Mechanisms of Morbid Hearing Loss Associated With Tumors of the Endolymphatic Sac in von Hippel-Lindau Disease

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Endolymphatic sac tumors (ELSTs) are highly vascular, benign, but locally aggressive neoplasms of the endolymphatic system that often destroy the surrounding temporal bone (FIGURE 1).1-3 ELSTs occur sporadically but are a common manifestation of von Hippel-Lindau disease (VHL), in which they can also occur bilaterally.3,4 ELSTs are associated with significant audiovestibular morbidity, including sudden irreversible hearing loss.3-5 Despite the effects of ELSTs and their association with VHL, the underlying pathophysiologic mechanisms of audiovestibular dysfunction associated with ELSTs, the high incidence of unexplained audiovestibular dysfunction in patients with VHL, and the optimal timing of treatment for ELSTs have not been defined.

Since clinicians have determined the presence of ELSTs in the VHL syndrome, prospective screening protocols have been developed and used at the National Institutes of Health. Information from these evaluations now provides insight into the mechanisms of symptom formation, early imaging features, and the natural history of ELSTs. To determine the mechanisms underlying hearing loss and other vestibular symptoms, both of these pathophysiologic mechanisms occur with small tumors that are not associated with otic capsule invasion.


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tibulopathy in patients with ELSTs, we analyzed the serial imaging and clinical findings in consecutive patients with VHL with ELSTs.

**METHODS**

**Patients**

Clinic charts, audiograms, MRI, and CT images were analyzed for patients with VHL whose cases were monitored at the National Institutes of Health between May 25, 1990, and December 18, 2006. All patients were studied under National Institute of Neurological Disorders and Stroke internal review board–approved protocols (NIH 79-N-0089 and NIH 00-N-0140) after providing informed consent. Patients were prospectively monitored for the development of audiovestibular symptoms and included if diagnostic imaging showed evidence of ELST.

**Imaging Studies**

Neuroradiologists blinded to the presence and degree of audiovestibular findings reviewed all imaging studies and recorded the results.

**CT Imaging**

To determine the presence of otic capsule invasion and extent of bony erosion by ELSTs, temporal bone CT imaging (axial and coronal; 0.625- to 1.5-mm slice thickness; bone algorithm reconstruction kernel) was performed. For analysis purposes, ELSTs were divided into 2 groups based on CT imaging evidence of otic capsule invasion by tumor or lack thereof.

**Magnetic Resonance Imaging**

Inner ear MRI was used to identify the extent of soft tissue mass in the temporal bone and to evaluate signal within the sensory labyrinth. Because the studies spanned several years, there was some variation in technique commensurate with technical improvements in methodology. Before 1999, MRI included spin echo T1-weighted precontrast and postcontrast and fast spin echo T2-weighted sequences using slice thickness of 3 mm or less. After 1999, examinations used 1.6-mm overlapping spoiled gradient recall T1-weighted precontrast and postcontrast and fast spin echo T2-weighted sequences using slice thickness of 3 mm or less. After 1999, examinations used 1.6-mm overlapping spoiled gradient recall T1-weighted precontrast and postcontrast, T2-weighted fast induction of steady state acquisition, and 3- to 5-mm fluid-attenuated inversion recovery. Image resolution was less than 1 mm in plane in all cases.

Because the contents of the vestibular aqueduct may normally enhance on high-resolution postcontrast T1-weighted spoiled gradient recall sequences, small in situ ELSTs were identified by asymmetrical enhancement of the endolymphatic duct on MRI together with bony erosion of the vestibular aqueduct on CT imaging. The presence of intralabyrinthine hemorrhage was defined on MRI as abnormal isolated intralabyrinthine increased signal on precontrast T1-weighted images. Intralabyrinthine lipoma, which could also appear as a precontrast T1-weighted hyperintensity, was excluded on fat-saturated MRI. To quantify and compare tumor size, the largest tumor diameter was determined from a single axial slice using MRI and recorded.

