Objectives: To characterize the natural history and possible mechanisms of hearing loss in Stickler syndrome (OMIM 108300; or hereditary progressive arthroophthalmopathy) and to determine if the auditory phenotype is a useful discriminating feature for the differential diagnosis of this group of disorders.

Design: Multifamily study.

Setting: Outpatient audiology and otolaryngology clinics at the Warren Grant Magnuson Clinical Center of the National Institutes of Health, Rockville, Md.

Subjects: Forty-six affected individuals from 29 different families segregating Stickler syndrome.

Interventions: Clinical audiologic and otolaryngologic examinations were performed on all individuals, including pure-tone audiometry, speech audiometry, and middle ear immittance testing. Otoacoustic emissions, auditory brainstem response, infrared video electronystagmography, and temporal bone computed tomography were performed on a subset of participants.

Results: The hearing loss was most often sensorineural in adults, and approximately 28 (60%) of the 46 adult patients had 2 or more thresholds greater than the corresponding 95th percentile values for an age-matched, otologically normal population. The hearing loss most often affected high frequencies (4000-8000 Hz) and was generally no more progressive than that due to age-related hearing loss. Type AD tympanograms (classification using the Jerger model), indicating hypermobile middle ear systems, were observed in 21 (46%) of the 46 affected individuals. Computed tomography of the temporal bones revealed no inner ear malformations in 19 affected individuals.

Conclusions: The hypermobile middle ear systems observed in ears with normal-appearing tympanic membranes represent a novel finding for Stickler syndrome and are likely to be a useful diagnostic feature for this disorder. The overall sensorineural hearing loss in type 1 Stickler syndrome is typically mild and not significantly progressive. It is less severe than that reported for types II and III Stickler syndrome linked to COL11A2 (OMIM 120290) and COL11A1 (OMIM 120280) mutations, respectively, or the closely related Marshall syndrome. This difference will be a useful discriminatory feature in the differential diagnosis of this group of disorders.

SUBJECTS, MATERIALS, AND METHODS

SUBJECTS

Forty-six individuals from 29 families segregating Stickler syndrome composed the study group. The diagnosis of Stickler syndrome was based on family history and clinical evaluation by a medical geneticist (H.P.L., R.M.L., or C.A.F.). Nineteen males and 27 females, ranging in age from 9 months to 70 years (average age, 22.8 years for males and 38.8 years for females), participated in this study after receiving informed consent. This study was approved by the institutional review board of the National Human Genome Research Institute, National Institutes of Health, Rockville, Md.

CLINICAL EVALUATIONS

Otolaryngological histories were obtained and physical examinations, including pneumatic otoscopy, were performed on each subject. Audiologic evaluations consisted of pure-tone air and bone conduction audiometry, speech audiometry, and middle-ear immittance testing (tympanometry and acoustic reflex testing) in American National Standards Institute (ANSI)–approved conditions.19,20 Young children were evaluated by play or visual reinforcement audiometry according to their age. Some patients also underwent transient-evoked or distortion product otoacoustic emissions testing (model ILO96 Otodynamic Analyzer; Otodynamics, London, England) or auditory brainstem response testing (Nicolet Spirit; Nicolet Biomedical Inc, Madison, Wis). Six of the patients underwent video electronystagmography testing (House IR/Video ENG System, Torrance, Calif, Copyright Eye Dynamics, 1997). Nineteen of the 46 patients underwent computed tomography of the temporal bones with 1-mm axial and coronal sections.

CLINICAL DATA ANALYSIS

The type of hearing loss was classified as sensorineural, conductive, or mixed according to the European Working Group on Genetics of Hearing Impairment.21 Conductive hearing loss was defined as normal bone conduction thresholds (<20 dB) and an averaged air-bone gap of 15 dB or more for 500, 1000, and 2000 Hz. Mixed hearing loss was defined as a bone conduction threshold greater than 20 dB in combination with an averaged air-bone gap 15 dB or more for 500, 1000, and 2000 Hz. Sensorineural hearing loss was defined as an averaged air-bone gap of less than 15 dB for 500, 1000, and 2000 Hz.

