COMPARISON OF FRONTAL AND MASTOID BONE-CONDUCTION THRESHOLDS IN VARIOUS CONDUCTIVE LESIONS

DONALD D. DIRKS *and* CAROLYN M. MALMQUIST

University of California School of Medicine, Los Angeles, California

Unoccluded and occluded bone conduction (BC) and Sensorineural Acuity Level (SAL) thresholds at the frontal bone and the mastoid process were compared on 60 subjects with conductive hearing loss. The results were based on calibrated norms obtained on 32 subjects with normal hearing and validated on 10 cases with sensorineural hearing loss. The mastoid BC thresholds for the entire conductive group were more depressed than comparable frontal measurements, but the average difference was only five dB. The threshold data for subjects with surgically confirmed middle-ear lesions ($N = 38$) were analysed in greater detail by dividing the group by frontal-mastoid differences and observed physical changes within the middle ear. Approximately 20% of the group showed frontal-mastoid differences that exceeded the normal range, and these cases had either malleus fixation or an ossicular discontinuity due to incus necrosis or absence of the incus. Average results for 17 cases with stapes fixation suggested that there were no frontal-mastoid differences and that both BC curves were somewhat similarly influenced by the middle-ear impairment. The SAL and occluded BC thresholds at the frontal bone were always in close agreement and differed from the unoccluded frontal-bone measurements for the conductive cases by the amount of the average occlusion effect observed for normals. The advantages of unoccluded bone conduction at the frontal bone are stressed, and the possible use of a comparison of BC thresholds at the two sites for diagnostic purposes is suggested.

Traditionally, clinical bone-conduction measurements have been performed with the vibrator located on the mastoid process. However, it was suggested by Bekesy (1932) and Barany (1938) that this position on the skull may be one of the least favorable for clinical testing. Of other possible sites on the skull, the frontal bone has received the most attention. Principally three arguments have been advanced in favor of placement of the vibrator on the frontal bone rather than on the mastoid process.

It is suggested that there is an increase in the test-retest reliability of bone-conduction measurements favoring forehead placement. Second, intersubject variability may be reduced when measurements are obtained at the frontal bone. Third, theory indicates that measurements performed at the frontal bone reduced the influence of the middle ear on the bone-conduction threshold.

There are a few other practical motives for testing at the frontal bone rather than at the mastoid process, such as the ease of performing the Weber and Bing tests without altering the vibrator position, avoiding replacement of the vibrator to the opposite side when testing the second ear, and reducing the suggestion on the part of the patient and the tester that the ear being tested is the one closest to the vibrator. These latter reasons are of interest; however, they are not as significant as the initial three arguments.

First Argument. The hypothesis that the test-retest reliability of bone-conduction measurements on the forehead is more reliable than those on the mastoid process was based originally on observations by Bekesy (1932). He noted that the tip of the bone vibrator can be moved greater distances on the frontal bone than on the mastoid process without changing bone-conduction thresholds. Results by Hart and Naunton (1961) indicated there was less variation from the average of five repeated measurements when tests were performed at the frontal bone as compared to tests at the mastoid. However, the comparative results of other investigators on larger groups of individuals and using hearing-aid-type vibrators have not always been as impressive. Studebaker (1962) could find no statistical difference in test-retest reliability when comparisons were made between bone-conduction thresholds at the mastoid and the frontal bone on normal listeners. One of the current authors (Dirks, 1964) made similar test-retest comparisons on a group of 24 normal listeners. The results showed that test-retest scores at the frontal bone were not appreciably different from the measurements at the mastoid. When various sets of data were reviewed by the author, test-retest variability from measurements obtained at the frontal bone were more often smaller than for corresponding scores obtained at the mastoid process. However, the differences did not appear to be of great practical advantage. It may be noteworthy that these investigations (Studebaker, 1962, and Dirks, 1964) were performed with hearing-aid-type bone vibrators while the tests by Hart and Naunton (1961) were conducted with a vibrator containing a small vibrating tip excited by a driving system. The original observations may not apply as well when a large vibrating surface, such as found in the hearing-aid-type vibrator, is employed.

Second Argument. The second argument favoring frontal-bone placement has been concerned with intersubject variability, or the variations in thresholds among a group of normal listeners. It has been suggested that differences in bone-conduction thresholds among individuals would be reduced if they were obtained at the forehead rather than at the mastoid process. The results of Studebaker (1962) and one of the current authors (Dirks, 1964) seem to verify this argument. However, while intersubject variability was reduced at the forehead in both experiments, the difference in variability at the two positions was rather small.

Third Argument. The final argument for forehead placement evolved primarily from the classical investigation by Barany in 1938. He suggested that the participation of the middle ear in the bone-conduction threshold was greater for measurements made at the mastoid process than at positions along the median sagittal plane of the skull. Experimental results by Link and Zwislocki (1951) for cases with otitis media demonstrated less hearing loss from measurements at the frontal bone than at the mastoid process. Studebaker (1962) compared bone-conduction hearing loss measured at the forehead with similar measurements at the mastoid process on 39 individuals with middle-ear disease. Of these subjects, 22 were diagnosed as having otosclerosis, 7 had residuals of radical mastoid surgery, 6 had inactive otitis media, 3 had suppurative otitis media, and 1 had a retracted ear drum. There was less hearing loss by bone conduction for the group when measurements were carried out at the frontal bone rather than at the mastoid process. However, the average threshold difference over the test frequencies was approximately 4 dB.

It appeared to us that this final argument for measurements at the frontal bone was potentially the most powerful of the three and deserved more attention. Thus, our study was designed to explore the differences in hearing loss by bone conduction at the frontal bone and mastoid process on persons with conductive hearing loss for whom specific surgical findings were available following the measurements. A group of normal listeners was used in calibrating the bone-conduction and SAL systems, and subjects with sensorineural hearing loss were tested to validate the normative data. Because of the recent development of a reliable artificial mastoid, it was possible to calibrate the bone-vibrator system physically and report the results in force values. Finally, since recent emphasis (Jerger and Tillman, 1960; Herer, 1964; Jerger et al., 1965) has been placed on the SAL test and on occluded bone-conduction measurements as estimates of sensorineural acuity, these tests were included for comparison in the experimental battery.

METHOD

Subjects

Thirty-two subjects with normal hearing were our control group. Negative otologic histories and passage of a screening test at 15 dB re ISO-64 norms were required for inclusion in the normal group. The mean age for these subjects was 21.8 years, and the age range was 18-32 years.