**Clinical Evaluation**

Patients underwent complete neurologic and audiologic examinations (see “Audio-

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**Figure 1. Anatomical Relationships of the Endolymphatic Sac**

The endolymphatic sac is located on the posteromedial surface of the petrous temporal bone, covered by dura. The endolymphatic duct lies within the vestibular aqueduct and connects the endolymphatic sac to the remainder of the membranous labyrinth. The bony otic capsule encases the membranous labyrinth. Tumors of the endolymphatic sac can result in hearing loss directly through invasion of adjacent sensory structures housed within the otic capsule or indirectly through intralabyrinthine hemorrhage or endolymphatic hydrops. CN indicates cranial nerve.
logic Assessment” section) at intervals of 6 to 24 months or when audiovestibular symptoms developed. The presence of audiovestibular symptoms including tinnitus, vertigo, aural fullness, and specific evidence of other cranial nerve abnormalities were recorded at each visit.

Audiologic Assessment
Audiometric evaluations were performed in conjunction with clinical evaluations and included air and bone conduction, pure tone thresholds, and speech discrimination assessment. Hearing loss was characterized as mild (26-40 dB), moderate (41-55 dB), moderate to severe (56-70 dB), severe (71-90 dB), or profound (≥91 dB). The time span over which the sensorineural hearing loss (SNHL) evolved was classified as sudden (<24 hours) or gradual (weeks-months). StatXact 6, version 6.2.0 (Cytel Inc, Cambridge, Massachusetts) and SPSS for Windows, version 11.5.0 (SPSS Inc, Chicago, Illinois). P level of significance was less than .05.

RESULTS

Overall Patient and Tumor Characteristics
A total of 38 ears affected by ELSTs (23 left [61%]; 15 right [39%]) were identified in 35 patients with VHL (19 female [54%]; 16 male [46%]; Figure 2). Bilateral ELSTs were detected in 3 patients (9%). Mean age (SD) at symptom onset was 31 (13) years (range, 11-63 years). Mean (SD) follow-up time was 7.78 (4.75) years (range, 0.25-16 years). All patients with imaging evidence of ELST developed audiovestibular symptoms including hearing loss, tinnitus, vertigo, aural fullness, and aural pain and facial nerve weakness combined (TABLE). Nineteen patients (54%) had a triad of the most common symptoms that included SNHL, tinnitus, and vertigo (9 additional patients [26%] had 2 of these symptoms). Mean tumor diameter (SD) was 1.4 cm (1.0 cm) (range, 0.2-5.2 cm). Tumor size was not associated with SNHL ($P$ = .23) or with audiovestibular symptoms (analysis of variance; $P$ = .83; FIGURE 3). Seven ears (6 patients; 18%; $P$ = .01) had tumor-associated otic capsule invasion and 31 ears (30 patients; 82%) had no evidence of otic capsule invasion (Figure 2).

Ears With Otic Capsule Invasion
Clinical Findings. Seven ears (4 right; 3 left) among 6 patients (2 male; 4 female) had ELSTs that invaded the otic capsule. Two of these patients had bilateral ELSTs. One patient had unilateral invasion of the otic capsule and the other had bilateral invasion of the otic capsule. Mean (SD) age at audiovestibular symptom onset was 32 (13) years (range, 14-34 years). Overall, mean (SD) follow-up was 7.68 (4.43) years (range, 3.25-14.83 years).

Table. Findings in 38 Ears Affected by Endolymphatic Sac Tumors in 35 Patients With von Hippel-Lindau Disease