The degree of hearing loss was categorized in 2 different ways: employment of commonly used age-independent clinical guidelines,12 and comparison of thresholds to age-dependent percentiles.23,24 The age-independent analysis defined degree of hearing loss as the greatest observed degree of impairment at any threshold according to the age-independent guidelines established by the World Health Organization.22 Impairment was audiometrically classified using the following pure-tone threshold ranges: normal, 0 to 25 dB; mild, 26 to 40 dB; moderate, 41 to 55 dB; moderately severe, 56 to 70 dB; severe, 71 to 90 dB; and profound, 91 to 110 dB.

The age-dependent analysis of the degree of hearing loss plotted pure-tone air conduction thresholds at 500, 1000, 2000, and 4000 Hz, and pure-tone averages (PTAs) for 500, 1000, and 2000 Hz, against corresponding 95th percentiles.23 Similarly, pure-tone air conduction thresholds at 8000 Hz were plotted against corresponding 90th percentile values.23 Ninety-fifth percentile values for 300,
1000, 2000, and 4000 Hz were obtained from a uniformly otologically screened population, and 90th percentile values for 8000 Hz were obtained from the 1990 International Organization for Standardization standards. Ninetieth percentile values were chosen for 8000 Hz owing to a lack of established 95th percentile data for this frequency.

The percentage of study subjects with pure-tone thresholds above the 95th percentile was calculated separately for men and women 25 years and older. Air conduction thresholds were used for the analysis at frequencies with no air-bone gap, whereas bone conduction thresholds were used at frequencies with air-bone gaps of 15 dB or more. Only data from subjects with complete sets of bone conduction thresholds were included. Subjects with a history of trauma, otologic surgery, ototoxic reactions, noise exposure, or concurrent medical conditions known to cause hearing loss were excluded from the analysis.

Configuration of hearing loss was classified according to the European Working Group on Genetics of Hearing Impairment. Audiometric configurations were defined as midfrequency U-shaped, 15-dB or more difference between the poorest thresholds in the midfrequencies and those at higher frequencies; low-frequency ascending, 15-dB or more from the poorer thresholds to the higher frequencies; flat, less than 15-dB difference between 250 and 8000 Hz; high frequency, 15-dB or more difference between the mean thresholds at 500 and 1000 Hz and the mean thresholds at 4000 and 8000 Hz. High-frequency hearing loss was further described as either gently or steeply sloping.

Clinical and nonparametric statistical analyses were performed using JMP software (SAS Institute Inc, Cary, NC).

ment was prevalent among all age groups. A lesser percentage of subjects had hearing loss in the moderate to profound categories. Profound impairment was most prevalent in the oldest age group, although these profound losses were only observed in the highest frequencies. Figure 1B shows the type of hearing loss as a function of age of affected subjects. Hearing loss in children was most commonly conductive. Normal hearing was most common in the 21- to 30-year age group, whereas sensorineural hearing loss becomes more common in the older age groups. Mixed hearing losses were present in 4 of the 7 age groups. The pure-tone audiometric configuration was classified into 1 or more of the following categories: high frequency, midfrequency U-shaped, low-frequency ascending, or flat. Figure 1C shows that high frequencies were most commonly affected, with increasing prevalence of this configuration in age groups older than 10 years. Low-frequency and midfrequency thresholds were most commonly affected in the youngest age groups. High-frequency configurations in young children were gently sloping, whereas older subjects had steeply sloping high-frequency configurations.

To identify the contribution of the underlying gene mutations to the observed sensorineural hearing loss, audiotric thresholds in 1 or both ears above the 95th percentile value (for 500, 1000, 2000, or 4000 Hz) or the 90th percentile value for 8000 Hz.

