Some hearing-impaired patients who need a hearing aid can be fitted only with a bone conduction hearing aid because of chronic draining ears or aural atresia. For many years, only the conventional bone conductor was available, which transmits the sound vibrations transcutaneously to the skull. This bone conductor has a number of drawbacks, such as variation in speech recognition, caused by variation in the pressure between the transducer and the mastoid, and the pressure of the transducer itself, which can cause various complaints, such as local pain, skin irritation, and headaches. These drawbacks have led to the development of new types, such as the Swedish percutaneous bone-anchored hearing aid (BAHA) and the temporal bone stimulator (TBS). These two devices are discussed in other articles by Tjellström and coworkers, and Hough and coworkers, respectively. The present paper discusses the application of the BAHA, with special attention to the audiologic and subjective results.

Since the introduction of the BAHA, several studies have been conducted to compare patients' performances with the BAHA and with a conventional hearing aid. In some studies, a standard BAHA and a standard conventional bone conductor were compared; in other studies, the patients' own BAHA and previous hearing aids were compared. To find out whether or not the BAHA is a success in daily practice, we followed the latter option, by comparing the subjective and objective results of the individually fitted BAHA and the previous hearing aid. Because it is important to know how many individuals benefited from the new hearing aid, the percentages of pa-
Patients who improved or deteriorated significantly on speech recognition tests are presented. Questionnaire results were evaluated in a comparable way.

PATIENTS

In the Nijmegen BAHA implantation program, only patients who fulfilled the following selection criteria were eligible for participation: (1) a minimum age of 10 years; (2) bilateral conductive or mixed hearing loss with a total hearing loss of at least 30 dB hearing level (HL) in the better ear at 0.5, 1, and 2 kHz; and (3) a sensorineural hearing loss component that did not exceed 65 dB HL. Furthermore, in all patients surgery was not an option, and a conventional bone conductor had been used and rejected because of pain or skin irritation owing to the pressure of the bone conduction transducer or because of serious problems with the appearance of this often disfiguring device.

According to the criteria, several patients with a sensorineural hearing loss component exceeding 40 dB HL were fitted with a BAHA. These patients were considered borderline cases or had been rejected for the application of a conventional bone conductor. Some improvement was expected in these patients, because it has been found that the percutaneous coupling, instead of the conventional transcutaneous coupling, leads to more efficient stimulation of the cochlea.8

All patients but 1 who were fitted with a BAHA between 1988 and the middle of 1992 participated in the study (n = 65). Some characteristics of the patient group are presented in Table 1. In all patients, the BAHA was applied monaurally. One patient rejected the BAHA because he experienced unexplained pain at the implant site (only) when applying the BAHA; on his request, the percutaneous abutment was removed. All the remaining 64 patients except for 1 were using the BAHA on a daily basis (see later). Forty-six patients were fitted with the standard BAHA HC-200.7,22 They had a normal or moderately impaired inner ear function, as expressed by the average bone conduction thresholds at 0.5, 1, and 2 kHz (PTAbc). Eighteen patients had more severe inner ear impairment (PTAbc from 33 to 63 dB HL) and were fitted with the more powerful BAHA HC-220.7 22 All of the patients had used a hearing aid prior to the fitting of the BAHA; 48 patients had used a conventional bone conductor, and 16 patients air conduction hearing aids.

The follow-up varied from 18 to 68 months (cumulative 3600 months). During this time, four implanted fixtures were lost because of trauma (n = 2) or infection (n = 2). In 3 of the 4 patients, the fixtures were replaced, and the

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Total Group</th>
<th>HC200 Users</th>
<th>HC220 Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>64</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td>Median age in years (range)</td>
<td>48 (10–77)</td>
<td>45 (10–70)</td>
<td>59 (32–77)</td>
</tr>
<tr>
<td>Median PTAac in dB HL (range)*</td>
<td>62 (30–105)</td>
<td>56 (30–92)</td>
<td>85 (57–105)</td>
</tr>
<tr>
<td>Median PTAbc in dB HL (range)*</td>
<td>25 (1–64)</td>
<td>20 (1–41)</td>
<td>47 (33–64)</td>
</tr>
<tr>
<td>History of Draining ears (%)</td>
<td>91</td>
<td>87</td>
<td>100</td>
</tr>
<tr>
<td>Aural atresia (%)</td>
<td>9</td>
<td>13</td>
<td>0</td>
</tr>
</tbody>
</table>