<table>
<thead>
<tr>
<th>Finding</th>
<th>No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, No. (%) of patients</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>19 (54)</td>
</tr>
<tr>
<td>Male</td>
<td>16 (46)</td>
</tr>
<tr>
<td>Tumor location</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>23 (61)</td>
</tr>
<tr>
<td>Right</td>
<td>15 (39)</td>
</tr>
<tr>
<td>Bilateral</td>
<td>3 (8)</td>
</tr>
<tr>
<td>Otic capsule invasion</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>7 (18)</td>
</tr>
<tr>
<td>No</td>
<td>31 (82)</td>
</tr>
<tr>
<td>Signs and symptoms</td>
<td></td>
</tr>
<tr>
<td>Sensorineural hearing loss</td>
<td>34 (89)</td>
</tr>
<tr>
<td>None</td>
<td>4 (11)</td>
</tr>
<tr>
<td>Mild</td>
<td>6 (16)</td>
</tr>
<tr>
<td>Moderate</td>
<td>10 (26)</td>
</tr>
<tr>
<td>Profound</td>
<td>18 (47)</td>
</tr>
<tr>
<td>Tinnitus</td>
<td></td>
</tr>
<tr>
<td>Intermittant</td>
<td>14 (37)</td>
</tr>
<tr>
<td>Continuous</td>
<td>13 (34)</td>
</tr>
<tr>
<td>Vertigo</td>
<td>24 (69)</td>
</tr>
<tr>
<td>Intermittant</td>
<td>23 (65)</td>
</tr>
<tr>
<td>Continuous</td>
<td>4 (11)</td>
</tr>
<tr>
<td>Aural fullness</td>
<td>14 (37)</td>
</tr>
<tr>
<td>Intermittant</td>
<td>12 (32)</td>
</tr>
<tr>
<td>Continuous</td>
<td>2 (5)</td>
</tr>
<tr>
<td>Aural pain (continuous)</td>
<td>4 (11)</td>
</tr>
<tr>
<td>Facial nerve weakness (continuous)</td>
<td>2 (5)</td>
</tr>
</tbody>
</table>

Data are for number of ears unless otherwise noted.
When otic capsule invasion was detected, SNHL was present. The SNHL was mild in 1 ear and severe to profound in the remaining 6 ears (Figure 3). Additional audiovestibular and cranial nerve findings included vertigo (4 patients; 67%), tinnitus (4 ears; 57%), aural fullness (4 ears; 57%), facial nerve weakness (1 patient; 17%), and aural pain (1 ear; 14%). Vertigo was intermittent in all patients with vertigo (4; 100%). Tinnitus was continuous in 1 ear (25%) and intermittent in 3 ears (75%). Aural fullness was intermittent in all affected ears (4; 100%). Aural pain was continuous in the 1 affected patient (100%).

**Imaging.** All ELSTs with otic capsule invasion had the typical imaging features of ELST (Figure 4). Nonenhanced T1-weighted MRI revealed ELSTs as heterogeneous in intensity with associated areas of hyperintensity, suggestive of intratumoral hemorrhage and cholesterol granuloma formation (Figure 4). Precontrast iso-intense portions of the ELSTs enhanced on postcontrast T1-weighted MRI. ELSTs on CT imaging were isodense with gray matter, with foci of bone density indicating bone destruction and permeation, centered on the region of the vestibular aqueduct (Figure 4). Mean (SD) tumor diameter was 2.2 cm (1.6 cm) (range, 0.5-5.2 cm).

**Ears Without Otic Capsule Invasion**

**Clinical Findings.** Thirty-one ears (11 right, 20 left) among 30 patients (14 male, 16 female) were affected by ELSTs that did not involve the otic capsule. One patient had bilateral ELSTs that were not associated with otic capsule invasion. Mean (SD) age at audiovestibular symptom onset was 32 (13.1) years (range, 11-63 years). Overall, mean (SD) follow-up was 95.4 (56.2) months (range, 3-192 months).

Twenty-seven of the 31 ears (87%) without otic capsule invasion had SNHL (4 ears had normal hearing). SNHL in these ears was mild to moderate in 15 ears (56%) and severe to profound in 12 ears (44%). The hearing loss in the 27 patients with SNHL occurred either suddenly (14 ears; 52%) or gradually (13 ears; 48%) over months to years. Additional audiovestibular findings included tinnitus (23 ears; 74%), vertigo (21 patients; 70%), aural fullness (10 ears; 32%), aural pain (3 ears; 10%), and facial nerve weakness (1 ear; 3%). Tinnitus was continuous in 12 affected ears (52%) and intermittent in 11 (48%). Vertigo was continuous in 4 affected patients (19%) and intermittent in 17 (81%). Aural fullness was continuous in 2 affected ears (20%) and intermittent in 8 (80%). Aural pain was continuous in 3 affected ears (100%).

