Hearing Performance Benefits of a Programmable Power Baha® Sound Processor with a Directional Microphone for Patients with a Mixed Hearing Loss

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INTRODUCTION

The requirement of patients with a mixed hearing loss for a more powerful bone conduction sound processor have been well documented (1, 2). A report by Bosman et al. (1) identified benefits of the Intenso sound processor for patients with mixed hearing loss. The Intenso was found to support an increased fitting range, while providing a sufficient dynamic range to ensure adequate

Objectives. New signal processing technologies have recently become available for Baha® sound processors. These technologies have led to an increase in power and to the implementation of directional microphones. For any new technology, it is important to evaluate the degree of benefit under different listening situations.

Methods. Twenty wearers of the Baha osseointegrated hearing system participated in the investigation. The control sound processor was the Baha Intenso and the test sound processor was the Cochlear™ Baha BP110power. Performance was evaluated in terms of free-field audibility with narrow band noise stimuli. Speech recognition of monosyllabic phonetically balanced (PB) words in quiet was performed at three intensity settings (50, 65, and 80 dB sound pressure level [SPL]) with materials presented at 0 degrees azimuth. Speech recognition of sentences in noise using the Hearing in Noise Test (HINT) in an adaptive framework was performed with speech from 0 degrees and noise held constant at 65 dB SPL from 180 degrees. Testing was performed in both the omni and directional microphone settings. Loudness growth was assessed in randomly presented 10 dB steps between 30 and 90 dB SPL to narrow band noise stimuli at 500 Hz and 3,000 Hz.

Results. The test sound processor had significantly improved high frequency audibility (3,000-8,000 Hz). Speech recognition of PB words in quiet at three different intensity levels (50, 65, and 80 dB SPL) indicated a significant difference in terms of level ($P<0.0001$) but not for sound processor type ($P>0.05$). Speech recognition of sentences in noise demonstrated a 2.5 dB signal-to-noise ratio (SNR) improvement in performance for the test sound processor. The directional microphone provided an additional 2.3 dB SNR improvement in speech recognition ($P<0.0001$). Loudness growth functions demonstrated similar performance, indicating that both sound processors had sufficient headroom and amplification for the required hearing loss.

Conclusion. The test sound processor demonstrated significant improvements in the most challenging listening situation (speech recognition in noise). The implementation of a directional microphone demonstrated a further potential improvement in hearing performance. Both the control and test sound processors demonstrated good performance in terms of audibility, word recognition in quiet and loudness growth.

Key Words. Baha, Bone conduction, Hearing implant, Osseointegration, Sensory aids, Hearing aids, Directional microphones, Hearing in noise, Speech recognition
audibility across numerous input levels. For patients with mixed hearing loss, a number of authors have compared the performance of the Intenso sound processor with that of hearing aids (3, 4). The studies highlighted the relationship between the degree of cochlea loss and the size of the air-bone gap. As both of these factors increase, hearing-aid performance decreases significantly to a point where the Baha® processor provides better audibility. Importantly, the size of the air-bone gap does not affect Baha’s performance because the conductive component of the hearing loss is effectively bypassed. Therefore, when considering the best amplification option, a high power Baha sound processor may provide improved hearing outcomes when compared to hearing aids for patients with a large air-bone gap. De Wolf et al. (4) urged Baha system developers to improve signal processing and the fitting process so that it would be more comparable to the latest generation of hearing aids.

Consistent with that view, a number of reports have discussed the benefits in terms of hearing performance received from newer multiple-channel non-linear Baha sound processors (5-8). Additionally, with these systems, amplification targets are prescribed through the dedicated fitting software, rather than through trim pots, where the frequency response is adjusted to the patient’s hearing loss configuration. These latest generation of sound processors have advanced signal processing technologies such as automatic adaptive directional microphones. Recently, a sound processor combining increased gain and output built on the same DSP technology has become available for patients with a mixed hearing loss.