*PTA, average hearing threshold at 0.5, 1, and 2 kHz; ac, air conduction; bc, bone conduction.
replacements have been in use for at least 15 months without any further problems. In the remaining patient, the fixture was not replaced because of feelings of pain ascribed by the patient to the implant; she resumed using the conventional bone conductor. The two patients who lost a fixture because of an infection were resident pupils of the same institute for hearing-impaired children, and the lack of appropriate care for the skin around the implant at the institute could have been a significant factor in the loss. In accordance with other studies, we concluded that the percutaneous implant to which the BAHA is coupled is a stable implant.

**METHODS**

Free-field aided thresholds as well as speech recognition in quiet and in noise were determined in order to make a comparison between the patients’ performances with their individually fitted BAHA and their previous hearing aids. The tests and the measurement protocol have been described in detail elsewhere. Aided thresholds were obtained at the frequencies 0.25, 0.5, 1, 2, 4, and 8 kHz.

To measure speech recognition in quiet, the free-field phoneme recognition score was obtained using monosyllables presented at a level of 60 dB (comfortable listening level for subjects with normal hearing) (PS60). If the PS60 was below 100%, phoneme scores were also obtained at 70 and 80 dB, or even at 90 dB. The maximum phoneme score (MPS) was used in the analysis as well as the PS60. If the MPS or the PS60 of a patient obtained with the previous hearing aid differed from that with the BAHA, the significance of the difference was tested. The percentage of patients whose MPS or PS60 improved or deteriorated significantly using the BAHA is presented in Table 3.

To measure speech recognition in noise, we used the sentence recognition test described by Plomp and Mimpen. This test determines sentence recognition in steady-state, speech-shaped noise of 65 dB(A). The speech reception threshold of the sentences is established with an adaptive procedure and called the speech-in-noise score (SNS). For each patient, the difference in the SNS between the BAHA and the previous hearing aid was tested for significance. The percentage of patients who improved or deteriorated significantly with the BAHA is presented in Table 3. Five patients with severe inner ear impairment found this test too difficult, so it was discontinued.

An important advantage of both the MPS and SNS is that, in principle, they are independent of the volume setting (gain level) of the hearing aids. The PS60, however, depends directly on the gain level.

Data on the patients’ opinions about their previous hearing aid and the BAHA were gathered by means of a questionnaire that was filled out twice, the first time to determine evaluation of the previous hearing aid before surgery and the second time, of the BAHA 5 months after it had been fitted. The questions concerned speech recognition in quiet (five subquestions) and in noisy situations (nine subquestions). The patients were asked to rate their answers to the relevant subquestions on a scale from 1 to 10. The average score of the subquestions was calculated, and the percentages of patients who preferred the BAHA or the conventional hearing aid in quiet and in noisy surroundings were derived.
THE GAIN PROVIDED BY THE HEARING AIDS

Patients Who Previously Used a Bone Conductor

To study the amount of amplification or "gain" of the conventional and the new bone conductor, aided free-field thresholds were derived with each device separately. Because it is the patient who controls the gain by using the volume wheel, it was expected that the aided thresholds with the two devices would be the same on average. Table 2 shows the average difference in aided thresholds between the BAHA and the conventional bone conductor (CBHA) averaged at all test frequencies. Surprisingly, the average value was significantly negative for both subgroups (Student t test). This means that the BAHA was worn at a relatively higher gain level than the previous bone conductor. Figure 1 depicts the results of a similar evaluation, but now for each of the six test frequencies separately. Significant improvements in the frequency range from 0.5 to 8 kHz were found in the group of patients who were using the BAHA HC-200. For the group of patients using the BAHA HC-220, nonsignificant improvements were found.

In Table 2, the change in the speech recognition score at 60 dB presentation level (PS60) is also presented. As stated before, this measure depends directly on the gain level of the hearing aids (see "Methods"). Therefore, it was not surprising that these scores also improved significantly. This result suggests that on average, these patients benefited significantly from the change in the type of bone conduction device that was caused by a relatively higher gain level. The reason they were using the BAHA at a relatively higher gain level is discussed later.

