Longitudinal Tracking of Sound Exposure and Hearing Aid Usage through Objective Data Logs

John B. Doyle¹, Rohit R. Raghunathan, MS², Ilana Cellum, AuD¹, Gen Li, PhD², and Justin S. Golub, MD, MS¹

Abstract

Objective. To use data-logging technology to objectively track and identify predictors of hearing aid (HA) usage and aided sound exposure.

Study Design. Case series with planned data collection.

Setting. Tertiary academic medical center.

Subjects and Methods. Individuals with HAs between 2007 and 2016 were included (N = 431; mean, 74.6 years; 95% CI, 73.1-76.0). Data-logging technology intrinsic to new-generation HAs was enabled to track usage and sound exposure. With multivariable linear regression, age, sex, number of audiology visits, duration of audiologic follow-up, pure tone average, and HA side were assessed as predictors of usage (hours/day) and aided sound exposure (dB-hours/day; ie, “dose” of sound per day).

Results. Mean follow-up was 319 days (95% CI, 277-360). Mean HA usage was 8.4 hours/day (95% CI, 8.0-8.8; N = 431). Mean aided sound exposure was 440 dB-hours/day (95% CI, 385-493; n = 110). HA use (β < 0.001, P = .45) and aided sound exposure (β = −0.006, P = .87) were both stable over time. HA usage was associated only with hearing loss level (pure tone average; β = 0.030, P = .04). Aided sound exposure was associated only with duration of audiologic follow-up (β = 0.100, P = .02).

Conclusion. While measurement of HA use has traditionally relied on subjective reporting, data logging offers an objective tool to longitudinally track HA use and sound exposure. We demonstrate the feasibility of using this potentially powerful research tool. Usage and sound exposure were stable among patients throughout the study period. Use was greater among subjects with greater hearing loss. Maximizing aided sound exposure might be possible through continued audiology follow-up visits.

Keywords
data logging, hearing aid usage, hearing aid sound exposure, objective measures of hearing aid use, predictors of hearing aid use

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Age-related sensorineural hearing loss is the third most common chronic condition among older adults in the United States, with nearly 28.6 million individuals >60 years old affected. In addition to reduced quality of life and social interaction, hearing loss was independently associated with other morbid states, including depression, dementia, and even early mortality.

Amplification with hearing aids (HAs) can be used to treat hearing loss, and an estimated 3.8 million (14.2%) Americans ≥50 years old wear HAs at least once a day. HA use has been associated with improved social, emotional, and cognitive abilities. Nonetheless, hearing loss remains vastly undertreated, as <15% of Americans with hearing loss actually own HAs.

While HA ownership is 1 metric to gauge hearing loss treatment levels, HA usage is a more meaningful measure. However, HA utilization has been incompletely characterized due to a reliance on subjective, nonstandardized measures of use. Much of the existing literature assessing HA usage among older adults has relied on questionnaires and self-reporting that lack precision and are vulnerable to recall bias. Furthermore, few studies have described the sound environment to which patients are exposed while wearing HAs. Sound exposure may be a more meaningful measure than hours of HA use because it more closely represents the acoustic stimulus experienced by individuals while wearing HAs. Whereas usage measures how much an HA was

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turned on, sound exposure measures how much an HA was used for hearing sound. This distinction is important because hearing loss was recently associated with worse cognition and dementia.\textsuperscript{4,6} It is theorized that a lack of stimulating auditory input could mediate this association.\textsuperscript{12} Sound exposure is a better proxy of stimulating auditory input than the duration of time that the HA was used.

To better understand HA-associated outcomes and clinical benefits, objective characterization of HA usage and sound exposure is critical. Data-logging technology intrinsic to new-generation HAs offers an objective tool to digitally track HA use and sound exposure over time. This study analyzed data logs of 431 HA owners to longitudinally track HA use and sound exposure without relying on patient recall, self-report, or other subjective measures. Furthermore, given the underutilization of HAs, we sought to identify predictors of HA usage and sound exposure.

**Materials and Methods**

This was a case series with planned data collection. This study was approved by the Institutional Review Board of Columbia University.

**Subjects**

Subjects were 431 adult HA owners (mean age, 74.6 years; 95% CI, 73.1-76.0) who were seen by audiologists at a tertiary care academic medical center and had an HA with data-logging capabilities. Eligible subjects had at least 1 digital data log recorded between January 1, 2007, and June 1, 2016 (n = 451). Subjects <18 years old (n = 16) were excluded. In addition, subjects with mean recorded usage >18 hours/day (n = 4) were excluded, as we intended to capture usage and sound exposure only while they were awake. There was no limit to the number of data logs recorded per subject during the study period, and subjects with unilateral (n = 156) and bilateral (n = 275) HAs were included. HA manufacturers included Oticon (Smorum, Denmark; n = 116), ReSound (Ballerup, Denmark; n = 37), Widex (Lyngby, Denmark; n = 8), Phonak (Stafa, Switzerland; n = 88), and Unitron (Kitchener, Canada; n = 182).