The experimental group of subjects consisted of 70 individuals with hearing loss, 60 with conductive loss and 10 with sensorineural loss. The conductive group was divided on the basis of surgical information obtained after the preoperative audiological examination. Twenty-two cases were excluded from this subgrouping process because of incomplete medical or surgical information. The medical classification of the remaining 38 subjects with conductive loss was as follows:

1. Seventeen cases with stapes fixation due to otosclerosis.
2. Two cases with malleus fixation, one in which the malleus was fixed by a bony growth and the other in which the malleus and incus were fixed by granulation tissue. Both had intact ossicular chains and mobile stapes footplates.
3. Ten cases with ossicular discontinuity due to chronic otitis media. Three of these had a perforation of the tympanic membrane and cholesteatoma; one had a cholesteatoma with an intact tympanic membrane. Of the remaining six, three cases had a perforation of the tympanic membrane and three had no impairment other than the ossicular discontinuity.
4. One case with a perforated tympanic membrane only. The middle-ear cavity was clear and the ossicular chain intact and mobile.
5. Two cases with middle-ear fluid.
6. Six postoperative mastoidectomy cases on whom a second surgical procedure was later performed. Of these six cases, two had no ossicles or tympanic membrane, three had no ossicles with intact tympanic membranes, and one had an intact stapes and a small remnant of the incus which was attached to an intact tympanic membrane because of previous reconstruction.

Notice in the above classification that the emphasis had been placed on the physical change that had taken place in the middle ear rather than on the disease process. Although it is typical to divide conductive lesions on the basis of the disease process (such as otosclerosis, otitis media, etc.), the audiometric results are more closely related to the physical alterations of the system caused by the disease—not to the disease itself.

Apparatus

We used a Beltone 15C audiometer for the air- and bone-conduction signals. The pure tone was fed to a fixed attenuator which provided additional attenuation of the signal when necessary. The test signal was terminated either in an earphone (TDH-39 encased in MX41/AR cushion) or in a hearing-aid-type bone vibrator (Radioear B70-A).

We used a narrow-band masking unit (Beltone, Model NB 102) as our noise source for the SAL and for masking the nontest ear during bone-conduction measurements. The output of the masker went directly to an insert receiver (Beyer DT 507) during bone-conduction measurements; during the SAL test, the noise passed through an amplifier (McIntosh, Model 162K) and terminated in a second hearing-aid-type vibrator (Radioear B70-A). A volt meter monitored the output of the SAL noise across the terminal of the bone vibrator. When masking was required for air-conduction testing, the second channel of the Beltone 15C audiometer provided white noise. The air- and bone-conduction signals were calibrated, acoustically, prior to, and periodically throughout, the experiment. We used a 6 cc coupler and associated microphone (Bruel & Kjaer, Type 4132) and assembly (Bruel & Kjaer audio frequency spectrometer, Type 2112) to calibrate the air-conduction system. We calibrated the bone-conduction signals on an artificial mastoid (Beltone, Model 5A) with accompanying amplifier and volt meter. We made daily calibrations by monitoring the voltage at the receivers' terminals.

Procedure

Normal Listeners. Four tests were administered to each subject:

1. Sensorineural Acuity Level (SAL).
   a. Air conduction in quiet (ACq).
   b. Air conduction in the presence of bone-conduction noise (ACn).
2. Unoccluded bone conduction with mastoid placement (BCM).
3. Unoccluded bone conduction with frontal placement (BCFu).
4. Occluded bone conduction with frontal placement (BCFo).

The SAL test was always administered first, the ACq test to each ear and the ACn portion to the test ear only. The right or left ear was chosen alternately as the test ear. The subject's ACq thresholds in the nontest ear were collected only to determine appropriate masking levels for succeeding bone-conduction conditions. The order of presentation for the bone-conduction tests was counterbalanced according to site of vibrator placement (mastoid or frontal) and occlusion state (unoccluded or occluded). The frontal bone-conduction tests, however, were always presented consecutively so that it was not necessary to remove the vibrator from the forehead between tests.

Pure-tone thresholds were obtained at 250, 500, 1000, 2000, and 4000 Hz for each of the test conditions. The ascending technique, described by Carhart and Jerger (1959), was used. The order of frequency presentation was 1000, 2000, 4000, 1000, 500, and 250 Hz.

With two modifications the SAL test was administered in the manner originally described by Jerger and Tillman (1960). First, we used narrow bands of noise and set the noise level for each band at 0.5 volts by monitoring the voltage at the terminals of the bone vibrator. Second, the resultant SAL norm was based on the difference between 0 dB HL re ISO-64 norms and the masked threshold (ACn).

For SAL and frontal-bone conduction, a commercially available holder and strap held the vibrator to the forehead. In both conditions force was kept constant at approximately 600 grams. For bone-conduction measurements at the mastoid process we used a standard bone-vibrator holder. No measurements of the vibrator's application force were performed during the experimental session. However, earlier measurements (Dirks, 1964) under very similar conditions suggested that the vibrator was affixed to the mastoid process of adults with an average pressure of 350 grams.

All threshold measurements were monaural. The test ear was unoccluded for BCM and BCFu and covered by an earphone (TDH-39 with an MX41/AR cushion) for the BCFo. The nontest ear always was masked for bone-conduction conditions at an effective level of 30 dB. Narrow bands of noise from a commercially available noise generator (Beltone, Model NB 102) were presented to the nontest ear via an insert receiver. The acoustic output of noise was calibrated with a 2 cc coupler and accompanying microphone and calibration assembly (Bruel & Kjaer, Type 2112).

Subjects with Hearing Loss. We used a method similar to that used for our normal group for our subjects with hearing loss, except for the masking procedure and the way we selected the experimental ear. The ear with the greatest loss of hearing, or the ear already selected for surgery, was routinely chosen as the experimental test ear. In most instances, the ear with the greatest loss was also the ear selected for surgery. We used the masking technique described by Hood (1957) for masking the nontest ear during the bone-conduction conditions and during the ACq condition when masking was required. If the nontest ear was masked during the ACq condition, the same level of contralateral masking was used to obtain the ACn portion of the SAL procedure. From a practical point of view, the plateau, determined by the Hood procedure, was usually found with the noise in the nontest ear at an effective level of 30 dB.

RESULTS

Normal Group

Figure 1 shows the results of the bone-conduction thresholds for the 32 listeners with normal hearing. Each datum point represents the mean threshold for the 32 subjects for the reported condition and frequency. The thresholds were reported in force values (dB re 1.0 dyne RMS) determined from measurements on the artificial mastoid. As previous investigators have observed (Studebaker, 1962; Dirks, 1964; Whittle, 1965; and Weston, Gengel and Hirsh, 1967), greater energy is required to reach threshold at the frontal bone than at the mastoid process. The differences in threshold between the two locations vary from 11.6 dB at 250 Hz to 1.7 dB at 4000 Hz. The thresholds at the mastoid process that we obtained in this study are in good agreement with the values suggested for an interim norm by the standards committee of the Hearing Aid Industry Conference (HAIC) and reported by Lybarger (1966). The bone-conduction thresholds at the frontal bone are very similar to those recently published by Weston et al. (1967).