Figure 2 presents the individual aided threshold (average value at the most important frequencies for speech recognition: 0.5, 1, and 2 kHz) as a function of the sensorineural hearing loss component. It should be noted that the aided thresholds are expressed in dB HL. Only the results obtained with the BAHA are shown. Furthermore, the 45-degree line is shown: if the average aided threshold for a given patient is on this line, the patient was using the BAHA to compensate for the (total) air-bone gap; if the average aided threshold is below the 45-degree line, the patient was also using the hearing aid to compensate (partly) for the sensorineural hearing loss component. A second, dotted line is

Table 2. THE CHANGE IN AIDED THRESHOLDS AND PHONEME SCORE (PS60) WITH BONE-ANCHORED (BAHA) AND CONVENTIONAL (CHA) HEARING AIDS

<table>
<thead>
<tr>
<th>Patient Subgroup*</th>
<th>Aided Threshold†: BAHA−CHA (dB)</th>
<th>PS60‡: BAHA−CHA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>CBHA/HC-200</td>
<td>5.8</td>
<td>5.6</td>
</tr>
<tr>
<td>ACHA/HC-200</td>
<td>1.7</td>
<td>5.4</td>
</tr>
<tr>
<td>CBHA/HC-220</td>
<td>6.2</td>
<td>8.8</td>
</tr>
<tr>
<td>ACHA/HC-220</td>
<td>5.1</td>
<td>8.9</td>
</tr>
</tbody>
</table>

*CBHA, conventional bone conduction hearing aid; ACHA, air conduction hearing aid.
†BAHA threshold minus the CHA threshold averaged over the six test frequencies.
‡Phoneme score at a presentation level of 60 dB. BAHA score minus the CHA score.
\(P<0.05\).
\(\delta P<0.01\).
\(\ddagger P<0.001\).
Figure 1. The difference in aided thresholds (BAHA thresholds minus the threshold obtained with the previous bone conductor [CBHA]) as a function of frequency averaged over the patients with a BAHA HC200 and, separately, over those with a HC220. Standard deviations (+1 SD) are indicated. Only the mean values at 0.5, 1, 2, 4, and 8 kHz for the group of patients with the BAHA HC200 were significantly different from zero (Student t-test, P<0.05).

drawn to indicate half of the sensorineural hearing loss component; it is generally acknowledged that the amount of amplification in patients with pure sensorineural hearing loss should be about half the hearing loss.\(^2\)\(^1\)\(^8\) Therefore, in general, this line can be considered the target line for aided thresholds.

Surprisingly, the majority of the patients with normal inner ear function or a minor inner ear dysfunction (up to 30 dB HL sensorineural hearing loss) were using their BAHA to compensate only partly for the air-bone gap. Several of the patients with more severe inner ear impairment used the BAHA in a similar way. Only two of these patients were using the BAHA at a gain level high enough to result in aided thresholds near to the target line. The effect of the relatively high (unfavorable) aided thresholds is illustrated in Figure 3, which relates the PS60 obtained with the BAHA to the sensorineural hearing loss component; an evident decrease in the score is seen with increasing hearing loss.

Two questions therefore remain: Why do the patients use the BAHA at a relatively higher gain level than they used the previous bone conductor? and Why do they use both types of hearing aid at such poor (absolute) gain levels? In answer to the first question, according to the patients, the relatively higher gain level when using the BAHA is due to the fact that the sound quality remains good at higher gain settings. In technical terms, this can be explained by the more efficient way of transmitting the sound vibrations to the skull. Therefore, the BAHA can be used at a relatively higher gain level than conventional bone conductors without saturation of the hearing aid amplifier. With
regard to the second question, the main reason for the poor absolute gain levels, even with the BAHA, is also most likely the saturation or headroom problem.\textsuperscript{17,20} Saturation occurs when the amplified signal exceeds the capability of the amplifier, resulting in clipping and consequent distortion of the signal. The patient can resolve this problem by reducing the gain. In general, because of the (very) inefficient stimulation mode, bone conductors are provided with powerful amplifiers. Nevertheless, saturation seems to be a limiting factor,\textsuperscript{19} even for the new types of bone conductors.\textsuperscript{6,20} Therefore, there is still a need for even more powerful bone conductors. This need is emphasized by Figure 3. Apart from confusing factors, such as neural presbycusis or steeply sloping audiograms, speech recognition of words in quiet by patients with sensorineural hearing loss up to 50 to 60 dB HL who have been successfully fitted with hearing aids has to be close to 100%. The fact that many of the current patients do not even approach the 100% score may be caused by the confusion factors mentioned but also by a too-low volume setting chosen by the patient to prevent poor sound quality due to saturation of the hearing aid.