**Data Collection and Variable Creation**

Data logs were accessed with the Noah System 4 database (Hearing Instrument Manufacturers’ Software Association, Copenhagen, Denmark). Data logs were automatically recorded whenever an audiologist connected a subject’s HA to the Noah software during an audiology visit. A data log period represented the time span between these individual audiology visits; there was no ability to analyze shorter intervals. Although HA manufacturers collected different metrics for a given data log period, each recorded the start date, end date, and either (1) the mean daily HA use over that period or (2) the total hours of HA use in that period, from which mean daily HA use was calculated. Thus, the duration of data-logged time and mean daily HA use (in hours/day) was recorded for each given data log across all manufacturers.

Data-logged information about sound environment was collected for a subset of the cohort (n = 110). Due to significant variability among HA manufacturers in recording sound environment data, only subjects wearing Oticon HAs were included in this subgroup analysis. Oticon was chosen because it was the most popular device company with sound environment data available. Through Oticon’s fitting software, sound exposure (ie, intensity of sound) was reported as a percentage of time spent in discrete decibel levels (<40, 40-50, 50-60, 60-70, 70-80, >80 dB-SPL) while wearing HAs. These data were recorded separately for each given data log period. For clarity, these dB-SPL measures represent the preamplified intensity of sound environment detected by the HA, rather than the postamplification intensity experienced by the cochlea.

In addition to data-logging information, subjects’ audiograms during the study period were collected and the pure tone average (PTA; mean dB-HL for 0.5, 1, 2, and 4 kHz) calculated. Other information collected included sex, age at conclusion of the most recent data log, the number of audiology visits made during the study period (June 1, 2016–January 1, 2007), and the duration of audiology follow-up (days between first visit and most recent visit prior to June 1, 2016).

For subjects with unilateral HAs, daily usage and PTA were analyzed from the one side of use; for subjects with bilateral HAs, daily usage and PTA were analyzed from the side with the greater daily usage. Aided sound exposure (dB-hours/day) was calculated to measure the “dose” of sound received per day by study subjects while wearing HAs. This value was calculated by multiplying the mean dB-SPL level of sound to which each subject was exposed while wearing an HA by his or her HA usage (hours/day) during the data log period. This yielded the unit dB-hours/ day. A dB-hour technically represents 1 hour exposed to a particular dB-SPL level. For example, 100 dB-hours means that the subject was exposed to a mean sound intensity of 100 dB-SPL over a duration of 1 hour (100 dB-SPL × 1 hour). If a subject had 100 dB-hours/day of sound exposure, then the “dose” of sound received by the HA (preamplification) over the course of that 24-hour day was 100 dB-hours. This could be achieved by listening to 100 dB-SPL for 1 hour (100 × 1 = 100) over 24 hours or by listening to 50 dB-SPL for 2 hours (50 × 2 = 100) over 24 hours.

It makes practical sense to normalize this dose of sound to typical hours of HA usage per day. In this case, 100 dB-hours/day of sound exposure is equivalent to a mean exposure of 12.5 dB-SPL over 8 hours of usage per day (100/8 = 12.5). The conversion formula is as follows: If E represents sound exposure in dB-hours/day and a subject uses HA for U hours/day, then she or he was exposed to sound with a mean intensity of E/U dB-SPL over those U hours of usage.

**Statistical Analysis**

With multivariable linear regression models, age, sex, HA side, PTA, duration of audiology follow-up, and number of audiology visits were assessed as predictors of daily HA...
usage and aided sound exposure. A paired $t$ test was separately performed to evaluate differences in daily usage between ears in bilateral HA users. Additionally, independent $t$ tests were used to evaluate differences in usage and aided sound exposure between users of unilateral and bilateral HAs and users with $\geq 30$ and $<30$ days of data-logging duration. Stata 14.1 (StataCorp, College Station, Texas) and R 3.3.0 (R Foundation, Vienna, Austria) were used.

Longitudinal trends of HA usage and aided sound exposure were also analyzed. This first required managing the diversity of the data log time intervals, which were inconsistent among and within subjects. To account for the fact that a single subject may have multiple overlapping time intervals, the unions of overlapping intervals were used as the new time partitions. These intervals were determined by aggregating all time intervals with common time points into 1 time interval. Once intervals were established, correlations between time and the outcomes of interest were determined with mixed effects models.