Figure 1 also contains the threshold measurements obtained at the frontal bone with the test ear occluded. The magnitude of the occlusion effect can be determined by comparing the BCFu and BCFo curves. The occlusion effect was 19.3 dB at 250 Hz, 19.0 dB at 500 Hz, and 7 dB at 1000 Hz. At 2000 and 4000 Hz the occlusion effect was virtually absent. These results are in general agreement with previously published data on the magnitude of the occlusion

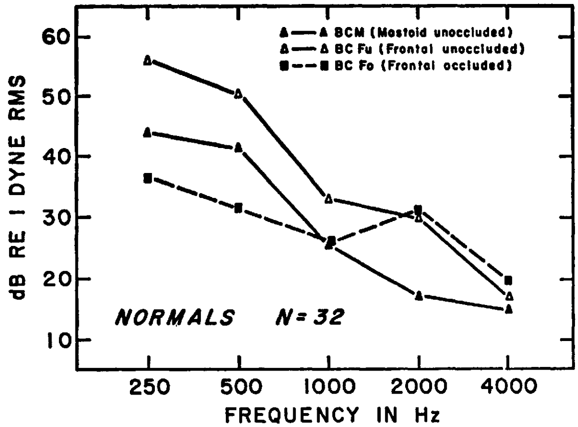

FIGURE 1. Mean bone-conduction thresholds in dB re 1 dyne RMS for 32 subjects on 3 conditions at 5 test frequencies.

effect obtained with similar earphones and cushions (Elpern and Naunton, 1963; Hodgson and Tillman, 1966; Dirks and Swindeman, 1967). The thresholds in Figure 1 were values we used for the calibrated bone-conduction norms in this investigation.

Sensorineural Group

We tested a group of 10 medically diagnosed cases of sensorineural hearing loss, using the SAL procedure and the three experimental bone-conduction conditions. We used only one ear from each of the cases to obtain the average thresholds in Figure 2. The primary purpose of including a group of individuals with sensorineural hearing loss in this study was to validate the normative data used for calibration purposes. We reasoned that the individuals with sensorineural hearing loss should demonstrate bone-conduction and SAL thresholds that were reduced from those obtained in the normal group by an amount equivalent to their air-conduction loss.

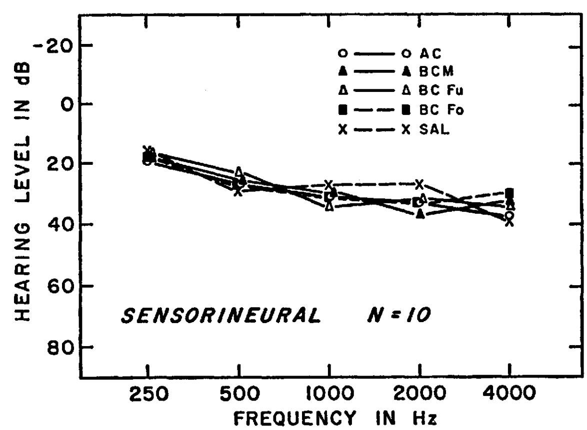

FIGURE 2. Mean thresholds in dB re hearing level of 10 sensorineural cases for 5 test frequencies and conditions.

The results (Figure 2) suggest that our calibration values are appropriate for the normal listeners. Observe that the audiometric curves for SAL and bone-conduction thresholds interweave with the air-conduction thresholds at test frequencies. There is one minor exception. The spread of the test results at 2000 Hz is somewhat larger than that observed at other frequencies. SAL and BCM differ from the air-conduction threshold by approximately 5 dB, the SAL tending to underestimate the degree of loss and the BCM to overestimate it. Except for these deviations, sensorineural group results emphasize the validity of the calibration values obtained from the normal group.

One other observation should be emphasized from the sensorineural group results. It concerns the good agreement of SAL and the three types of bone-conduction measurements with the air-conduction thresholds. Regardless of whether unoccluded (BCM, BCFu) or occluded (BCFo, SAL) measurements were performed, all the test results indicated equivalent thresholds for patients with sensorineural loss as long as the appropriate norm was applied. The results suggested that either relative (open ear) or absolute (occluded ear) bone-conduction and SAL measurements give equivalent estimates of sensorineural acuity on patients with sensorineural hearing loss.

Conductive Group

Studebaker (1962) reported the differences of calibrated frontal and mastoid bone-conduction thresholds on a group of 39 subjects with varied middle-ear lesions. Although the types of otologic impairments were listed, the comparison between results at the mastoid and frontal bone was based on threshold responses from the total group. We present the mean results for the total conductive group of this study to compare them with Studebaker's results (1962) and to illustrate the relationship of occluded and unoccluded test measurements on middle-ear lesion cases. The later division of patients into subgroups, however, provided the most informative and clinically useful "frontal-mastoid" results.

Figure 3 shows the mean threshold responses at the five test frequencies and conditions for the entire conductive group. Observe that the two unoccluded bone-conduction measurements (BCM and BCFu) differ slightly at most test frequencies. BCM is consistently poorer than BCFu, but the average difference is only 5 dB. Another interesting result (Figure 3) is the close agreement between the two occluded bone-conduction tests (BCFo and SAL). Tillman (1963) and Jerger and Jerger (1965) have cautioned against comparison of "occluded" SAL with unoccluded bone-conduction measurements. Our current findings again demonstrate the inappropriateness of such a comparison. Notice that SAL thresholds interweave with the occluded frontal-bone thresholds and that both differ from the unoccluded thresholds, the difference approximately equaling the average occlusion effect (BCFu − BCFo) found in the normal group.

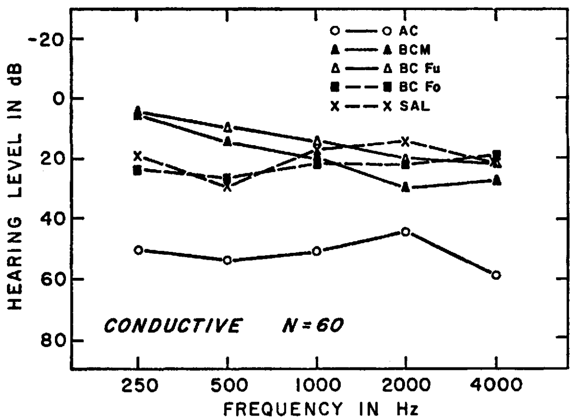

FIGURE 3. Mean thresholds in dB re hearing level of 60 cases with conductive hearing loss for 5 frequencies and conditions.

Table 1 presents the average differences between the unoccluded bone-conduction thresholds at the mastoid process and frontal bone for the conductive group and the comparable differences reported by Studebaker (1962). The results of both studies indicate a similar trend. The frontal bone-conduction thresholds show less hearing loss than those at the mastoid process, but the average differences are small.

TABLE 1. Mean difference in dB re hearing level between frontal and mastoid bone-conduction thresholds (BCFu-BCM) for conductive loss groups with diverse middle-ear impairments. $N = 60$ for current data; $N = 39$ for Studebaker's data (1962).