Cross-sectional analysis of hearing loss progression was carried out in a similar manner to that of Kusni et al. Fifthieth percentile thresholds were subtracted from observed thresholds and plotted vs age to determine the degree of progression relative to that in a normal population. Fiftieth percentile thresholds for 500 Hz to 4000 Hz were obtained from Morrell et al and 50th percentile thresholds for 250, 6000, and 8000 Hz were derived from International Organization for Standardization 1990 standards. Linear regression analysis was performed on all normally distributed adjusted threshold data (see “Clinical Data Analysis” subsection herein). Slopes of the regression lines were calculated to determine the rate of progression of hearing loss and were compared with those calculated for the uniformly otologically screened population.

Serial audiograms were available for 8 subjects and were analyzed for linear hearing loss progression according to the European Working Group on Genetics of Hearing Impairment. Progression was defined as a deterioration of 15 dB or more in the PTA or in 2 or more frequencies within a 10-year period.

Pure-tone averages for the subjects with Stickler syndrome were compared with those for affected individuals of a previously described Marshall syndrome kindred and 5 affected members of a previously unreported kindred that was ascertained as part of our study. The Shapiro-Wilk test for normality was performed on both PTA distributions, and a t test was performed to determine if a statistically significant difference existed between the 2 distributions. Parametric and nonparametric statistical analyses were performed using JMP software (SAS Institute Inc, Cary, NC).
The subjects with types A, B, C, and AD tympanograms were observed in 18 (39%) of the 46 ears. Approximately 14 (31%) of 46 ears had type AD tympanograms, representing hypermobile middle ear systems in at least 1 ear. The mean (±SD) static compliance was 2.9±1.3 mmho for adults analyzed by pneumatic otoscopy. Seven (15%) of 46 ears were 37, 5, 11, and 33 years, respectively. There were several anamnestic reports of progression of the hearing losses primarily affected high frequencies (Figure 1C). Linear regression analysis was performed only on the 4000-, 6000-, and 8000-Hz thresholds. Figure 4 shows the regression analysis of pure-tone air conduction audiometric thresholds from 4000 to 8000 Hz. Slopes of the regression lines in the cross-sectional analysis of hearing thresholds in this study were: −0.03 dB per year at 4000 Hz, 0.16 dB per year at 6000 Hz, and 0.25 dB per year at 8000 Hz, with the absolute mean value slope of 0.12 dB per year. Data of Morrell et al revealed a maximum slope of approximately 2 dB per year at all of the frequencies they analyzed. Therefore, there was little, if any, progression of thresholds above that expected from normal aging from 25 to 65 years in our study.

Figure 5 shows the PTAs of subjects with Marshall and Stickler syndromes as a function of age. A strong ascertainment bias would be present in an analysis restricted to this small subset of study subjects who had previously undergone audiometric testing. Therefore, a cross-sectional analysis of age-adjusted binaural hearing thresholds was performed for subjects aged from 25 to 65 years (Figure 4). The Shapiro-Wilk test for normality revealed that the 500- and 2000-Hz adjusted threshold data were not normally distributed, thus prohibiting linear regression analysis of these data. Moreover, most of the hearing losses primarily affected high frequencies (Figure 1C). Linear regression analysis was performed only on the 4000-, 6000-, and 8000-Hz thresholds. Figure 4 shows the regression analysis of pure-tone air conduction audiometric thresholds from 4000 to 8000 Hz. Slopes of the regression lines in the cross-sectional analysis of hearing thresholds in this study were: −0.03 dB per year at 4000 Hz, 0.16 dB per year at 6000 Hz, and 0.25 dB per year at 8000 Hz, with the absolute mean value slope of 0.12 dB per year. Data of Morrell et al revealed a maximum slope of approximately 2 dB per year at all of the frequencies they analyzed. Therefore, there was little, if any, progression of thresholds above that expected from normal aging from 25 to 65 years in our study.