Results

Table 1 summarizes the study cohort ($N = 431$). The mean age was 74.6 years (95% CI, 73.1-76.0). Of subjects with audiometric data ($n = 416$, 97%), the mean PTA was 52.2 dB-HL (50.6-53.7; see Supplemental Table S1 in the online version of the article). Subjects had a mean of 1.9 (1.8-2.0) recorded data logs, representing a mean total duration of 319 days (277-360) of data-logged time. The mean number of audiology visits per subject during the study period was 10.7 (9.9-11.4; range, 2-49), and the mean duration of audiology follow-up was 915.3 days (843.4-987.3).

Mean HA usage as recorded by data logs was 8.4 hours/day (95% CI, 8.0-8.8). There were no significant differences in usage between subjects with unilateral and bilateral HAs ($P = .33$). For patients with bilateral HAs, there were no significant differences in usage between the right and left sides ($P = .17$). Furthermore, there were no significant differences in subjects with $<30$ days ($n = 123$) or $\geq 30$ days ($n = 308$) of data log duration ($P = .96$). Upon multivariable linear regression, daily HA usage was associated only with PTA ($\beta = 0.030$, $P = .04$; Table 2). Longitudinal analysis demonstrated that HA usage was stable over time ($\beta < 0.001$, $P = .45$; Figure 1). These analyses were unchanged if better-ear PTA was used instead of that from the ear with greater HA use (data not shown).

In subjects where sound environment information was available ($n = 110$, 26%), mean aided sound exposure was 439.7 dB-hours/day (95% CI, 385.6-493.8). There were no significant differences in aided sound exposure between subjects with unilateral and bilateral HAs ($P = .19$). There were no significant differences in subjects with $<30$ days ($n = 21$) or $\geq 30$ days ($n = 89$) of data log duration ($P = .76$). Unlike with daily HA use, aided sound exposure was only associated with duration of audiology follow-up ($\beta = 0.099$, $P = .02$) (Table 2). In longitudinal analysis, aided sound exposure was stable over time ($\beta = -0.006$, $P = .87$) (Figure 2).

<table>
<thead>
<tr>
<th>Variable</th>
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<th>Mean</th>
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<th>Range</th>
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<td>Female</td>
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<td>9.9-11.4</td>
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<td>8.0-8.8</td>
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<td>Aided sound exposure,$^d$ dB-h/d</td>
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<td>439.7</td>
<td>385.6-493.8</td>
<td>4.3-1099.5</td>
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</table>

Abbreviations: HA, hearing aid; PTA, pure tone average.

$^a$Age calculated at the conclusion of the most recent data-logged period.

$^b$At 0.5, 1, 2, and 4 kHz of the ear analyzed in this study. For subjects with unilateral HAs, PTA was analyzed from the side of use; for subjects with bilateral HAs, PTA was analyzed from the side with the greater daily usage.

$^c$For subjects with bilateral HAs, daily HA use was analyzed from the side with the greater daily usage.

$^d$Aided sound exposure (dB-hours/day) was calculated to measure the “dose” of sound that study subjects received per day while wearing HAs. This value was calculated by multiplying the mean dB-SPL level of sound to which each subject was exposed while wearing an HA by an individual’s HA usage (hours/day) during the data-logged period.

Discussion

This study reports the largest cohort of HA usage measured by an objective quantitative method and is the first to assess sound exposure as a quantitative variable. For 431 HA users seen at a tertiary care academic medical center, data-logging technology recorded a mean use of 8.4 hours/day and a mean aided sound exposure of 440 dB-hours/day. This latter statistic means that if a subject wore an HA for 8 hours/day (approximately the mean usage among subjects), he or she would have been exposed to a mean preamplified sound level of 54.9 dB-SPL. For reference, 60 dB-SPL is the intensity of conversational speech. Thus, the mean intensity of sound while wearing HAs was just under that of conversational speech. Over a mean data-logged period of 319 days per subject, daily HA use and sound exposure were stable. The only analyzed predictor that was significantly associated with HA use was level of hearing (PTA), while aided sound exposure was significantly associated with duration of audiologic follow-up.
Data-logging technology innate to most new-generation HAs is a valuable research tool, as it automatically records objective measures of HA usage time and the sound environment to which a subject is exposed. Studies reporting HA usage lacked consistency in measuring usage, and most used subjective questionnaires potentially containing recall bias. A handbook of recent studies compared subjective patient reporting of HA use with objective use as measured by data-logging technology, and most found that subjective patient surveys tend to overestimate usage relative to objective measures. In the largest of such studies, mean patient surveys tend to overestimate usage relative to objective measures of HA usage time and the sound environment to which a subject is exposed. Studies reporting HA usage lacked consistency in measuring usage, and most used subjective questionnaires potentially containing recall bias. A handbook of recent studies compared subjective patient reporting of HA use with objective use as measured by data-logging technology, and most found that subjective patient surveys tend to overestimate usage relative to objective measures.

