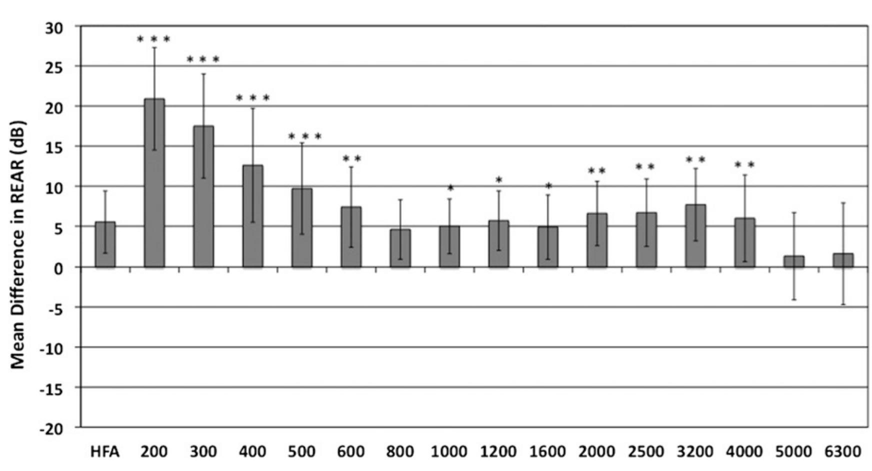

Figure 10. The mean difference (delta) in REAR (in dB SPL) between the microphone and t-coil output of 39 test hearing aids for 15 discrete test frequencies with the digispeech input signal set to 70 dB SPL. $^{***}p \leq 0.001$; $^{**}p \leq 0.01$; $^{*}p \leq 0.05$. The HFA is included at the far left. The error bars represent ±1 SD.

Measuring t-coil performance using real-ear measures is not novel. Grimes and Mueller (1991) proposed a real-ear measurement protocol for t-coil verification nearly 20 yr ago. In their study, a speech-shaped signal was directed to one telephone handset, and this signal was delivered to a second telephone handset with the receiver held to the casing of the hearing aid that was fit to the ear. The experimental equipment required to conduct t-coil real-ear measurements in this manner, however, is not typical for audiologists to undertake in a clinical setting. The fact remains that real-ear measurement of the t-coil frequency response has not evolved into conventional practice for clinicians. In the present study, the frequency response of the default t-coil was measured in a real-ear condition using a TMFS to present the EM signal to the hearing aid situated on the ear rather than using a series of telephones as described by Grimes and Mueller (1991). This real-ear measurement could be performed quickly and easily by an audiologist when using a Fonix 7000 with the TMFS that is typically shipped with the FP40 hearing aid analyzer.

Pilot data were also gathered over the course of this project with the intent of determining if any differences in the relationship of the default t-coil and programmed microphone frequency response exist between manufacturers, as the data reported here were collected from one manufacturer. Unfortunately, a limited number of BTE products from the other manufacturer were available for measurement. The trend in the data from the second manufacturer suggests that the default t-coil frequency response not only matched the programmed microphone frequency response in the pure-tone coupler test condition as hearing aids used in this study do but in some cases exceeded the microphone output. There also appeared to be less disparity between the microphone and t-coil in the real-ear condition, although there were not substantial data to perform statistical analyses to determine if significant differences were present.

Acknowledgments. The authors would like to thank Karen Steger-May, MA, of the Department of Biostatistics at Washington University in St. Louis School of Medicine, for completing statistical analysis of the data; A.U. Bankaitis, PhD, of Oaktree Products, Inc., for serving as a second reader for the capstone paper that served as the basis for this manuscript; and George and Kristina Frye of Frye Electronics, Inc., for providing the FP40 telewand, footswitch, demonstrator ear, and information on the Fonix 7000 hearing aid analyzer.

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