Given this significant development in sound processor technology for people with a mixed hearing loss (up to 55 dB sensorineural hearing loss [SNHL]), it is important that this technology is evaluated to determine whether these mechanical and signal processing technologies increase hearing performance for this population. To determine the degree of benefit provided, an evaluation was performed to investigate potential performance improvements of the Cochlear™ Baha® BP110 power sound processor (Cochlear Bone Anchored Solutions AB, Gothenburg, Sweden). For comparison, the Baha Intenso was selected as the control device because it represents the current generation of Baha sound processors for the equivalent fitting range.

### Table 1. Demographic data describing the attributes of the 20 participants and preferred volume control settings for Intenso

| ID | Gender | Age (year) | Own device | Baha side | Type of HL | 4 frequency BC PTA | Preferred Intenso VC setting (dB/HL) |
|----|--------|-----------|------------|-----------|------------|---------------------|-------------------------------------|
| 1  | M      | 65        | Compact    | Left      | Mixed     | 29                  | 2                                   |
| 2  | F      | 74        | Intenso    | Right     | Mixed     | 31                  | 2                                   |
| 3  | M      | 55        | Compact    | Right     | Mixed     | 43                  | 1.5                                 |
| 4  | M      | 70        | Intenso    | Left      | Mixed     | 31                  | 2.5                                 |
| 5  | F      | 70        | Compact    | Left      | Mixed     | 44                  | 1.5                                 |
| 6  | M      | 79        | Intenso    | Right     | Mixed     | 26                  | 2                                   |
| 7  | M      | 72        | Intenso    | Right     | Mixed     | 33                  | 2                                   |
| 8  | F      | 63        | Compact    | Right     | Mixed     | 15                  | 2                                   |
| 9  | F      | 73        | Intenso    | Right     | Mixed     | 34                  | 2.5                                 |
| 10 | F      | 66        | Divino     | Right     | Mixed     | 43                  | 2.3                                 |
| 11 | M      | 63        | Divino     | Right     | Mixed     | 30                  | 2.5                                 |
| 12 | F      | 74        | Compact    | Right     | Mixed     | 31                  | 1.5                                 |
| 13 | F      | 72        | Intenso    | Left      | Mixed     | 51                  | 1.8                                 |
| 14 | M      | 65        | Intenso    | Left      | Mixed     | 36                  | 1                                   |
| 15 | M      | 66        | Compact    | Right     | Mixed     | 36                  | 1.9                                 |
| 16 | F      | 63        | Intenso    | Right     | Mixed     | 40                  | 2.5                                 |
| 17 | M      | 60        | Divino     | Left      | Mixed     | 19                  | 2                                   |
| 18 | F      | 74        | Classic    | Left      | Mixed     | 30                  | 1.3                                 |
| 19 | F      | 55        | Divino     | Right     | Mixed     | 53                  | 2                                   |
| 20 | F      | 75        | Classic    | Right     | Mixed     | 35                  | 1.5                                 |

HL, hearing level; BC, bone conduction; PTA, pure tone average; VC, volume control.

*Average of 500, 1,000, 2,000, and 3,000 Hz bone conduction audiometric thresholds.

**Fig. 1.** Mean bone conduction and air conduction thresholds for the study participants demonstrating the mixed hearing loss. The shaded area highlights one standard deviation of the mean.

**MATERIALS AND METHODS**

**Subjects**
In total, 20 adults with skin penetrating titanium implants for standard attachment of a Baha sound processor participated in this study (Table 1). A total of 21 subjects were originally enrolled, but one was withdrawn for not meeting the inclusion criteria of measurable open-set sentence recognition in noise with the control sound processor (Intenso). All subjects had a mixed hearing loss, defined as bone conduction thresholds (PTA, 500, 1000, 2000, and 3000 Hz), between 15 and 55 dBHL with at least a 10 dB air/bone gap. The average bone conduction and air...
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the sound processor volume control setting in program 1 to
guide for professionals (13) were followed. The patients adjusted the
sound processors as the purpose of the study was to investigate
what clinical differences in hearing performance might be ex
pected for each sound processor.

A sub-analysis comparing the comparative performance between
subjects 1-10 and 11-20 demonstrated no significant differences
across the test measures (P > 0.05). Fig. 2 compares and full-on-
gain of the Intenso and BP110power. The BP110power was de
signed to have a higher possible full-on-gain than the Intenso,
which should be considered in any evaluation of performance. The
gain and maximum output was not matched between the
sound processors as the purpose of the study was to investigate
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pected for each sound processor.