**Imaging.** Thirty (97%) of 31 ELSTs without otic capsule invasion had imaging features consistent with an ELST. The mean (SD) tumor diameter for these tumors was 1.2 cm (0.7 cm) (range, 0.2-2.6 cm), which was smaller (analysis of variance; P = .01) than those ELSTs that invaded the otic capsule (mean (SD) diameter 2.2 cm [1.6 cm]; range, 0.5-5.2 cm). One ELST (3%) was not visible on MRI or CT imaging, but was suspected because of intralabyrinthine hemorrhage (visible on T1-weighted MRI) that corresponded with sudden SNHL, vertigo, and tinnitus. Surgical exploration revealed a small ELST (2 mm) that was resected.

Hyperintense signal on precontrast T1- and fluid attenuated inversion recovery-weighted MRI, indicative of intralabyrinthine hemorrhage (Figure 5), was seen in 11 of the 14 ears (79%) in which sudden SNHL was identified clinically (χ² test; P < .001). In the 13 ears without otic capsule invasion in which SNHL occurred gradually, there was no evidence of intralabyrinthine hemorrhage (on precontrast T1-weighted or fluid attenuated inversion recovery MRI; Figure 6). Similarly, none of the 4 patients without otic capsule invasion and normal hearing had evidence of intralabyrinthine hemorrhage. There was no correlation between tumor size and the presence of intralabyrinthine hemorrhage (univariate analysis of variance; P = .13) among the ELSTs without otic capsule invasion.

**COMMENT**

**ELSTs in VHL Disease**

VHL has an incidence of 1 in 39,000 individuals. It is an autosomal dominant neoplasia syndrome that is the result of a germline mutation or deletion of the VHL tumor suppressor gene on the short arm of chromosome 3. VHL is associated with variable penetrance and heterogeneous clinical findings. Affected individuals often develop benign and
malignant visceral and central nervous system lesions.8,10 Visceral manifestations include renal cysts and carcinomas, pheochromocytomas, pancreatic cysts and neuroendocrine tumors, as well as reproductive adnexal organ cystadenomas.8,11,12 Central nervous system manifestations include retinal, cerebellar, spinal cord, and brainstem hemangioblastomas, as well as ELSTs.8,10 ELSTs were clinically established as part of the VHL syndrome by Manski et al3 and confirmed by genetic analyses of Vortmeyer et al.13,14 While these tumors rarely occur in the general population, they are found frequently in patients with VHL by MRI or CT imaging with an estimated incidence of 11% to 16%.3,4,15 VHL is the only condition identified that is associated with bilateral ELSTs.3,4 While 9% of patients in this study had bilateral ELSTs, previous reports have suggested that bilateral tumors may occur in as many as 15% to 30% of patients with VHL with ELSTs.3,16 These previous estimates may be higher in part because they were based on summaries of case reports or isolated smaller series.

All patients in this series developed audiovestibular symptoms. Analogous with a pathophysiologic process within the endolymphatic system, most patients presented with a triad of findings frequently associated with Menière disease that includes hearing loss, tinnitus, and vertigo (Table).1,4,17 This often led to a referral diagnosis of Menière disease before discovery of an ELST. Consistent with previous reports that describe a 90% incidence of either gradual or sudden SNHL in patients with ELST,3,4,18 the most common ELST-associated clinical finding in this series was hearing loss. SNHL occurred in 31 patients (89%) or 34 of the affected ears (89%) and was frequently moderate or profound (Figure 2). Other less frequent ELST-associated findings included aural fullness, aural pain, facial nerve weakness, and aural pain and facial nerve weakness combined (Table).

Consistent with the anatomic origin and known progressive erosive nature of ELSTs, otic capsule invasion occurred with tumors that were significantly larger than those that did not invade the otic capsule. Analysis of tumor size and its relationship to the presence of SNHL and audiovestibular symptomology revealed no association (Figure 3). The lack of correlation between tumor size and SNHL, as well as the presence of SNHL and vestibulopathy in patients without otic capsule invasion, supports the hypothesis that mechanisms other than otic capsule destruction by tumor expansion underlie the audiovestibular morbidity linked to ELSTs.

