Short-Term and Long-Term Effects on the Masking Level Difference following Middle Ear Surgery

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Abstract
The masking-level difference (MLD) was measured in a group of adult listeners having unilateral otosclerosis before stapedectomy surgery, 1 month following surgery, and 1 year following surgery. The results indicated that the MLD in this group improved significantly over each of the sequential tests. In contrast, for a group of normal-hearing listeners, the MLD did not change significantly over sequential testing. The results support an interpretation that a period of exposure to abnormal binaural auditory input (as occurs in a unilateral conductive loss) can blunt sensitivity to binaural cues after normal binaural input has been restored in most adult listeners, however, there appears to be a relatively long-term readjustment or adaptation, such that the sensitivity to binaural cues recovers to a normal or near-normal level at the 1-year postsurgery retest. Two of eight listeners did not show recovery to a normal MLD value over this time period. The efficiency and rate of readjustment may differ among individuals.

Key Words: Auditory deprivation, binaural hearing, masking-level difference (MLD), otosclerosis

Several previous studies have shown that listeners having mild or moderate conductive hearing losses show reduced binaural hearing performance on measures of localization, lateralization, and the masking-level difference (MLD) (Jonkees and van der Veer, 1957; Nordlund, 1964; Roser, 1966; Quaranta et al, 1978; Haussler et al, 1979, 1983; Jerger et al, 1984; Hall and Derlacki, 1986; Hall et al, 1990). Poor binaural performance in these listeners may be related to several factors, including: (1) the reduced sensation level of the stimuli; (2) asymmetry of intensity at the level of the cochlea, due to asymmetric conductive loss; (3) acoustic cross-over resulting in degraded and/or unnatural binaural difference cues; (4) a phase/time shift caused by middle ear mechanical anomaly; and (5) central effects related to auditory deprivation.

Some studies have indicated that poor binaural hearing may persist in cases of conductive hearing loss, even after the loss has resolved. For example, Nordlund (1964) showed poor localization performance in cases of otosclerosis, even after normal hearing thresholds were restored through middle ear surgery. Hall and Derlacki (1986) and Hall et al (1990) found similar results for the MLD in subjects who were tested 2 to 3 months after surgery. Magliulo et al (1990) have reported similar results. One interpretation of these results was in terms of auditory deprivation (interpretations due to middle ear anomaly were also suggested). Apparently related results have been reported in studies investigating the MLD in children with a history of otitis media with effusion (OME). Studies by Pillsbury et al (1991) and Hall and Grose (1993) indicated that the MLD is usually reduced in children with hearing loss due to OME. Furthermore, the MLD sometimes remains abnormally small in these children even after normal hearing thresholds have been restored (Moore et al, 1991; Pillsbury et al, 1991; Hall and Grose, 1993). Again, one possible interpretation of these results is that poor binau...
nal hearing may be due in part to effects related to auditory deprivation, an interpretation that has also been suggested to account for results in cases of cochlear hearing loss where amplification was not provided (Silman et al, 1984).

While there is evidence that some listeners have relatively poor MLDs even after successful middle ear surgery (Hall and Derlacki, 1986; Hall et al, 1990), there is little available information on whether the binaural hearing ability may improve as the time following corrective surgery increases. At least two previous studies on normal-hearing listeners may have some bearing upon this issue. These studies examined binaural adaptation effects in normal-hearing subjects using ear plugs to induce asymmetric conductive losses (Bauer et al, 1966; Florentine, 1976). The results of these studies indicated a binaural adaptation effect (a shift in lateralization or localization) after 3 to 10 days of monaural occlusion, with a somewhat longer readaptation phase required after removal of the plug. The study by Magliulo et al (1990) on the effect of otosclerosis on the MLD is also relevant to this question. This study confirmed that the MLD sometimes remains abnormally small shortly after corrective ear surgery, but also addressed the question of the long-term postsurgery effect by following a few patients up to a year following the middle ear surgery. The 1-year follow-up indicated that the MLD recovered to a normal value in some subjects, but not in others. Unfortunately, the number of patients followed over the 1-year interval was not large enough, nor was the control data sufficient, to allow statistical analysis. The present study further investigates the MLD in adults having a history of conductive hearing loss, examining the MLD 1 month after surgery, and 1 year following surgery. The results of this investigation are relevant to the question of how binaural auditory abilities may be subject to a relatively long term of adaptation to the changing binaural asymmetry of hearing.