The control sound processor was fitted as it would be fitted in
a clinical situation. The procedures outlined in the Baha fitting
guide for professionals (13) were followed. The patients adjusted
the sound processor volume control setting in program 1 to
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ing situations. Once the preferred level was set, this setting was

Fig. 2. Comparison of the maximum gain between the control and
test sound processors. Due to improved design and feedback, the
available gain in the test sound processor is higher across the mid
frequencies by approximately 5 dB.

Procedures
All measurements were conducted in a sound-insulated room
meeting ANSI standards for maximum permissible noise levels
(ANSI S3.1-1999). Audiometric evaluation consisting of air and
bone conduction testing was performed in accordance with ANSI
S3.21 in a sound-insulated test room using a Madsen Conera
Audiometer. All procedures were randomized between sound
processors to control for learning and/or procedural effects. For
comparison purposes, bone conduction thresholds were obtained
at 500, 1,000, 2,000, 3,000, and 4,000 Hz with narrow-band
noise applied via air conduction to the contra-lateral ear when
necessary. Measurement of free-field audibility was collected via
loudspeakers placed approximately one meter from the partici-

T echnical verification confirmed that the prototype sound proces-
sors were equivalent to the commercially available BP110power
(10-12). The PS1 and PS2 prototypes were equivalent in terms
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used for all test measurements. All settings were confirmed to
be free from acoustic feedback. Table 1 details the volume con-
trol settings used by the participants. The test sound processor
was fitted using the Baha Fitting Software ver. 2.0. The Client,
Indication and Connection type were configured using the BC
Select step. This enables the hearing care professional to quickly
set up the sound processor and incorporates the latest research
data on corrections for transcranial attenuation, cross hearing,
and transmission loss through the skin (7, 14). The final gain set-
tings were based on the measurement of actual thresholds
through the BC Direct function of the fitting software (15). The
patients were not allowed to adjust the volume control setting
during the test procedures.

Instruments
Two sound processors were compared. The Baha Intenso was
the control device and the Cochlear Baha BP110power was the
test sound processor. It should be noted that the current study
was performed with manufacturing prototypes PS1 and PS2, as
the study took place before the BP110power was CE marked.
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To evaluate speech recognition in quiet surroundings, mono-
syllabic phonetically balanced (PB) words were used (16-18).
Briefly, the test includes 12 monosyllabic phonemically balanced
word lists. Each list includes 50 words within carrier phrases. The
test was performed at 50, 65, and 80 dB sound pressure level
(SPL) and scores were recorded as the number of correct words
per list.

Speech recognition in noisy surroundings was conducted us-
ing the Swedish version of the Hearing in Noise Test (HINT) (19).
Speech was presented from the front loud-speaker (0 degrees)
with noise from the rear loud-speaker (180 degrees). The noise
level was kept constant at 65 dB SPL and the level of the speech
was adapted in 2 dB steps to provide a 50% level of under-
standing. For the comparisons, the sound processors’ signal processing
was fixed in the omni-directional mode. To compare speech-un-
derstanding performance in the omni versus directional micro-
phone mode, the sound processor was fixed in each mode prior
to testing. In all measures of speech recognition in noise, the
sound processor’s noise management system was disabled to en-
sure equivalence.

Measurement of loudness growth was conducted using narrow
band noise (1/3 octave) presented with a centre frequency at 500 Hz or 3,000 Hz. The presentation level was randomly varied in 10 dB steps between 30 dB SPL and 90 dB SPL. Participants were asked to respond using a 7-point visual analogue scale ranging between very soft and very loud (1, 20).

RESULTS

Audibility
Free-field audibility demonstrated that the test sound processor provided significantly (*) improved audibility from 3,000-8,000 Hz (Fig. 3). This is most likely related to two factors. First, the Cochlear Baha Prescription (CBP) specifically increases the amplification in the high frequencies to match the sloping hearing loss which is common in people with a mixed hearing loss. Since the control sound processor was fitted with-out fitting software, it can only increase the overall gain and not specifically match the hearing loss. Second, the test sound processor was designed to reduce the occurrence of internal feedback, making more gain available before feedback occurs.

