Influence of Loudness Compression on Hearing with Bone Anchored Hearing Implants

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***Abstract*—**Bone Anchored Hearing Implants (BAHI) are routinely used in patients with conductive or mixed hearing loss, e.g. if conventional air conduction hearing aids cannot be used. New sound processors and new fitting software now allow the adjustment of parameters such as loudness compression ratios or maximum power output separately. Today it is unclear, how the choice of these parameters influences aided speech understanding in BAHI users.

In this prospective experimental study, the effect of varying the compression ratio and lowering the maximum power output in a BAHI were investigated.

Twelve experienced adult subjects with a mixed hearing loss participated in this study. Four different compression ratios (1.0; 1.3; 1.6; 2.0) were tested along with two different maximum power output settings, resulting in a total of eight different programs. Each participant tested each program during two weeks. A blinded Latin square design was used to minimize bias.

For each of the eight programs, speech understanding in quiet and in noise was assessed. For speech in quiet, the Freiburg number test and the Freiburg monosyllabic word test at 50, 65, and 80 dB SPL were used. For speech in noise, the Oldenburg sentence test was administered.

Speech understanding in quiet and in noise was improved significantly in the aided condition in any program, when compared to the unaided condition. However, no significant differences were found between any of the eight programs. In contrast, on a subjective level there was a significant preference for medium compression ratios of 1.3 to 1.6 and higher maximum power output.

***Keywords*—**Bone Anchored Hearing Implant, Compression, Maximum Power Output, Speech understanding.

I. Introduction

APPROXIMATLY 10% of the population in industrialized countries suffer from a substantial hearing loss [1], [2]. Depending on the aetiology and degree of the hearing loss, several therapeutic options are open. The most common therapy are conventional or air conduction hearing aids, where the incoming sound is amplified, processed according to the hearing loss of the user and emitted through a miniature speaker into the external auditory canal.

A different therapeutic option is the use of a Bone Anchored Hearing Implant system (BAHI). A BAHI consists of a percutaneous, osseointegrated titanium implant placed behind the ear and an externally worn sound processor, which can be attached and removed by the user (Fig. 1). In these systems, sound is transmitted directly through the implant to the skull and ultimately to the inner ear (bone conduction) and not through the external auditory canal. BAHIs are used for patients who cannot use conventional hearing or who do not obtain a sufficient benefit from conventional hearing aids due to e.g. a missing auditory canal (atresia), other malformations, draining ears, chronic ear infections, or other forms of conductive hearing loss. BAHIs have been shown repeatedly to improve hearing, speech understanding and the quality of life of the users substantially [3]–[8].

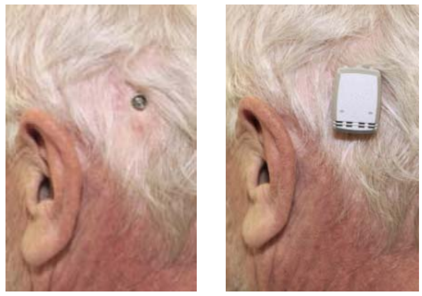

Fig. 1 A Bone Anchored Hearing Implant (BAHI) System. Left hand side: Patient with a percutaneous titanium implant. Right hand side: the same patient with a Baha BP100 sound processor (Cochlear Inc., Sweden) attached to it

Until recently, signal processing in BAHI systems used to be relatively basic, with a mostly linear amplification and limited possibility to adjust the frequency response and the overall gain of the system. As a consequence, sound processors were fitted by simply adjusting potentiometers with a screwdriver.

With the advent of digital and digitally programmable sound processors for BAHI systems, such as e.g. the Baha BP100 (Cochlear Bone Anchored Solutions AB) in 2010, the signal processing and fitting options have increased substantially. In these processors, gain and loudness compression can be adjusted in 10 audiologist accessible frequency channels, and several other options, such as feedback reduction and directionality (none, fixed or adaptive) of the two-microphone frontend can be activated and adjusted according to the specific needs of the user. Fitting of this new generation of sound processor is performed using product specific fitting software [7]. With the new fitting options, two important parameters can be adjusted separately: the maximum power output (MPO) and the compression ratio (CR). The MPO is the highest sound level which can be generated by the sound processor and is hardware related. In BAHIs, higher MPOs generally require larger transducers and

This work was supported by the ARTORG Center of the University of Bern and by Cochlear Inc.

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batteries and therefore result in larger and slightly heavier sound processors.