	Frequency in Hz					
Data	*250*	*500*	*1000*	*2000*	*4000*	*Average Difference*
Ours	–1.8	–4.7	–4.9	–8.1	–5.8	–5.1
Studebaker's	–1.4	–4.6	–4.1	–4.0	–5.2	–3.8

Conductive Subgroups

It was our intent in this study to examine the relationship of various bone-conduction tests on individuals for whom rather precise medical and surgical information was available. Twenty-two cases were excluded from the final analysis because no surgery was performed. The remaining cases with conductive loss ($N = 38$) were divided initially into two groups: stapes fixation and no stapes fixation. It would have been desirable to divide the entire group into a larger number of categories specially related to the physical changes in the middle ear. However, the diversity of middle-ear lesions was large, as is true in most groups of conductive hearing loss cases, and with an N of 38 it was impractical to subdivide the cases further by precise physical changes.

Observation of the frontal-mastoid difference scores for the two groups suggested reasonable homogeneity for the stapes-fixation group but a wide dispersion of scores for the no stapes-fixation subjects. Therefore, the no stapes-fixation group was divided on the basis of the average BCFu − BCM differences (5 test frequency scores were combined to obtain average differences). Because the normal and the stapes-fixation groups revealed frontal-mastoid difference scores ranging from ± 7 dB (in dB re calibrated norms), the arbitrary point for delineating a significant BCFu − BCM difference was 8 dB. Thus, individuals with a BCFu − BCM difference of ± 7 dB fell into a no stapes-fixation group labeled *group A*. Those with a difference of 8 dB or greater were placed in the no stapes-fixation group, *group B*.

Figure 4 presents the frequency distributions of the BCFu-BCM difference scores in dB re HL for the normal and the three conductive subgroups. Since the number of subjects in each group varied, the ordinate in the figure designates the percentage of subjects within each subgroup that demonstrated various difference scores. The frequency distribution of the difference scores (BCFu − BCM) for three of the groups (normal, stapes fixation, and no stapes-fixation group A) are relatively similar. Group B, however, differs from the other three by definition, for it includes the subjects who demonstrated BCFu-BCM differences of 8 dB or greater. The average difference between the mastoid and frontal bone-conduction thresholds for group B was 12 dB. This group, however, represents only 18% of the conductive cases ($N = 38$).

Table 2 provides the mean and median difference scores for the subjects with normal hearing and the three conductive subgroups. Note that these scores for group A are negative and differ by 2 to 3 dB from the comparable difference scores for the normal and the stapes-fixation group. Some individuals in group A had relatively large difference scores at one or more of the test frequencies or consistent but small differences over the frequency range. However, the limited number of cases and the use of a discrete frequency-testing technique did not permit a more subtle analysis of the BCFu − BCM differ-

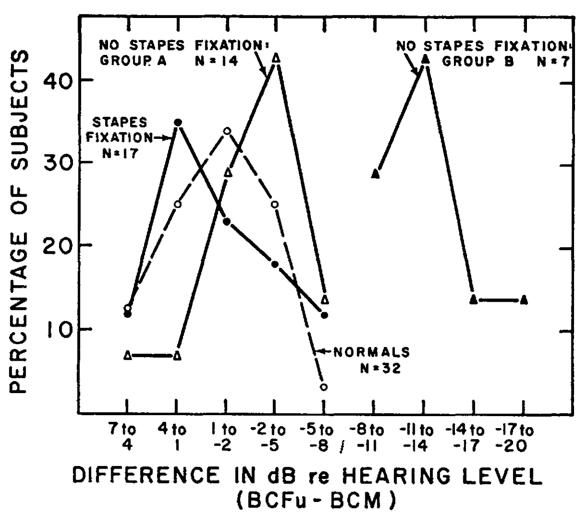

FIGURE 4. Frequency distribution of average BCFu − BCM difference scores for subjects with normal hearing and for three conductive subgroups.

TABLE 2. Mean and median BCFu — BCM difference scores in dB re hearing level for normal listeners and three conductive subgroups.

Test Groups	N	BCFu — BCM Difference Scores in dB Re Hearing Level	
		Mean	Median
Normal	32	0	0.5
Stapes Fixation	17	0.5	0.5
No Stapes Fixation			
Group A	14	−2.1	−2.8
Group B	7	−12.1	−12.0

ences. The frontal-mastoid relationships for group B are obviously different from the other groups. These large differences are of significance and, unlike the differences found in group A, should be easily differentiated from the normal group. Thus, the division of the no stapes-fixation cases into only two groups on the basis of BCFu — BCM difference scores is considered to be a conservative approach.

Figure 5 includes the mean results for each condition at the five test frequencies for the subjects with stapes fixation. Although the stapes-fixation group in Figure 5 was composed of 17 cases, the number of responses varied slightly in the higher frequencies because the maximum shift for the SAL test was not measurable in a few cases with severe air-conduction losses. If the SAL threshold could not be exactly determined for an individual at a particular frequency, the threshold values at that frequency for the SAL and the other experimental conditions were excluded in obtaining the mean results. The exclusion of these thresholds permitted a more accurate comparison of SAL with the BC thresholds and resulted in only minimal changes in the mean results. The group had approximately a 60-dB air-conduction loss, and the configuration of the curve demonstrated the characteristic stiffness tilt.

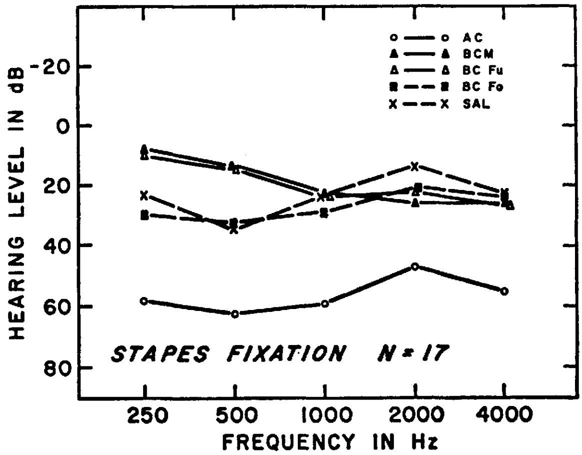

FIGURE 5. Mean thresholds in dB re hearing level of 17 cases with stapes fixation for 5 frequencies and conditions.

The results for the two unoccluded bone-conduction tests (BCM and BCFu) were similar. This finding suggested that among cases with stapes fixation the frontal-mastoid differences were similar to those obtained on individuals with normal hearing.

The close agreement of the two occluded "bone-conduction" tests (SAL and BCFo) in Figure 5 is also obvious. It appears that the only real difference among the battery of bone-conduction tests is related to the presence or absence of the occlusion effect in the normals. Although the SAL test is based on air-conduction shifts in the presence of bone-conducted noise, rather than actual bone-conduction thresholds, the SAL thresholds are equivalent to the BCFo thresholds.