**METHOD**

**Subjects**

A total of eight conductive-impaired patients (5 female and 3 male) having otosclerosis participated. The age range for the patients was 28 to 54 years (mean = 37.5 years, standard deviation [SD] = 11.0). In presurgical testing, all listeners had a unilateral conductive hearing loss, with normal (20 dB HL or better) thresholds measured by bone conduction at frequencies between 250 and 4000 Hz. Although testing of the better ear generally indicated normal hearing, it is possible that the better ear was not entirely free of disease, as otosclerosis is often a bilateral condition. Average audiograms with standard deviations for these listeners are shown in Figure 1. The mean presurgery air-conduction thresholds at the test frequency (500 Hz) were also determined by forced-choice testing (see below), and are summarized in Table 1. Forced-choice testing in quiet at the signal frequency was also conducted at 1-month and 1-year following surgery, and these results are also summarized in Table 1. The postsurgery testing results indicated an improvement in hearing, approximately 40 dB, at the test frequency.

Eight control subjects (5 female and 3 male) participated. The age range for the control group was 21 to 42 years (mean = 31.0 years, SD = 8.6). These subjects had no history of ear disease and had normal hearing (thresholds better than 20 dB HL bilaterally, and no air–bone gap greater than 10 dB) at octave frequencies between 250 Hz and 8000 Hz. The mean thresholds in quiet at the signal frequency are again summarized in Table 1. As with the otosclerosis group, the normal-hearing listeners were also tested on...
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Table 1 Summary of Threshold and MLD Data

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th></th>
<th>Test 2</th>
<th></th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N_So</td>
<td>N_Sn</td>
<td>MLD</td>
<td>ThrQ Better</td>
<td>ThrQ Worse</td>
</tr>
<tr>
<td>Normal</td>
<td>77.3</td>
<td>59.4</td>
<td>17.9</td>
<td>10.1</td>
<td>11.4</td>
</tr>
<tr>
<td>SD</td>
<td>(0.4)</td>
<td>(1.3)</td>
<td>(1.4)</td>
<td>(3.0)</td>
<td>(3.2)</td>
</tr>
<tr>
<td>OTO</td>
<td>77.9</td>
<td>69.4</td>
<td>8.6</td>
<td>19.5</td>
<td>59.1</td>
</tr>
<tr>
<td>SD</td>
<td>(1.9)</td>
<td>(2.3)</td>
<td>(1.4)</td>
<td>(5.1)</td>
<td>(4.9)</td>
</tr>
<tr>
<td>OTO1</td>
<td>74.8</td>
<td>66.0*</td>
<td>8.8*</td>
<td>16.8</td>
<td>54.2*</td>
</tr>
<tr>
<td>OTO2</td>
<td>76.8</td>
<td>69.5*</td>
<td>7.3*</td>
<td>20.0*</td>
<td>64.2*</td>
</tr>
<tr>
<td>OTO3</td>
<td>80.0*</td>
<td>71.0*</td>
<td>9.0*</td>
<td>14.2</td>
<td>58.0*</td>
</tr>
<tr>
<td>OTO4</td>
<td>80.5*</td>
<td>73.8*</td>
<td>6.7*</td>
<td>29.2*</td>
<td>65.2*</td>
</tr>
<tr>
<td>OTO5</td>
<td>78.8</td>
<td>68.5*</td>
<td>10.3*</td>
<td>24.5*</td>
<td>52.5*</td>
</tr>
<tr>
<td>OTO6</td>
<td>77.5</td>
<td>67.3*</td>
<td>10.2*</td>
<td>15.8</td>
<td>56.5*</td>
</tr>
<tr>
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<td>76.8</td>
<td>69.5*</td>
<td>7.3*</td>
<td>20.0*</td>
<td>64.2*</td>
</tr>
<tr>
<td>OTO8</td>
<td>78.5</td>
<td>69.5*</td>
<td>9.0*</td>
<td>15.5</td>
<td>57.5*</td>
</tr>
</tbody>
</table>

*ThrQ Better" and "ThrQ Worse" refer to thresholds in quiet for the better ear and worse ears, respectively. Masking noise (N) was interaurally in phase with the pure-tone signal interaurally in phase (S), or 180 degrees out of phase (S). Mean data with SDs (shown in parentheses) are shown for the normal (Normal) and otosclerosis (OTO) groups, as well as individual data for the eight otosclerosis listeners. Asterisks indicate data outside the 95th percentile of the normal-hearing listeners. Threshold data are reported in dB SPL, and MLD data are reported in dB.