Loudness compression is an established sound processing concept in conventional hearing aids. It is mainly used in the form of wide dynamic range compression (WDRC). In loudness compression, amplification is high at low input levels and reduced for high input levels. With this approach, uncomfortably loud output levels can be avoided and pathological loudness growth (loudness recruitment) can be compensated in users with cochlear hearing loss. The static properties of a loudness compressor are characterized by the compression ratio (CR) indicating the degree of compression and the compression threshold (CT), i.e. input level where compression starts. In a conventional hearing aid, these parameters are usually chosen on the basis of a prescription formula based on theoretical concepts such as e.g. NAL, NAL-RP, or NAL-NL1 (National Acoustic Laboratories, Australia) [9].

In contrast to conventional hearing aids, which are used mostly for cochlear hearing loss, BAHIs are used mainly for conductive or mixed hearing loss. There is evidence, that loudness growth and therefore possibly the optimal compression ratios for a sound processor are different in cochlear and conductive hearing loss and for air conduction and bone conduction [10], [11]. To our knowledge, the influence of choice of the compression ratio in BAHIs on speech understanding and on subjective sound impression has not been investigated experimentally.

The primary goal of this investigation is to assess the effect of different compression ratios on speech understanding and on the subjective preference of actual BAHI-users experimentally.

The optimal compression ratio in BAHIs may also depend on the MPO. As lower MPOs would potentially allow physically smaller sound processors, the second goal of this investigation is to assess, how the optimal CR changes, when the MPO is reduced by 5 dB.

II. Materials and Methods

A. Subjects

Twelve adult subjects, aged 33–75 (mean 60.6 years; 5 females, 7 males) with a mixed hearing loss participated in the study. All were users of a BAHI device (6 right, 6 left) with a hearing experience of 1 to 17 years (mean 7.5 years) with their system. Fig. 2 shows a synopsis of the unaided hearing thresholds of all participants. At the time of testing, the sound processors they used in their everyday life were Baha BP110 (1), Baha BP100 (7) Baha Intenso (1), Baha Divino (1) and Baha Compact (2).

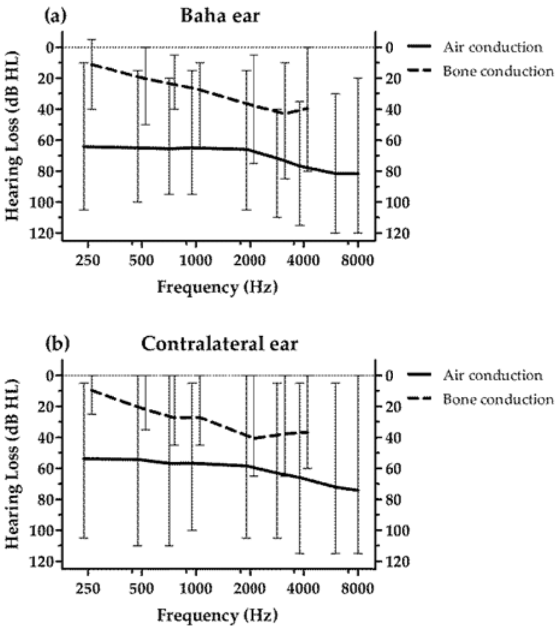

Fig. 2 Air conduction and bone conduction hearing thresholds of the 12 participants; Upper graph (a) thresholds of the ear at the side of the BAHI; Lower graph (b) thresholds of the contralateral ear Lines denote averages, error bars minima and maxima

B. Ethical Considerations

This investigator-initiated study has been approved by the Ethical Committee of Bern (number 015/12). All procedures followed the Helsinki declaration.

C. Procedure

Each participant was seen for a total of five appointments, numbered (1) through (5), over an 8 week period. After baseline testing at appointment (1), four follow-up appointments, (2) through (5), followed at intervals of 2 weeks.

A total of 8 combinations of 4 compression ratios (CR of 1.0, 1.3, 1.6 and 2.0) and two maximum power outputs (original, maximal MPO and MPO reduced by 5 dB) were tested. Table I shows a synopsis of the 8 combinations. Between any two appointments, each subject used a BAHI with 2 out of the 8 possible programs in two separate, user accessible programs in the test device. The order of the test programs was varied systematically between subjects using a Latin square design and the programs were blinded for the patients.

TABLE I
Tested Compression Ratio (CR) and Maximum Power Output (MPO) Combinations

MPO	CR	CR	CR	CR
MPO original	1.0	1.3	1.6	2.0
MPO reduced	1.0	1.3	1.6	2.0

1. Baseline Testing:

During appointment (1), air conduction (AC) and bone conduction (BC) thresholds were measured for each ear separately, using masking of the contralateral ear whenever necessary. For all measurements in the sound field, the contralateral ear was blocked with an earplug and covered with a PeltorOptime II hearing protector (Aero Ltd, Poynton, U.K.).

Unaided speech reception thresholds were measured with the German two-digit numbers from the Freiburg test [12] . Speech understanding in quiet was measured with the Freiburg monosyllabic word test. Two lists of 20 monosyllabic words presented at each of the levels of 50 dB, 65 dB, and 80 dB SPL.