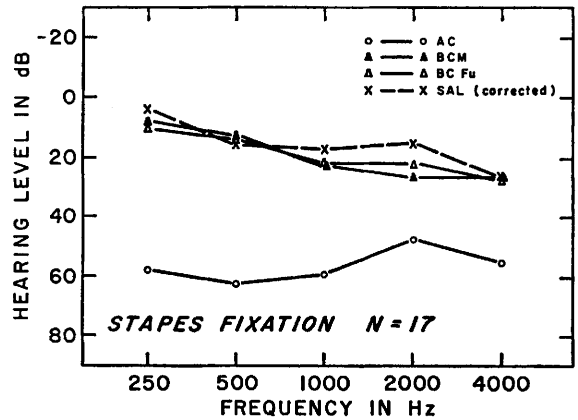

FIGURE 6. Comparison in dB re hearing level between "unoccluded," or corrected, SAL and unoccluded mastoid and frontal BC thresholds for 17 cases with stapes fixation.

In Figure 6, SAL was plotted with BCFu and BCM as an unoccluded-test result. The SAL was corrected at each frequency by the amount of the average occlusion effect for the normal group. The purpose of this article is not to discuss all the merits of relative (unoccluded) or absolute (occluded) bone conduction. However, it is obvious that if one expects agreement between SAL and unoccluded frontal bone-conduction thresholds on conductive cases, such a correction must be made unless the earphone employed produces no occlusion effect for normals. Even after this correction, however, SAL can not always be expected to agree with unoccluded BCM, although the curves interweave for this particular group.

Figure 7 shows the mean thresholds for the experimental conditions at the five test frequencies for patients with no stapes-fixation group A. The average air-conduction loss for the group in the frequency range from 500 to 2000 Hz was 46 dB. The configurations of the BCM, BCFu, and the corrected SAL thresholds interweave and indicate a substantial conductive loss. Each of the three estimates of sensorineural acuity is reduced in the high frequencies. The curve for BCM exhibits a small notch with the greatest reduction occurring at 2000 Hz, but the results from the entire battery suggest that the threshold values at 2000 and 4000 Hz are practically equal. It is likely that this reduction in bone-conduction thresholds is primarily due to factors other than sensorineural loss. Notice that the air-conduction curve revealed a stiffness tilt, characteristic of conductive lesions, with only a mild drop between 2000 and 4000 Hz. Other investigators (Naunton and Fernandez, 1961; Tonndorf, 1966) have also reported a depression in the bone-conduction thresholds around 2000 Hz in cases of middle-ear impairment other than stapes fixation.

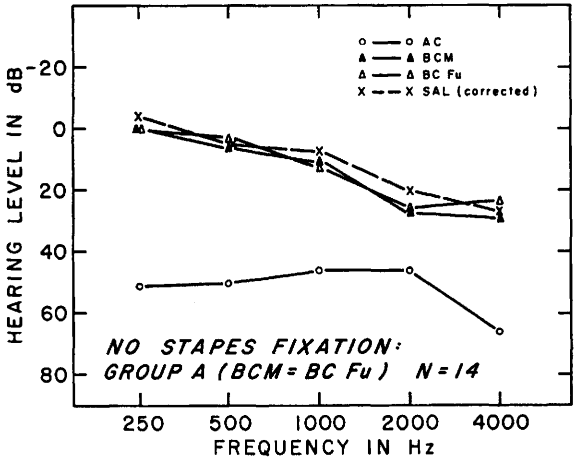

FIGURE 7. Mean thresholds in dB re hearing level for 4 test conditions for 14 subjects with no stapes fixation and in which BCM = BCFu.

Group A was composed of 14 cases with middle-ear impairments. Four of the cases had no ossicles due to previous radical mastoidectomies, and two of these had perforations of the tympanic membrane. One case had a previous mastoidectomy and tympanoplasty. The surgery report from the day following the testing procedure indicated that the stapes was intact and a fragment of the incus was resting on the tympanic membrane. Two of the cases had fluid in the middle ear but an intact ossicular chain. Six of the cases had ossicular discontinuity and perforations of the tympanic membrane. In most of the cases with ossicular discontinuity there was either fibrous tissue or cholesteatoma present. It is possible that the fibrous connections or cholesteatoma may have substituted as a secondary ossicular chain for the transmission of sound. The final case had only a perforation of the tympanic membrane. To summarize, four cases had no ossicles, three patients had intact ossicular chains, and the remaining seven cases had an ossicular discontinuity with a cholesteatoma. Nine of the 14 cases had perforations of the tympanic membrane.

Figure 8 shows the results of the experimental conditions for the seven pathological subjects who formed group B. This group contains cases in which there was a difference between frontal and mastoid bone-conduction thresholds which exceeded the differences observed for the normal listeners. The air-conduction thresholds show an average deficit of approximately 47 dB in the range from 500 to 2000 Hz. A stiffness tilt characterizes the configuration of the curve. The frontal-mastoid differences in this group averaged

12 dB. While the greatest difference between thresholds at the mastoid and frontal bone was 17 dB at 500 Hz, the smallest difference was 8 dB at 250 Hz. Observe again that the SAL results, corrected by the normal occlusion effect, agree extremely well with the BCFu results.

In comparing groups A and B (Figures 7 and 8), it is interesting to note that the average air-conduction losses for the two groups are practically identical. The frontal-bone thresholds are also quite similar. The marked difference between the two groups is found in the thresholds taken at the mastoid process. Although the configurations of the BCM curves are similar, the thresholds for group B are considerably more reduced than those for group A.

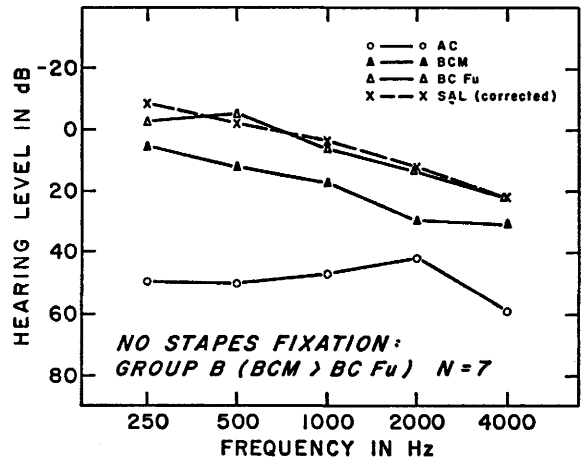

FIGURE 8. Mean thresholds in dB re hearing level for four test conditions for seven subjects with no stapes fixation and BCM > BCFu by 8 dB or more.

Four of the cases in group B had an ossicular discontinuity due to incus necrosis or absence of the incus. Two of the four cases had a perforation of the tympanic membrane and one of these had a cholesteatoma which filled the entire attic, antrum, and adicus. The fifth case had had a radical mastoidectomy and at the time of testing the attic was filled with cholesteatoma. The remaining two cases had malleus fixation: in one the malleus was fixed by bony growth to the lateral attic, and in the other thick granulation tissue enveloped the malleus and incus. As far as it can be determined, the interesting commonality of these cases is the presence of a mobile and intact stapes with a fixed malleus or a discontinuity due to necrosis or absence of the incus.