While we did not find a link between tumor size and SNHL, Manski et al.3,12

![Figure 4. Large Endolymphatic Sac Tumor With Invasion of the Otic Capsule Associated With Profound Hearing Loss](image-url)
al\textsuperscript{3} reported that increased tumor size was associated with loss of functional hearing in 13 patients with VHL with 15 ELSTs. The most likely reason for this difference is related to the timing of ELST discovery. Until Manski et al\textsuperscript{3} made the definitive clinical association of ELSTs in VHL, patients with VHL were not routinely screened for ELSTs. Thus, detection of ELSTs, including those in the series of Manski et al\textsuperscript{3} were delayed and patients frequently had large tumors that were associated with long-standing hearing loss at diagnosis. Improvements in imaging resolution, as well as the development of targeted clinical and imaging screening protocols, now permit early detection of very small ELSTs and their effects on the inner ear. The results of these studies, as described in this series of patients, reveal that audiovestibular morbidity occurs frequently with small ELSTs (2-3 mm in diameter; Figure 3).

The detection of smaller ELSTs and their associated effects (ie, intralabyrinthine hemorrhage) give insight into the mechanism of the previously reported high incidence of audiovestibular dysfunction (including unexplained sudden hearing loss) in patients with VHL without radiographic evidence of ELST.\textsuperscript{3,4} Using serial high-resolution MRI and CT imaging with specific sequences to evaluate the inner ear, we detected several small tumors (<5 mm diameter) and found that a large number of patients in this study (29%) had intralabyrinthine hemorrhage that corresponded with sudden SNHL that may not have been detected using lower-resolution imaging or imaging that was not clinically correlated with audiovestibular dysfunction (ie, before the inclusion of ELSTs in the VHL syndrome). This point is underscored by the detection of a small ELST by the presence of intralabyrinthine hemorrhage on MRI and confirmed surgically to be in the vestibular aqueduct.

**Mechanisms of Hearing Loss**

Based on the relationship between the imaging and clinical findings in these patients, 3 distinct mechanisms (either alone or in combination) may account for the audiovestibular morbidity associated with ELSTs. These include direct invasion of the otic capsule by tumor, intralabyrinthine hemorrhage, and endolymphatic hydrops.

**Otic Capsule Invasion by Tumor**

Because otic capsule destruction is a well-described mechanism of hearing loss and vestibulopathy and because

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_Figure 5. Small Endolymphatic Sac Tumor With Intralabyrinthine Hemorrhage Associated With Sudden Hearing Loss_

_A_ Precontrast Computed Tomography Image

_B_ Precontrast T1-Weighted Magnetic Resonance Image

_C_ Fluid Attenuated Inversion Recovery (FLAIR) Magnetic Resonance Image

A small endolymphatic sac tumor (ELST) that did not involve the otic capsule in a 68-year-old patient with von Hippel-Lindau disease and sudden hearing loss (normal to profound hearing loss on audiogram) resulting from intralabyrinthine hemorrhage. A, Axial computed tomography (CT) image demonstrates erosion of the posterior temporal bone by an ELST (black arrowhead) located at the vestibular aqueduct with no extension anteriorly toward the otic capsule. Axial magnetic resonance images (MRIs) of the temporal bone, B (T1-weighted) and C (FLAIR), reveal a hyperintense signal (black arrowheads) in the location of the tumor. Evidence of intralabyrinthine hemorrhage is seen in the vestibule and in the cochlea (white arrowheads). The morphology of the labyrinth of the inner ear is normal in all images. CN indicates cranial nerve.
previous descriptions of ELST-associated hearing loss and vestibulopathy occurred most often in the context of large tumors, previous reports emphasized that hearing loss associated with ELSTs was the result of direct invasion of the otic capsule by tumor.\(^1,4,19,20\) Similarly, this report demonstrates that larger tumor size is associated with radiographic evidence of otic capsule invasion. Although it is possible that diagnostic imaging could miss detection of histologic invasion of the otic capsule, previous reports of small ELSTs with imaging evidence of an intact otic capsule did not have histologic evidence of otic capsule invasion.\(^2,5,16\) When an ELST directly erodes into the inner ear, it destroys the membranous labyrinth and disrupts endolymphatic flow, causing hearing loss and vestibulopathy (Figure 4).