**Figure 2.** Individual aided thresholds (average aided threshold at 0.5, 1, and 2 kHz) obtained with the BAHA as a function of the average sensorineural hearing loss component at these frequencies. The broken line represents the 45 degree line, the dotted line represents half of the sensorineural hearing loss. Different symbols refer to different subgroups.

Patients Who Previously Used Air Conduction Hearing Aids

For the patients who previously used air conduction hearing aids (ACHAs), the differences in aided thresholds and in the PS60 between the BAHA and the previous hearing aid, as presented in Table 2, were negative (on average,
better thresholds with the BAHA) but nonsignificantly different from zero. The individual average aided free-field thresholds and PS60 values with the BAHA as a function of the sensorineural hearing loss component for this subgroup (see Figs. 2 and 3) shows that the conclusions about the lack of sufficient gain for the patients who previously used a bone conductor also applies to this subgroup.

**SPEECH RECOGNITION, SUBJECTIVELY AND OBJECTIVELY EVALUATED**

In the following section, the PS60 values, the MPS and SNS values (which are in principle independent of the volume setting), and the scores on the questions concerning speech recognition in quiet (SIQ) and in noisy surroundings (SIN) will be discussed. The average change (score with the BAHA minus that with the previous hearing aid averaged for all the patients) as well as the number of patients who significantly improved or worsened their score with the BAHA are presented. Additionally, the average change in SIQ and SIN is presented as well as the number of patients who, according to these questionnaire scores, prefer either their BAHA or their former hearing aid. The results of the subgroups of patients who previously used bone conductors and those who used air conduction hearing aids will be presented separately.
Patients Who Previously Used a Bone Conductor

The average change in the PS60, MPS, and SNS, and the questionnaire scores SIQ and SIN for the subgroup of patients who previously used a bone conductor are presented in Table 3. (According to Plomp and Mimpen,\textsuperscript{8} the SNS values are expressed in percentage sentence recognition instead of dB.) Positive values were found for all five measures, which means that on average, the score with the BAHA was better. The average change for all five measures was significantly different from zero (Student t-test, \( P<0.001 \)). On an individual level (Table 3, second and third rows), it is seen that none of the patients had a significantly poorer score with the BAHA on either the PS60, MPS, or SNS. The MPS improved in a minority of the patients: Several of the patients had an MPS of 100\% with both of the hearing aids (ceiling effects). For the SNS, it can be seen that almost two thirds of the patients improved performance significantly with the BAHA. The subjective opinion of the majority of these patients regarding speech recognition in quiet surroundings was that it had improved with the BAHA, whereas 10\% of the patients felt it had deteriorated. For the speech recognition in noisy situations, a comparable result was observed. The average improvement was 1.7 points on a scale from 1 to 10. The improvements of the patients with normal cochlear function or mild dysfunction and those with more severe inner ear impairment were comparable, which means that the patients benefit to approximately the same extent, irrespective of the size of the sensorineural hearing loss component.

In a separate experiment, we retested nine nonselected patients using a standard BAHA HC-200 and a standard conventional bone conductor (Philips S1594 with Oticon transducer).\textsuperscript{14} The improvements observed in the MPS and SNS and the improvements obtained with the individually fitted BAHA and previous conventional bone conductor were comparable. This means that the improvements found cannot be ascribed solely to the quality of the individual fittings, but are at least in part due to the BAHA itself.

Table 3. AVERAGE CHANGES (± S.D.) AND THE PERCENTAGE OF PATIENTS WITH A SIGNIFICANT IMPROVEMENT OR DETERIORATION ON PHONEME RECOGNITION, SPEECH-IN-NOISE, AND SUBJECTIVE REPORTS ON SPEECH RECOGNITION IN QUIET AND NOISY SURROUNDINGS