DISCUSSION

Theoretical Implications

The results of this study require some comment about the theory of bone conduction and the implications for the clinical testing of bone conduction. Recently Tonndorf (1966) presented a revised theory of bone conduction based in part on numerous experiments with laboratory animals. It is impossible to present all of the ramifications of Tonndorf's theory of bone conduction here, but some definite relationships appear to exist between our current results and the findings he derived from his laboratory investigations.

Tonndorf compared the changes in response to bone-conduction stimuli in four animal species following immobilization of the tympanic membrane or "amputation of the middle ear." The frequency of maximal loss by bone conduction correlated with the resonant point of the ossicular chain in each species. A similar result was found when the stapes of the cat was fixated with dental cement. The maximal loss in the bone-conduction response was found in the frequency area around 500-600 Hz, which corresponds to the resonant point of the ossicular chain in the cat. The explanation that the "Carhart notch" is due to the loss of the middle-ear inertial component generally has not been advanced, for it has often been suggested that this contribution to bone conduction is greatest in the low frequencies. Therefore, the accepted theory concerning inertia bone conduction and the presence of a BC notch at 2000 Hz in man did not appear to be related. Tonndorf suggests the earlier explanation of inertia bone conduction is too simple and overlooks the fact that the ossicular-chain vibrating system also has a resonant point which varies in different animals. Since the ossicular chain has a resonant point near 2000 Hz (Groen, 1962) in man, the maximal loss should be found in this frequency area when the chain is fixated.

Tonndorf's evidence suggests that it is essentially the missing ossicular inertial component that determines the frequency value of the point of maximal bone-conduction loss when the middle ear is amputated. He reported reductions in bone conduction around 500-600 Hz due to amputation of the middle ear in cats. However, a greater loss was observed when the middle-ear was amputated than when the stapes was fixed. Tonndorf suggested that somewhat similar results should occur in man after radical mastoidectomy and presented the audiogram of one such case.

Figure 9 shows the average air- and bone-conduction thresholds at the mastoid and frontal bone and the SAL results for seven patients who had radical mastoidectomies but no reconstructive surgery. Five of these cases are included in the Results section of this article, and we evaluated two patients recently, using similar experimental procedures. Our results in Figure 9 agree on two major points with the conclusions reached by Tonndorf: (1) Bone-conduction thresholds are depressed from normal. (2) The frequency area of maximal loss corresponds to the resonance point of the ossicular chain in man.

The depression of the bone-conduction curves probably was not due to a sensorineural component, for the bone-conduction thresholds improved at 4000 Hz, compared to those at 2000 Hz, and speech discrimination scores were above 90%. Of further interest for this study is the general agreement between BCFu and corrected SAL thresholds. The results of tests conducted at the frontal bone indicated less hearing loss than the results obtained at the mastoid process. The average difference between the frontal and mastoid-process mea-

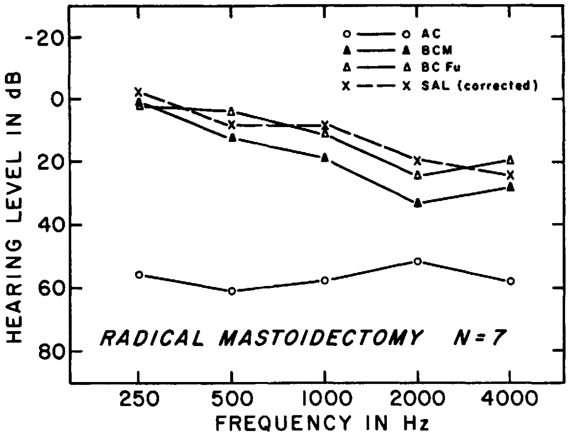

FIGURE 9. Mean thresholds in dB re hearing level for four test conditions for seven postoperative radical mastoidectomy cases who have had no reconstruction surgery.

surements is approximately 7 dB. As in earlier results, there is little difference at 250 Hz between frontal and mastoid measurements.

Compare the audiometric configuration of these seven patients who have had radical mastoidectomy (Figure 9) with the results observed on patients with surgically confirmed stapes fixation (Figure 6). Notice that in both groups the greatest reduction in bone conduction is observed in the higher frequencies, especially around 2000 Hz. In the cases with stapes fixation the notch is not complete since the thresholds at 4000 Hz remain equal to that at 2000 Hz. This may be because some of the cases with stapes fixation also had sensorineural components or other secondary ossicular lesions. In general, our results for cases with stapes fixation and radical mastoidectomy support Tonndorf's theory that the maximal loss in bone conduction due to impairment or elimination of the ossicular inertial component will be found within frequencies of the resonance of the ossicular chain.

The purpose of our investigation was to test the hypothesis that cases with middle-ear lesions show less hearing loss for bone conduction at the frontal bone than at the mastoid process. While this may be true for some middle-ear problems, it does not necessarily hold true for all middle-ear impairments; results on the patients with stapes fixation (Figure 5) suggest that this concept is too elementary. In unpublished data, Herer (1964) also compared bone-conduction thresholds at the mastoid process with SAL thresholds on cases with stapes fixation. The two measurements showed equivalent reductions in the higher frequency region. Thus, it would appear that some alterations in the middle ear similarly affect mastoid and frontal bone-conduction thresholds. It comes as no surprise that thresholds at the frontal bone can also be significantly affected by impairments in the middle ear. Studebaker's (1962) results showed only a small difference between thresholds at the frontal bone and the mastoid process on a group of various conductive lesions, and both sets of thresholds were depressed compared with normals. Naunton and Fernandez (1961) reported considerable changes in thresholds at the frontal bone in three cases of otitis media. They observed an improvement in bone-conduction thresholds in the low frequencies but a reduction around 2000 Hz. In each of these studies, the contribution of middle-ear inertia was partially or completely eliminated and the largest reduction in bone-conduction or SAL threshold at the frontal bone was observed around 2000 Hz.

Kirikae's (1959) evidence regarding oscillations of the skull from bone-conducted signals may be of interest here. Kirikae observed that in higher frequencies (above 1500 Hz) the oscillations of the skull became extremely varied and complicated. He concluded that the location of the vibrator on the skull made relatively little difference for skull oscillations in high frequencies. Thus, the contribution from the middle-ear inertial effect would be similar regardless of vibrator placement in the higher frequency region. If middle-ear impairment eliminates this contribution to the total bone-conduction response, somewhat similar threshold changes could occur from measurements at the mastoid process and the frontal bone for frequencies around 2000 Hz in man.

Among the individuals who demonstrated a substantial frontal-mastoid difference, one patient had surgically confirmed malleus fixation with an absence of other middle-ear changes. Results for this case are in Figure 10 and must be reviewed rather carefully since there was also a sensorineural component. Thresholds at the frontal bone indicated considerably less sensorineural involvement than mastoid process measurements did. The largest difference between measurements at the two sites was 21 dB at 2000 Hz. A large difference was present also at 4000 Hz. This difference gradually reduced as the test frequency was lowered and became nonexistent at 250 Hz. Results from the SAL test are not recorded in the figure; however, they were in good agreement with the frontal-bone thresholds. Since the ossicular chain was probably fixated in this instance, the frontal-mastoid difference in the high frequencies was not anticipated in light of the aforementioned results of Kirikae (1959).