Intralabyrinthine Hemorrhage

The results described in this study indicate that acute intralabyrinthine hemorrhage by an ELST explains the frequent occurrence of irreversible, sudden, and significant hearing loss that occurs in patients with ELSTs (Figure 5).\(^2,4\) This is supported by the presence of intralabyrinthine hemorrhage on MRI that was associated with sudden hearing loss in 77% of ears with SNHL and no evidence of otic capsule invasion (Figure 2). These findings are further underscored by a previously reported autopsy case demonstrating hemosiderin in the inner ear of a patient with VHL and sudden hearing loss associated with a microscopic ELST,\(^2\) a patient with ELST with sudden hearing loss coinciding with MRI evidence of intralabyrinthine hemorrhage,\(^21\) and ELSTs from patients with sudden SNHL (without otic capsule invasion) who demonstrate intratumoral hemosiderin and hemorrhage.\(^5\) The irreversibility of symptoms (particularly hearing loss) in such patients may be the result of neuronal degeneration caused by hemorrhage, secondary inflammation, or both.\(^2\)

Endolymphatic Hydrops

The remaining patients presented with a clinical syndrome (gradual hearing loss, tinnitus, and vertigo) typical of Ménière disease, suggesting that endolymphatic hydrops develops in patients with ELSTs (Figure 2; Table).\(^4\) In support of this, a patient with VHL and antemortem symptoms consistent with Ménière disease, including tinnitus, vertigo, and hearing loss was found to have endolymphatic hydrops and a microscopic ELST on postmortem histopathology.\(^2\) Blockage of endolymphatic sac resorption of endolymph, inflammation in response to hemorrhage, or excessive production of fluid by the tumor may
HEARING LOSS ASSOCIATED WITH TUMORS IN VON HIPPEL-LINDAU DISEASE

Individually or in combination cause hydrocephalus. Production of peritumoral fluid by ELSTs is analogous to the formation of peritumoral edema and cysts that are frequently associated with central nervous system hemangioblastomas and visceral tumors in VHL. Production of peritumoral fluid by ELSTs is analogous to the formation of peritumoral edema and cysts that are frequently associated with central nervous system hemangioblastomas and visceral tumors in VHL.8,24,25

Implications for Surveillance and Treatment

Previously, the management of ELSTs (particularly tumors that were small and asymptomatic) has been conservative because they have an uncertain natural history and are not considered malignant or fast growing.3,4 This study demonstrates that audiovestibular morbidity is frequently associated with small tumors (those not invading the otic capsule) and occurs by mechanisms that include intralabyrinthine hemorrhage and hydrocephalus. Since significant audiovestibular dysfunction, including deafness, can occur suddenly in a manner that is not related to tumor size, early surgical intervention may be warranted. While this study does not address the effectiveness of surgical resection, several small operative series indicate that complete resection of ELSTs can be curative, can alleviate vestibular symptomatology, and can be performed with hearing preservation and minimal morbidity.5,16,19,20 Therefore, in patients with hearing and imaging evidence of an ELST, surgery may be considered after weighing its potential risks to prevent neurologic worsening or amelioration of symptoms. To intervene early, prompt diagnosis based on clinical and imaging findings is necessary. Thus, serial clinical evaluations and high-resolution MRI and CT imaging to detect small ELSTs or intralabyrinthine hemorrhage are warranted in patients with VHL.

Author Contributions: Dr Butman had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Butman, Kim, Oldfield, Lonser. Acquisition of data: Butman, Kim, Baggenstos, Ammerman, Patalides, Patronas. Analysis and interpretation of data: Butman, Kim, Dambrosia, Patronas, Oldfield, Lonser. Drafting of the manuscript: Butman, Lonser. Critical revision of the manuscript for important intellectual content: Butman, Kim, Oldfield, Lonser. Statistical analysis: Dambrosia. Administrative, technical, or material support: Butman, Kim, Oldfield, Lonser. Study supervision: Butman, Kim, Oldfield, Lonser. Financial Disclosures: None reported. Funding/Support: This research was supported by the Intramural Research Program of the Clinical Center, National Institute of Neurological Disorders and Stroke and the National Institute on Deafness and Communication Disorders at the National Institutes of Health. Role of the Sponsor: The Intramural Research Program of the Clinical Center, National Institute of Neurologic Disorders and Stroke and the National Institute on Deafness and Communication Disorders at the National Institutes of Health did not participate in the design and conduct of the study; in the collection, management, analysis, and interpretation of the data; or in the preparation, review, or approval of the manuscript.

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