Although the N_So and N_Sn thresholds were analyzed below, the main measure of binaural hearing for this study is taken as the MLD (the difference between the N_So and N_Sn thresholds). Because binaural cues are utilized

**Stimuli and Conditions**

The masker for the MLD test was a 100-Hz wide band arithmetically centered on 500 Hz. One advantage of using such a narrow bandwidth is that the MLD is usually relatively large for narrowband maskers (Green and Yost, 1975), thus allowing a wide range over which masking release effects could be demonstrated. The masking noise was always interaurally in phase (N), and the 400-msec, 500-Hz pure-tone signal was either interaurally in phase (S), or 180 degrees out of phase (S). The signal had a cosine² rise/fall time of 50 msec. The MLD was derived by subtracting the N_Sn threshold from the N_So threshold. Thresholds in quiet (no masking background present) were obtained using the 100-Hz wide noise band centered on 500 Hz as the signal (400-msec duration, with 50-msec cosine² rise/fall time). All thresholds were expressed in dB SPL.

All stimuli were presented binaurally over Etymotic ER 3A insert earphones. Stimulus timing and response collection were controlled by microcomputer. For the masked threshold conditions, the 100-Hz wide noise masker was presented at a level of 60 dB/Hz (80 dB SPL overall). In all masking conditions the masking noise was presented continuously.

**Procedure**

A three-alternative, forced-choice, three-down one-up adaptive strategy was used to estimate the 79.4 percent detection threshold (Levitt, 1971). There were three observation intervals, with the signal being presented in only one, at random. After three correct responses in succession, the level of the signal was reduced; after one incorrect response, the level of the signal was increased. A threshold run was stopped after eight reversals in signal attenuation direction, and the average of the final four reversals was taken as the threshold for the run. Visual feedback was provided after each response. An initial step-size of 8 dB was reduced to 2 dB after the first two reversals. At least two threshold estimates were obtained and averaged to determine the final threshold for a condition, and a third estimate was obtained and included in the average if the first two thresholds had a range greater than 3 dB.

**RESULTS**

Although the N_So and N_Sn thresholds were analyzed below, the main measure of binaural hearing for this study is taken as the MLD (the difference between the N_So and N_Sn thresholds). Because binaural cues are utilized
in N_{S_e} detection, this threshold might also be considered to be a measure of binaural hearing. However, the N_{S_e} threshold is also influenced by the general processing efficiency of the listener (Patterson, 1976). Because the N_{S} threshold is also influenced by processing efficiency, the subtraction used to obtain the MLD derivation is assumed to essentially remove the general efficiency factor, making the MLD a theoretically "pure" measure of the utilization of binaural cues. Table 1 shows mean N_{S_e}, N_{S_e} thresholds in quiet, and MLD results for both the normal-hearing and otosclerosis listeners, as well as individual data for the hearing-impaired listeners, for all three tests. Analyses of variance on the normal-hearing listeners indicated that neither the N_{S_e} thresholds, the N_{S} thresholds, the MLDs, nor the thresholds in quiet differed significantly across the three tests. Therefore, the 95th percentiles for the thresholds and MLDs were derived by averaging all three of the intervals across the three tests (Test 1, Test 2, and Test 3). The 95th percentiles were estimated using ±2 SD. Data for individual hearing-impaired listeners (see Table 1) with asterisks are outside the 95th percentiles of the normal-hearing listeners. The most obvious feature of the data is that, for Test 1, all of the N_{S_e} thresholds and MLDs of the otosclerosis group were outside the normal limits, but that the N_{S_e} thresholds were generally within the normal range. Thus, when MLDs were abnormal, the cause was usually a relatively high N_{S_e} threshold. For seven of the eight listeners in the otosclerosis group, the MLD remained outside the normal limits in Test 2. Note, however, that the MLDs improved from Test 1 to Test 2 (by about 5 dB, on average), and that many of the MLDs that remained abnormal in Test 2 were close to the lower bound of the normal range. All but two of the listeners in the otosclerosis group had MLDs within the normal range by Test 3. Note that in Tests 2 and 3, abnormal MLDs were again usually associated with abnormally high N_{S_e} thresholds. There was only one case (OTO3 in Test 2) where the MLD was outside the normal limits but the N_{S_e} threshold was inside the normal limits; in this case, the relatively low N_{S_e} threshold appeared to be the main factor leading to a reduced MLD.