Notice that the postoperative air-conduction responses coincide closely with the preoperative frontal-bone hearing curve. The area of deviation is at 2000 Hz at which the air-conduction curve is approximately 6 dB better than the

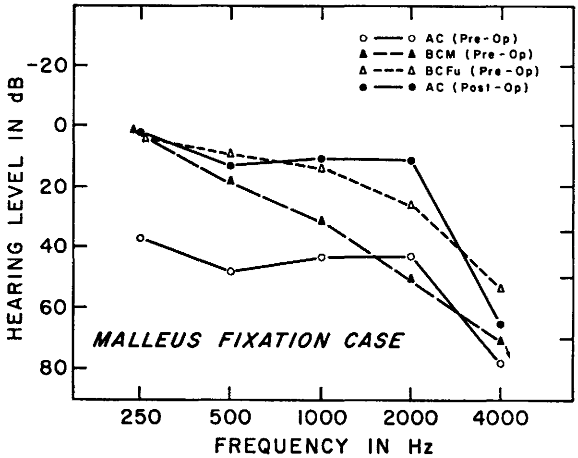

FIGURE 10. Preoperative AC, BCM, and BCFu thresholds and postoperative AC thresholds in dB re hearing level for an individual with malleus fixation.

preoperative bone-conduction result. This may be because there was also some reduction in the frontal-bone threshold due to the partial or complete elimination of the inertial effect or to variability in measurement.

Malleus fixation has some similarity with experimental fixation of the tympanic membrane, as reported by Tonndorf. In cats he found that fixation of the tympanic membrane resulted in a reduction of the bone-conduction response similar to that observed in stapes fixation; however, the notch became a flat-bottomed trough extending over a wider frequency range than that observed with stapes fixation. The case described in the current paper also demonstrates a reduction in mastoid bone-conduction thresholds covering a wider frequency range than that observed in stapes fixation.

It is obvious from our results that middle-ear lesion cases cannot be considered as a homogeneous group in terms of frontal-mastoid differences. Current evidence suggests the following:

1. When the stapes is fixated, the bone-conduction responses at the frontal bone and mastoid process are altered in a very similar manner.
2. If the ossicular chain is partially eliminated by a radical mastoidectomy, the thresholds for bone conduction at both sites are reduced maximally around 2000 Hz; however, the reduction is not as large for measurements at the frontal bone as for measurements at the mastoid process.
3. Bone-conduction thresholds at the mastoid process appear to be considerably more reduced than those at the frontal bone—for cases in which the stapes is intact and mobile but the malleus and incus are fixated, or for some cases of discontinuity at or involving the incudo-stapedial joint.

Clinical Implications

The use of bone-conduction or SAL measurements in clinical evaluations is generally based on the assumption that the bone-conduction threshold is not as dependent on the external and middle ear as is the air-conduction threshold. While clinically useful, it is obvious that this assumption requires considerable modification, precisely because the external and middle ear do contribute to the total bone-conduction threshold. If, however, it becomes possible to determine and predict the changes in bone-conduction thresholds that occur with various middle-ear impairments, the very modifications that limit the basic clinical assumption may become useful in the differential diagnosis of middle-ear lesions.

The extensiveness of the clinical testing procedure and the selection of appropriate diagnostic tests depend on questions asked by the diagnostician. If separation of cases with conductive and sensorineural loss is the only objective, the majority of patients with conductive hearing loss can be adequately classified with only one of the tests included in our experimental battery. However, at least two types of cases may be incorrectly diagnosed if only one test of sensorineural acuity is employed:

1. Conductive cases with very mild hearing loss may present little or no air-bone gap, especially if BCM is the test of choice. Because of individual variations in bone-conduction thresholds and vibrator placement effects, it is hazardous to classify these on the basis of one bone-conduction test.
2. Cases with mixed hearing loss may be misdiagnosed because the effects of middle-ear impairment depress bone-conduction thresholds. Our results indicate that BCM measurements would be the most severely depressed compared to bone-conduction tests at the frontal bone or SAL.

If clinical constraints (time, personnel, equipment, etc.) do not permit an extensive evaluation of each patient, the clinician must choose the test of sensorineural acuity that will differentiate the largest number of cases possible. The results of this experiment and other similar bone-conduction investigations (Studebaker, 1962; Link and Zwislocki, 1951) suggest that we seriously consider BCFu as the test of choice. Although the middle ear's condition may influence both frontal and mastoid bone-conduction thresholds, as illustrated in cases with stapes fixation (Figure 6) and radical mastoidectomies (Figure 9), BCFu generally was equal to, or better than, BCM in this study. However, in certain cases (Figure 8) the results of the frontal bone tests showed considerably less hearing loss than BCM. Thus, the use of frontal bone-conduction measurements may maximize the air-bone gap and result in the proper diagnosis of the largest number of hearing impairments.

There are other dividends from testing bone-conduction thresholds at the frontal bone. Although results from clinical studies have not been as impressive as some laboratory investigations, measurements at the frontal bone always indicate equal or greater inter- and intrasubject reliability than do comparative measurements at the mastoid process. A minor advantage of unoccluded bone-conduction measurements at the frontal bone (BCFu) is the ease of administering such tests (e.g. the audiometric Weber and Bing) because their test results can be obtained without disturbing the original placement of the bone vibrator at the frontal bone.

The only obvious disadvantage of BCFu is that, in general, more intensity is required to reach threshold than for comparable mastoid measurements. The SAL test has the same disadvantage, for the placement of the vibrator at the frontal bone reduces the maximum shift available. In cases of severe hearing loss, mastoid placement of the vibrator may be necessary in order to obtain threshold values. However, an additional evaluation with BCFu is highly recommended, since in some instances threshold measurements obtained at the mastoid process may be considerably depressed from their frontal bone-conduction counterparts.

A question also arises concerning the use of occluded, frontal bone-conduction measurements or SAL. Our experimental results have demonstrated that the SAL and BCFo tests provide similar information and differ from BCFu only in conductive cases. SAL and BCFo both involve vibratory placement at the frontal bone and occlusion of the test ear. The SAL is a particularly valuable test for evaluating cases who are difficult to mask properly for bone-conduction testing. If a relative or unoccluded threshold is desired, however, one must use either earphones that cause no occlusion effect or correct the SAL results for conductive loss cases by subtracting the average occlusion effect obtained from normal listeners fitted with the occluding earphone cushions. The correction procedure is recognizably a hazardous one on individual cases, but currently there are no "non-occluding" earphones that are practical for clinical use. We caution that before SAL results can be corrected, the clinician must rule out the presence of an occlusion effect by administering unoccluded and occluded BC tests.