Speech recognition in quiet situations
Speech recognition performance in quiet surroundings (Fig. 4) showed a small (4-5%) but not significant (F[1,19]=1.83, P > 0.05) improvement in speech recognition at 50 dB SPL and 65 dB SPL for the test sound processor. It is likely that for the presentation at 80 dB SPL, there was a ceiling effect since performance was above 97% for both conditions. There was, as expected, a significant improvement for each increase in presentation level (F[2,19]=286.93, P<0.0001). Importantly, this result demonstrates the benefit of the Baha solution as an intervention for people with mixed hearing loss in that it can provide open-set performance of more than 80% speech recognition at normal conversational levels without visual, grammatical or contextual cues.

Speech recognition in noisy situations
The test sound processor recorded on average a 2.5 dB improvement (and microphone mode fixed to omni-directional) in terms of signal-to-noise ratio (SNR) improvement (Fig. 5). To determine statistical significance, an ANOVA was performed (F[1,19]=26.25, P<0.0001) and indicated that performance was significantly better with the test sound processor than with the control sound processor. Importantly, each subject in the study had better speech recognition scores with the test than control sound processor. Performance comparison of the omni and directional microphone modes for the test sound processor indicated a significant benefit (F[1,19]=60.49, P<0.0001) of 2.3 dB (Fig. 5). Combined, in the most difficult listening situations, this provides an average improvement of 4.8 dB SNR over the control sound processor.

Loudness growth
Measurements of loudness growth at 500 Hz and 3,000 Hz are presented in Figs. 6, 7. Both Baha sound processors performed similarly and displayed a good dynamic range between very soft and very loud. That the average value at both 500 Hz and 3,000 Hz was below 7/7 (“very loud”) may indicate that for most participants the Maximum Power Output (MPO) of the Baha sound processor is often below the patient’s uncomfortable loudness level.
DISCUSSION

The present study clearly demonstrates the improved listening performance that the test sound processor (BP110power) provides for people with mixed hearing loss in challenging situations. The study demonstrates that the latest signal processing provides increased access to high frequency sounds. Importantly, a large and clinically significant improvement in speech recognition in noise was observed. The addition of an automatic directional microphone in the test sound processor showed a further 2.3 dB advantage in speech recognition in noise (P<0.0001). Error bars indicate one standard error. Better performance is indicated by 50% performance in a poorer SNR.

In their review of the Intenso, Bosman et al. (1) proposed that the next generation of power sound processors should have improved feedback performance, directional microphones and flexible fitting parameters. To address feedback issues, the BP110power has a new mechanical design where the transducer is physically isolated from the microphones to reduce internal sound transmission. This innovation has resulted in the potential for a significant increase in the available high frequency gain before feedback. Additionally, the newly patented transducer design, utilizing high-density transducer materials with Dynamic Output Stabilization, enables more powerful output and flatter frequency response to further enhance sound quality.

The addition of fitting software for patients with mixed hearing loss, where it can be hypothesized that there is more slope to the cochlear hearing loss, is invaluable. The gain and MPO were adjusted across the test sound processor’s 12 channels to match the patient’s hearing loss profile. It is interesting that a number of the patients with the control sound processor, despite, having on average, a large hearing loss, did not use the full volume control setting. It may be hypothesized that this is due to the sloping nature of the hearing loss and the participants setting the preferred volume control setting based on the perceived loudness in their area of best hearing acuity. Therefore, the ability to match the amplification to the hearing loss is invaluable. The audiometric results indicated that this enabled increased high-frequency amplification, leading to potentially enhanced communication performance.

In summary, the BP110power sound processor provides significant advantages in terms of supra-threshold audibility and speech recognition in noise when compared with previous gold standard sound processor such as the Baha Intenso. Loudness growth data indicate the effectiveness of prescribing amplification for this population. Furthermore, the directional microphone, available for the first time in a power processor, provides an additional increase in speech intelligibility in noisy surroundings and a reduction in listening effort.

CONFLICT OF INTEREST

All authors are employees of Cochlear Bone Anchored Solutions AB.
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