Repeated measures analyses of variance with test (Test 1, Test 2, and Test 3) as the within subjects factor and group (normal versus otosclerosis) as the grouping factor were performed to determine the significance of the test and group factors. The first analysis examined the MLD. This analysis indicated a significant effect of group (F = 81.0, df = 1,14, p < .01), a significant effect of test (F = 27.7, df = 2,28, p < .01), and a significant group by test interaction (F = 34.1, df = 2,28, p < .01). Because the interaction was significant, an analysis of variance for simple effects was performed (Kirk, 1968). This analysis indicated that the MLDs of the otosclerosis group were significantly smaller than those of the normal group for the presurgery test (F = 139.7, df = 1,42, p < .01), and the 1-month postsurgery test (F = 30.6, df = 1,42, p < .01), but not for the post 1-year test. The analysis also showed that the MLD increased significantly with sequential testing for the otosclerosis group (F = 112, df = 2,28, p < .01), but not for the normal group. Dependent t-tests indicated that the MLD for the otosclerosis group increased significantly from Test 1 to Test 2, and from Test 2 to Test 3.

Analyses of variance on the N_{S_e} and N_{S_e} thresholds confirmed that the MLD effects noted above were determined primarily by variation in the N_{S_e} thresholds. The analysis of variance on the N_{S_e} thresholds indicated no significant effect of group or test, and no significant interaction. The analysis on N_{S_e} thresholds indicated a significant effect of group (F = 56.4, df = 1,14, p < .01), a significant effect of test (F = 15.8, df = 2,28, p < .01), and a significant group by test interaction (F = 21.7, df = 2,28, p < .01). The analysis of variance for simple effects indicated that the N_{S_e} thresholds of the otosclerosis group were significantly higher than those of the normal group for the presurgery test (F = 96.0, df = 1,42, p < .01), the 1-month postsurgery test (F = 22.0, df = 1,42, p < .01), and for the post 1-year test (F = 7.24, df = 1,42, p < .05). The analysis also showed that the N_{S_e} threshold improved significantly with sequential testing for the otosclerosis group (F = 95.8, df = 2,28, p < .01), but not for the normal group. Dependent t-tests indicated that the N_{S_e} thresholds for the otosclerosis group improved significantly from Test 1 to Test 2, but not from Test 2 to Test 3.

Analyses were also performed to examine the likelihood that the differences in MLD within the otosclerosis group found between Tests 2 and 3 were related to threshold in quiet. Dependent t-tests indicated that the thresholds in quiet did not differ between Tests 2 and 3, nor did hearing threshold asymmetry for threshold in quiet. Correlations were performed between...
MLD and hearing threshold, and between hearing threshold asymmetry and MLD for both Tests 2 and Tests 3; none of the correlations was significant. Analyses, did, however, indicate that the thresholds in quiet of the otosclerosis group were significantly higher than for the normal group, even after the surgery. T-tests indicated higher thresholds in the otosclerosis group for worse and better ears (t = 3.6, df = 14, p < .01, and t = 2.9, df = 14, p < .05, respectively) for Test 2. Similar results were obtained for the worse and better ears in Test 3 (t = 3.2, df = 14, p < .01, and t = 2.8, df = 14, p < .05, respectively).