Our preference for unoccluded testing procedures, rather than occluded frontal bone-conduction or occluded SAL, is based partially on the most recent investigations of the occlusion effect by Tonndorf (1966). Tonndorf's evidence gathered from experimental animals indicates the occlusion effect for bone-conducted signals is based primarily on two factors: (1) When vibrating, the walls of the external canal radiate acoustic energy that is partially transmitted to the receptor organ via the middle ear, the open ear canal acting as a high-pass filter and its occlusion producing a low-frequency emphasis. (2) The air in the external canal constitutes a load upon the tympanic membrane, and changes in the resonant properties of the canal because modifications in length and/or occlusion alter the load effect. Thus, middle-ear impairments reduce or eliminate the occlusion effect.

Jerger et al. (1965) have suggested that SAL or occluded bone-conduction techniques give the best estimates of sensorineural acuity in conductive hearing loss cases because patients with middle-ear impairment have a built-in occlusion effect. The recent studies by Tonndorf (1966) however, suggest that the opposite is, indeed, the case. His results indicate that a functional tympanic membrane and ossicular chain are necessary for the presence of the occlusion effect, and middle-ear impairments generally eliminate the effect. Until substantial evidence to the contrary is presented, the use of an unoccluded bone-conduction or SAL test would be more appropriate.

Obviously, if a researcher or adventurous clinician wishes to perform tests at the frontal bone, he will need to collect normative data at this site. Clinics with an artificial mastoid may choose to perform threshold measurements on a group of normal subjects and calibrate their bone-conduction system in physical terms. The published data on frontal-bone measurements reported by Weston et al. (1967) or by Dirks, Malmquist, and Bower (1968) may prove helpful for comparison. Clinics lacking equipment to calibrate their systems in physical terms must periodically obtain threshold measurements at the frontal bone, as well as at the mastoid process, from normal hearing individuals, to determine dial corrections for their bone-conduction systems. We wish to emphasize that until the International Standards Organization has established bone-conduction norms for testing at the frontal bone and the mastoid process, rigorous calibration procedures (including testing of normal listeners) must be employed.

Rather than suggesting the abandonment of bone-conduction testing at the mastoid process, the results our current study indicate that the use of several diagnostic tests might be valuable in differentiating between various middle-ear impairments. Knowledge and technology in otology and audiology have reached a stage at which the description of conductive losses in the gross terms of loss should no longer be considered completely adequate. For cases in which the otologic examination and routine audiological evaluation fail to facilitate a precise differential diagnosis, additional audiological information can often be helpful. Along with other tests of middle-ear function (i.e., absolute and relative acoustic impedance), the difference between bone-conduction thresholds at the mastoid process and frontal bone should be considered a possible diagnostic tool.

ACKNOWLEDGMENTS

This investigation was supported by Public Health Service Research Grant No. NB 05883-03 from the National Institute of Neurological Diseases and Blindness and by the Hope for Hearing Research Foundation. The authors are indebted to Victor Goodhill and the resident doctors of the Head and Neck Surgery Department at UCLA.

REFERENCES

BARANY, E., A contribution to physiology of bone conduction. *Acta Otolaryng. (Stockholm)*, suppl. 26, 1-223 (1938).

BEKESY, G., Zur theorie des horens bei der schallaufnahme durch knochenleitung. *Ann. Physik*, **13**, 111-136 (1932).

CARHART, R., and JERGER, J., Preferred method for clinical determination of pure tone thresholds. *J. Speech Hearing Dis.*, **24**, 330-345 (1959).

DIRKS, D., Factors related to bone conduction reliability. *Arch. Otolaryng.*, **79**, 551-558 (1964).

DIRKS, D., MALMQUIST, C., and BOWER, D., Toward the specification of normal bone conduction threshold. *J. acoust. Soc. Amer.*, **43**, 1237-1242 (1968).

DIRKS, D., and SWINDEMAN, J., The variability of occluded and unoccluded bone conduction thresholds. *J. Speech Hearing Res.*, **10**, 232-249 (1967).

ELPERN, B., and NAUNTON, R., The stability of the occlusion effect. *Arch. Otolaryng.*, **77**, 376-384 (1963).

GROEN, J. J., The value of the Weber Test. Ch. 14 in H. F. Schuknecht (Ed.), *International Symposium on Otosclerosis.* Boston: Little Brown and Co. (1962).

HART, C., and NAUNTON, R., Frontal bone conduction tests in clinical audiometry. *Laryngoscope*, 71, 24-29 (1961).

HERER, G., A study of the effects of various forms of stapes surgery upon estimates of cochlear reserve. Unpublished doctoral dissertation, Northwestern Univ. (1964).

HODGSON, W., and TILLMAN, T., Reliability of bone conduction occlusion effects in normals. *J. Auditory Res.*, **6**, 141-151 (1966).

HOOD, J., The principles and practice of bone conduction audiometry; a review of the present position. *Proc. Royal Soc. Med.*, **50**, 689-697 (1957).

JERGER, J., and JERGER, S., Critical evaluation of SAL audiometry. *J. Speech Hearing Res.*, **8**, 103-125 (1965).

JERGER, J., and TILLMAN, T., A new method for the clinical determination of sensorineural acuity level (SAL). *Arch. Otolaryng.*, **71**, 948-953 (1960).

JERGER, J., VERVILLE, J., SHEA, J., and KINCHEN, K., Comparison of SAL and bone conduction audiometry in the prediction of gain from stapes surgery. *Acta Otolaryng.*, **60**, 467-478 (1965).

Kirikae, I., An experimental study on the fundamental mechanism of bone conduction. *Acta Otolaryng.* (Stockholm), suppl. 145, 1-111 (1959).

Link, R., and Zwislocki, J., Audiometrische knochenleitungsuntersuchungen. *Arch. Ohr Nas Kehlkopfheilk*, **160**, 347-357 (1951).

Lybarger, S., Special report-interim bone conduction thresholds for audiometry. *J. Speech Hearing Res.*, **9**, 483-487 (1966).

Naunton, R., and Fernandez, C., Prolonged bone conduction: observations on man and animals. *Laryngoscope*, **71**, 306-318 (1961).

Studebaker, G., Placement of vibrator in bone conduction testing. *J. Speech Hearing Res.*, **5**, 321-331 (1962).

Tillman, T., Clinical applicability of the SAL test. *Arch. Otolaryng.*, **78**, 36-48 (1963).

Tonndorf, J., Bone conduction studies in experimental animals. *Acta Otolaryng.* (Stockholm), suppl. 213, 1-132 (1966).

Weston, P., Gengel, R., and Hirsh, I., Effects of vibrator types and their placement on bone conduction threshold measurements. *J. acoust. Soc. Amer.*, **41**, 788-792 (1967).

Whittle, L., A determination of the normal threshold of hearing by bone conduction. *J. Sound Vibr.*, **2**, 227-248 (1965).

Received November 5, 1968.