**MIDDLE-EAR IMMITTANCE RESULTS**

Type A tympanograms, representing normal middle ear mobility and pressure, were observed in 18 (39%) of the 46 ears (Figure 3). Type B tympanograms, representing hypomobile middle ear systems, were observed in 5 (12%) of the 46 ears and could be attributed to patent tympanostomy tubes, middle ear effusions, or tympanic membrane perforations. Type C tympanograms, with negative tympanometric peak pressures, were observed in 2 (4%) of the 46 ears, and type AD tympanograms were found in 21 (46%) of the 46 ears. The average ages of the subjects with types A, B, C, and AD tympanograms were 37, 5, 11, and 33 years, respectively.

The type AD tympanogram, representing hypermobile middle ear systems, was the most common tympanometric type seen in our patients (Figure 3). The mean (±SD) static compliance was 2.9±1.3 mmho for adults and 2.2±0.6 mmho for 13 children with demonstrated hypermobile middle ear systems in at least 1 ear. Approximately 14 (31%) of 46 ears had type AD tympanograms with normal-appearing tympanic membranes examined by pneumatic otoscopy. Seven (15%) of 46 ears with type AD tympanograms had tympanic membranes that were abnormally flaccid and thin in at least one portion or all of the membrane; pneumatic otoscopy revealed that the amplitude of motion of these latter membranes was disproportionately greater than that of the long process of the malleus.

**ANALYSIS OF HEARING LOSS PROGRESSION**

There were several anamnestic reports of progression of hearing loss among the study subjects. Longitudinal analysis revealed that 4 of 8 subjects with serial audiograms had progressive hearing loss according to the criterion proposed by the European Working Group on Genetics of Hearing Impairment (data not shown). A strong ascertainment bias would be present in an analysis restricted to this small subset of study subjects who had previously undergone audiometric testing. Therefore, a cross-sectional analysis of age-adjusted binaural hearing thresholds was performed for subjects aged from 25 to 65 years (Figure 4). The Shapiro-Wilk test for normality revealed that the 500- and 2000-Hz adjusted threshold data were not normally distributed, thus prohibiting linear regression analysis of these data. Moreover, most of the hearing losses primarily affected high frequencies (Figure 1C). Linear regression analysis was performed only on the 4000-, 6000-, and 8000-Hz thresholds. Figure 4 shows the regression analysis of pure-tone air conduction audiometric thresholds from 4000 to 8000 Hz. Slopes of the regression lines in the cross-sectional analysis of hearing thresholds in this study were: −0.03 dB per year at 4000 Hz, 0.16 dB per year at 6000 Hz, and 0.25 dB per year at 8000 Hz, with the absolute mean value slope of 0.12 dB per year. Data of Morrell et al revealed a maximum slope of approximately 2 dB per year at all of the frequencies they analyzed. Therefore, there was little, if any, progression of thresholds above that expected from normal aging from 25 to 65 years in our study.