### Table 2. Multivariable Regression Analysis for Daily HA Use and Aided Sound Exposure.

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Daily HA Use</th>
<th>Aided Sound Exposure</th>
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<tbody>
<tr>
<td></td>
<td>β</td>
<td>P Value</td>
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<tr>
<td>Sex</td>
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<td>Age</td>
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<td>Unilateral vs bilateral HA</td>
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<td>PTA</td>
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<td>Audiology visits</td>
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<td></td>
</tr>
<tr>
<td>Number</td>
<td>0.035</td>
<td>.358</td>
</tr>
<tr>
<td>Duration</td>
<td>0.0005</td>
<td>.242</td>
</tr>
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</table>

Abbreviations: HA, hearing aid; PTA, pure tone average.

aDaily HA use measured in hours/day; n = 389, R² = 0.036.
bAided sound exposure measured in dB-hours/day; n = 93, R² = 0.17.

Finally, the present study assessed longitudinal trends in HA usage and sound exposure over a per-subject mean of 319 days of recorded data logs. Despite individual variability, HA usage and sound exposure were both stable over time when trended among the whole cohort. This is consistent with a study that found no significant changes in HA use over 6 months, but it is inconsistent with another, which found a tendency of adult HA wearers to decrease usage over the first 6 months of use. Unlike these previous studies, which relied on subjective reporting, the present one is the first observational study to assess HA usage longitudinally among adults with objective data-logging technology, thus making it likely more reliable. Deal et al recently...
reported relatively stable HA use at 3 visits (9.8, 9.2, and 9.7 hours/day) over 6 months for 20 patients, using objective data logs. However, this was part of a randomized controlled trial where subjects received best-practice hearing interventions. In contrast, our study, being observational, more accurately reflects the real-world usage of individuals seeking audiologic care. Notably, the present study did not restrict subjects based on the number of data-logged days and, as such, included those who used their devices for less than the 30- or 45-day trial period frequently granted first-time HA owners. Subjects with ≥30 or <30 days of recorded use were compared in terms of HA use and aided sound exposure, however, and there were no significant differences for either outcome between the groups.

This study has limitations. First, as a retrospective analysis, there was no randomization or intervention; thus, no causal relationships between predictors and HA use can be ascertained. Second, while an objective tool, data logging has inherent limitations. Some data logs reflect the amount of time that HAs are turned on, which does not necessarily correspond to true "use" (ie, functional device in the ear of an awake patient). Additionally, this study included 5 HA manufacturers, all with different data-logging algorithms, and so there may be small differences in how HA usage was recorded among them. Using multiple manufacturers does, however, improve the generalizability of our results. Due to significant variability in reporting of sound environment, only 1 manufacturer (Oticon) was used in the subgroup analysis of sound exposure. Finally, this study cohort may not be representative of HA owners in the general population. Only patients who received auditory care at a tertiary academic medical center and who had at least 1...
follow-up appointment during which data logs were recorded were included in this analysis. Subjects who did not follow up with audiology were not captured by our analysis.

Despite these limitations, this is the largest cohort of HA data logging in the present literature and, as such, contributes to a much-needed understanding of objective HA use and sound exposure. Furthermore, it demonstrates that increased duration of audiologic follow-up is associated with increased aided sound exposure. Firm guidelines on auditory rehabilitation with HAs requires precision and standardization in the measurement of HA use. Data logging offers such precision to better define HA-associated outcomes. We hope that future prospective studies utilize data logging to better refine outcomes of HA rehabilitation and to explore its relationships with experiential, emotional, and cognitive outcomes. Establishing such objective relationships may provide evidence for the utility of amplification in hearing loss for many individuals who remain untreated.

**Author Contributions**

John B. Doyle, led study design; data collection, analysis, interpretation; and writing of manuscript and approval; Rohit R. Raghunathan, contributed to data collection, analysis, and interpretation; contributed to writing Methods section and approval; Ilana Cellum, contributed to data collection, analysis, and interpretation; contributed to writing manuscript and approval; Gen Li, led data collection, analysis and interpretation of data; contributed to writing manuscript and approval; Justin S. Golub, led study design/ conduct, data collection/analysis/interpretation, and contributed to writing the manuscript and approval.

**Disclosures**

Competing interests: Justin S. Golub—Cochlear, travel expenses for meeting; Plural Publishing, book royalties.

Sponsorships: None.

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**Supplemental Material**

Additional supporting information is available in the online version of the article.

**References**