**DISCUSSION**

The finding that the MLD is reduced in listeners having hearing loss due to conductive hearing loss agrees with several other studies (Nordlund, 1964; Quaranta et al, 1978; Hauser et al, 1979, 1983; Jerger et al, 1984; Hall et al, 1990). The finding that the mean MLD is still somewhat reduced shortly after corrective surgery is also in general agreement with past studies (Hall and Derlacki, 1986; Hauser et al, 1990; Magliulo et al, 1990). In the present study, all but one of the 1-month post surgery MLD results (about 88%) were abnormally small; the previous studies by Hall and Derlacki (1986) and Hall et al (1990) indicated that only from 40 to 50 percent had abnormally small MLDs after surgery. It is possible that the present finding of relatively low MLDs in most subjects is related to the fact that the present MLDs were obtained 1 month after surgery, while the results of the previous studies were obtained 3 or more months after surgery.

Analyses indicated that the postsurgery thresholds in quiet for the otosclerosis group were slightly, but significantly, higher than for the normal group. This would leave open the possibility that the reduced MLDs found in some of the experimental listeners in Tests 2 and 3 could have been related to elevated threshold in quiet. An argument against this interpretation, however, is that the MLD performance in the otosclerosis group was not correlated with threshold in quiet nor with threshold asymmetry as measured in Tests 2 and 3. Therefore, it appears unlikely that threshold in quiet per se had a material influence on the differences found among the experimental listeners in Tests 2 and 3. Because there was a small difference between the thresholds in quiet between the normal group and the otosclerosis group (after surgery), it is difficult to rule out the possibility that the difference in threshold did not contribute to the differences between the normal and otosclerosis groups for the MLD and the $N_{S_o}$ threshold.

The present findings from the post 1-year test indicate that, to a large extent, the abnormality apparent soon after surgery is overcome within 1 year by most subjects. The data analysis was somewhat ambiguous on this issue, indicating no significant difference in MLD between the two groups for Test 3, but a significantly higher $N_{S_o}$ threshold for the otosclerosis group. It is clear, however, that the results of the otosclerosis group generally approached those of the normal-hearing group by Test 3. Although the MLD results of the otosclerosis group showed improvement between Tests 2 and 3, the MLD apparently remained abnormal in two subjects, even a year after surgery. This is in general agreement with the few 1-year postsurgery results reported by Magliulo et al (1990). If the changes in MLD from Test 2 to Test 3 represent some sort of central adaptation to a new set of peripheral cues, it is not unreasonable to hypothesize that the speed and/or efficiency of the adaptation process may differ among individuals. An attempt was made to determine even more long-term results for the two subjects who did not show normal results at the post 1-year test. Unfortunately, a retest could not be arranged for subject 4; however, a retest of Subject 6 showed that the MLD (10 dB) for this subject continued to be abnormally small (the $N_{S_o}$ threshold was 77.75 and the $N_{S_o}$ threshold was 67.75). One factor that possibly contributed to the poor recovery of the MLD in this subject was that the length of time of unilateral hearing loss prior to surgery was relatively long (approximately 15 years). Reliable data on duration of loss was unavailable for several of the listeners, so a correlation between duration of loss and the MLD could not be determined.

The most parsimonious explanation of the changes in binaural hearing of the otosclerosis group shown across the three tests is in terms of some kind of central adaptation/plasticity, but other explanations are possible. For example, Hall and Derlacki (1986) noted that mechanical anomalies might contribute to poor binaural hearing in cases of conductive hearing loss. Such mechanical anomalies could be either the result of a conductive lesion or related in some way to the middle ear surgical procedure (e.g., a mechanical change brought about by a surgical prosthesis). Mechanical anomalies might intro-
duce phase shifts, which are to some extent asymmetric. Thus, acoustic stimuli having no interaural phase shift may have some degree of interaural phase shift at the output of the middle ear systems. As the binaural system is slightly more sensitive to interaural differences for homophasic standards (Yost, 1974), such mechanical anomalies could potentially reduce binaural hearing. It is possible that a mechanical anomaly somehow changed between Tests 2 and 3 to a more favorable disposition. Another (probably more likely) possibility is that any mechanical anomaly remained relatively stable, but that the central auditory system was able to accommodate favorably over time.

In summary, the present results indicate significant postsurgery recovery of sensitivity to binaural difference cues in adults with otosclerosis. There appear to be individual differences in this recovery. We are presently investigating whether recovery of sensitivity to binaural cues is similar in children having histories of chronic otitis media.

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REFERENCES