**Table 1**

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-10 (n=6)</th>
<th>11-20 (n=9)</th>
<th>21-30 (n=3)</th>
<th>31-40 (n=6)</th>
<th>41-50 (n=7)</th>
<th>51-60 (n=7)</th>
<th>61-70 (n=4)</th>
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<td>Mean age, y</td>
<td>6.1 (2.6)</td>
<td>15.2 (2.7)</td>
<td>27.0 (2.7)</td>
<td>37.7 (2.1)</td>
<td>46.4 (3.2)</td>
<td>55.3 (0.8)</td>
<td>65.3 (3.4)</td>
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<td>PTAs, dB HL</td>
<td></td>
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<td></td>
<td></td>
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<td>Right ear</td>
<td>17.3 (9.9)</td>
<td>19.0 (10.5)</td>
<td>14.0 (9.9)</td>
<td>28.2 (13.1)</td>
<td>14.9 (6.2)</td>
<td>20.3 (10.0)</td>
<td>30.0 (8.5)</td>
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<td>Left ear</td>
<td>14.4 (8.9)</td>
<td>17.9 (9.1)</td>
<td>13.0 (5.0)</td>
<td>26.2 (8.7)</td>
<td>11.7 (6.5)</td>
<td>18.0 (5.9)</td>
<td>31.8 (6.2)</td>
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<td>Air conduction thresholds</td>
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<td>250 Frequency, H</td>
<td>18.5 (6.7)</td>
<td>17.2 (10.7)</td>
<td>15.0 (13.4)</td>
<td>27.5 (6.6)</td>
<td>17.5 (7.8)</td>
<td>20.0 (11.0)</td>
<td>29.4 (7.3)</td>
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<td>20.0 (12.4)</td>
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<td>36.1 (11.9)</td>
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<td>24.0 (17.3)</td>
<td>16.3 (10.0)</td>
<td>26.4 (10.0)</td>
<td>46.7 (14.0)</td>
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<td>4000 Frequency, H</td>
<td>15.9 (12.1)</td>
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<td>14.2 (6.7)</td>
<td>38.8 (17.1)</td>
<td>19.3 (11.9)</td>
<td>32.1 (15.5)</td>
<td>52.5 (16.7)</td>
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<td>22.1 (9.9)</td>
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<td>39.6 (17.8)</td>
<td>69.4 (22.8)</td>
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<tr>
<td>8000 Frequency, H</td>
<td>28.6 (10.3)</td>
<td>29.0 (18.7)</td>
<td>28.3 (15.4)</td>
<td>42.5 (17.4)</td>
<td>35.7 (22.9)</td>
<td>50.0 (20.0)</td>
<td>85.6 (19.2)</td>
</tr>
</tbody>
</table>

*Data are given as mean (SD). NA indicates sufficient data unavailable; dB HL, decibels hearing level.*
OTHER FINDINGS

Results of infrared videovestibular testing were incomplete in 6 subjects and confounded by concurrent ocular pathologic abnormality. Vestibular symptoms and signs were infrequent and consistent with imbalance rather than true vertigo. These findings were usually attributable to the typical rheumatologic and ocular abnormalities of Stickler syndrome.

Otoacoustic emissions testing in 7 subjects revealed responses that were consistent with the degree of hearing loss. Specifically, distortion product otoacoustic emissions and transient-evoked otoacoustic emissions accurately identified auditory status between 2000 and 4000 Hz, with the most robust emissions obtained when audiometric thresholds were lower than the 30-dB hearing level. As expected, emissions were absent in subjects with thresholds above 30 dB in the range of 1000 to 4000 Hz. Temporal bone computed tomographic scans of 19 affected subjects revealed no malformations of the inner or middle ears.

We have observed that the hearing loss in Stickler syndrome is typically mild overall and sensorineural with a steeply sloping, high-frequency configuration in adults, whereas it is most commonly conductive in children. The observed conductive hearing loss in children may be due to chronic otitis media or its sequelae, which commonly occurs in this population. Approximately 26 (60%) of our 44 adult subjects with Stickler syndrome had 2 or more thresholds above the 95th percentile, indicating that the sensorineural hearing loss in this disorder is an incompletely penetrant trait. These results are consistent with those of previous reports of smaller series of patients. Type A tympanograms were a common immittance finding in our subjects and have not been previously reported for Stickler syndrome. This tympanometric finding was not significantly associated with conductive hearing loss at any frequency in our study (not shown). Hypermobility was sometimes associated with thin, visibly hyperflaccid tympanic membranes, which is a common and otoscopically detectable sequela of chronic or recurrent otitis media and/or previous tympanostomy tubes. However, 6 (21%) of 28 affected subjects with hypermobility had completely normal-appearing tympanic membranes and no history of otitis media or previous tympanostomy tube insertions. Type II collagen is known to be present in the tympanic membrane and the ossicular joints and, therefore, hypermobility may be a sequela of otitis media, a direct result of the primary collagen defect, or a combination of both of these factors. We postulate that the type A tympanograms associated with normal-appearing tympanic membranes may be due to ossicular joint hypermobility, since hypermobility is also commonly observed in other articular joints in patients with Stickler syndrome. Ossicular joint hypermobility may be a useful diagnostic feature for Stickler syndrome.