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Previous Users of Bone Conductors</th>
<th>Previous Users of Air-conduction Hearing Aids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Change</td>
<td>% With Better BAHA Score</td>
</tr>
<tr>
<td>Phoneme recognition at 60-dB presentation level*</td>
<td>15 ± 16</td>
<td>52</td>
</tr>
<tr>
<td>Maximum phoneme score*</td>
<td>5 ± 8</td>
<td>30</td>
</tr>
<tr>
<td>Speech-in-noise score (% sentence recognition)</td>
<td>41 ± 31</td>
<td>64</td>
</tr>
<tr>
<td>Speech recognition in quiet (subjective report)</td>
<td>1.5 ± 1.6</td>
<td>74</td>
</tr>
<tr>
<td>Speech recognition in noise (subjective report)</td>
<td>1.7 ± 1.6</td>
<td>76</td>
</tr>
</tbody>
</table>

\*Percentage of phoneme recognition.
Patients Who Previously Used Air Conduction Hearing Aids

The average change on the five speech recognition measures, as listed in Table 3, fourth column, were tested for significance. The average changes were nonsignificantly different from zero, except for the SNS (t = 2.63, P<0.05). On an individual level (Table 3, fifth and sixth columns), it is seen that in the majority of patients, neither an improvement nor a deterioration in PS60 and MPS was present. On the other hand, the SNS in the majority of the patients improved. The subjective results reported in the questionnaire were poorer than those of the patients who had previously used a bone conductor; about one third of the patients preferred their air conduction hearing aid(s), and about half preferred the BAHA. The differences between the objective and subjective speech recognition in noise scores (SNS versus SIN) may have partly been caused by the fact that the BAHA was applied monaurally, whereas the air conduction hearing aids were fitted binaurally in most cases.

CONCLUDING REMARKS

In general, the patients who previously used a bone conductor preferred the BAHA, and the audiologic results (MPS, PS60, SNS) with the BAHA were obviously better. Results were similar for the patients who were using the BAHA HC-200 by the Gothenburg group and may be ascribed to the higher efficiency of the BAHA and, consequently, better sound quality. With the BAHA, relatively higher gain levels were chosen by the patients, which caused the superior PS60 values with the BAHA. When the influence of the relatively higher gain level was leveled out by using the MPS and SNS, better results were still found with the BAHA. This may be ascribed to less harmonic distortion, as was shown in a previous paper, and to better performance of the BAHA in the frequency range above 0.5 kHz, which is important for speech reception, than in the low frequencies.

Concerning the BAHA HC-220, no other studies are known; therefore, the present results cannot be compared with those reported by other studies.

Figure 3 shows poor PS60 values for patients with a sensorineural component exceeding 25 dB HL. The fact that on average, the conventional bone conductor provides even less gain (see Table 1) means that a similar evaluation for conventional bone conductors would have been even poorer. The figure suggests that the more powerful BAHA HC-220 should be fitted more often, even in patients with a sensorineural hearing loss component of 30 dB HL or even less. Furthermore, BAHAs with a higher output (which will need a more rigid coupling of the transducer to the implant) would most likely improve the rewarding results reported so far.

For the patients who previously used air conduction hearing aids, the results were ambiguous, as has been found by others. This does not mean that an air conduction hearing aid should still be the first choice; it should be realized that these patients were advised not to use their air conduction hearing aid any longer because of chronic draining ears that did not react sufficiently to medical treatment. In view of the overall better results of the BAHA compared with a conventional bone conductor, the BAHA seems to be the best available solution for this patient group, too. The patients should be informed beforehand, however, that speech recognition may be poorer than with their air conduction hearing aids. If the patients have been using binaural hearing aids, the possible imbalance owing to the monaural application of a BAHA should also be dis-
cussed beforehand. In our view, it is always essential to introduce the patient to a conventional bone conductor for at least a 4-week trial period prior to the application of a BAHA, to help shape his or her expectations.

To conclude, the BAHA is more than an alternative to the conventional bone conductor. Especially for patients with a more severe sensorineural hearing loss component, the benefit of the BAHA type HC-220 is unique. Therefore, in our view, the BAHA must be considered a valuable addition to the audiologists' tools.

SUMMARY

The bone-anchored hearing aid (BAHA) was evaluated in 65 patients by comparing speech recognition and questionnaire results with those obtained with the patients' own previous hearing aids. In the majority of patients who previously used a conventional bone conductor, significantly improved speech recognition scores were found with the BAHA. The majority preferred the BAHA to their previous bone conductors. For the patients who previously used air conduction hearing aids but had to stop because of chronic draining ears, the results were ambiguous. Nevertheless, the BAHA seems to be the best solution for this subgroup as well. It is concluded that the BAHA is a valuable addition to the audiologists' tools.

References


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