Although 4 (50%) of the 8 subjects with serial audiograms had progressive hearing loss, this ratio is likely to be an artificially high estimate due to ascertainment bias. Subjects with the most severe or progressive hearing loss were more likely to have had serial audiograms prior to their participation in our study. Our regression analysis of cross-sectional, age-adjusted hearing thresholds indicates that there is minimal progression beyond that associated with normal aging in individuals with Stickler syndrome. Therefore, the sensorineural component of the hearing loss caused by most Stickler syndrome mutations seems to be stable over long periods.

Nonprogressive hearing loss has also been reported in families with nonsyndromic deafness DFNA13 and Stickler syndrome mutations in COL11A2, although the sensorineural hearing loss associated with these mutations is more severe and appears to affect the middle and lower frequencies to a greater degree than we observed in our study subjects. In contrast, the hearing loss caused by type III Stickler syndrome and Mar-
shall syndrome mutations in COL11A1 is much more severe and progressive than that observed in our patients. Since none of our families with Stickler syndrome had ocular or craniofacial phenotypic features that were suggestive of linkage to COL11A2 or COL11A1, it is likely that most, if not all, of our subjects segregate type I Stickler syndrome (ie, mutations in COL2A1). The mild, nonprogressive sensorineural hearing loss we observed in our subjects may be used to clinically distinguish these patients from those with hearing loss linked to COL11A1 mutations (Figure 1A), or to the more severe, nonprogressive sensorineural hearing loss associated with COL11A2 mutations. This hypothesis is being addressed by ongoing genotypic analyses of our study subjects. Lastly, while the hearing loss attributable to the collagen mutations may be mild and nonprogressive, there will still be age-related changes that will make individuals with Stickler syndrome at risk for severe or profound hearing loss, especially in the high frequencies.

Figure 2. Comparison of thresholds for female and male subjects 25 years old and older (squares) with 95th percentile data (diamonds) or, for 8000 Hz, the 99th percentile from International Organization for Standardization 1990 standards as follows: A-G, 500 Hz; B-H, 1000 Hz; C-I, 2000 Hz; D-J, 4000 Hz; E-K, 8000 Hz; and F-L, pure-tone average right ear (squares), and left ear (triangles), respectively. dB HL indicates decibel hearing level.
messenger RNA in soft tissue elements of the mouse cochlea. Differing effects of notypes that can include osteogenesis imperfecta and Stickler syndrome mutations affect sound transmission within the cochlear partition. Collagen fibrils are thought to contribute tensile strength to the tissues in which they are expressed. Mutations affecting fibril morphology may alter their tensile strength, resulting in a range of disease phenotypes that can include osteogenesis imperfecta and Stickler syndrome. These observations are consistent with the observation of expression of Col2A1, Col11A1, and Col11A2 messenger RNA in soft tissue elements of the mouse cochlea and in earlier studies demonstrating expression of type II collagen within the cochlea. Differing effects of Marshall and Stickler syndrome mutations on auditory function may reflect differing contributions of these collagen genes to the synthesis, structure, and function of the extracellular matrix within the cochlea. These alterations could directly affect sound mechanotransduction, or they may also cause abnormal mechanical stress forces leading to hair cell degeneration and sensorineural hearing loss.

We are analyzing the correlation of hearing loss with extra-auditory phenotypic features such as palatal clefting, as well as the underlying fibrillar collagen genotypes in these patients. Our results and those of future studies should extend our understanding of how the extracellular matrix and its fibrillar collagens contribute to normal auditory function. They will also facilitate the diagnosis and care of patients with Stickler syndrome and its related disorders.

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