Unaided speech understanding in noise was measured using the Oldenburg sentence test (OLSA) [13] in sound-field conditions. Speech was presented from a loudspeaker in front of the participant and noise from the rear. The test room and equipment used is described below. The OLSA uses an adaptive test procedure to measure the signal-to-noise ratio required for 50% word understanding. It consists of 40 lists of 30 test sentences each. The noise signal is a speech babble signal generated by superimposing all test items and presented at a constant level of 65 dB SPL. The presentation level of the test sentences, consisting of five words each, is changed adaptively according to the number of correctly repeated words by a pre-defined scheme. Two training lists, the results of which were discarded, were completed by each subject before the actual testing began.

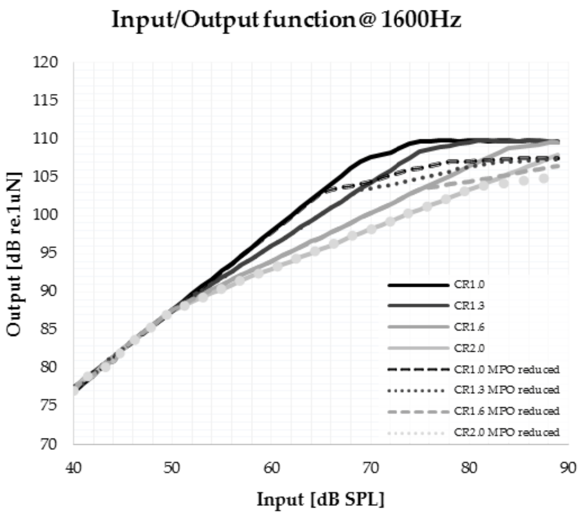

Fig. 3 Input/Output function of the sound processor Baha BP110 at 1600 Hz All 8 combinations of 4 different compression ratios and 2 different MPOSs are shown. The compression threshold was 50 dB SPL (input) in all instances

2. Fitting of the Sound Processor:

A Baha BP110 sound processor [7] was used for the investigation. It was programmed using the Cochlear Fitting Software 2.0 SR 2 (CFS). The microphone setting was omni directional, noise reduction was switched off, feedback management set to default and the position compensation activated.

Calculation of CR settings is based on the measured BC-direct values (bone conduction measured directly through the sound processor). The same CR settings were used for all frequency bands. For a CR of 1.0, soft and loud gain values in the fitting software were set to the same value. For a CR of 1.3, 2 dB were subtracted from the soft gain. To obtain a CR of 1.6, 4 dB are subtracted. A reduction of 5 dB from soft gain values yields a CR of 2.0.

The MPO was adjusted in the same fitting software by either keeping the MPO at its original, maximum level, or by reducing it by 5 dB over all frequency bands.

Fig. 3 shows the resulting, measured input-output functions, here for a frequency of 1600 Hz, and Table II shows the actual MPO settings used.

TABLE II
MAXIMUM POWER OUTPUT (MPO) VALUES

Frequencies (Hz)	250	500	750	1 k	1.5 k	2k	3k	4k	6k	8k
MPO original (dB)	95	113	123	118	111	107	104	102	100	100
MPO reduced (dB)	90	108	118	113	106	102	99	97	95	95

3. Diaries:

Two diaries [14] were handed at the beginning of each 2-week test period and instructions were given to alternate daily between the two programs of the speech processor. In this diary, daily judgments on a scale from 1-100% were to be given for the following categories: speech understanding, quality of sound, speech intelligibility in calm situations, speech intelligibility in noisy environment, recognition of sounds, noise in program, appreciation of music, sound quality of own voice.

4. Follow-up Appointments (2) to (5):

At each follow-up appointment, the following tests were administered for each of the two programs tested in the previous two week-period:

- Aided speech reception in quiet (Freiburg numbers)
- Aided speech understanding in quiet (Freiburger word test) at 50, 65, and 80 dB SPL
- Aided speech in noise testing using the German Oldenburger sentence test (OLSA)
- Discussion of diary and subjective preference of the programs.

D.Test Rooms and Test Equipment

All measurements took place in a double-walled, sound-attenuating chamber (6.0 x 4.1 x 2.2m) with an average reverberation time of 0.14 seconds and complying with the ISO 8325-1 standard. Speech in quiet tests was steered with a clinical audiometer (GSI61; Grason-Stadler, Mildford, NH, USA) and an active loudspeaker (Type 1030A, Genelec, Iisalmi, Finland) placed 1m in front of the listener. Tests were controlled using in-house developed software. Speech and noise were presented using an Audiobox amplifier (Merz Medizintechnik, Reutlingen, Germany) and Control 1 pro (JBL Ins., CA, USA) loudspeakers positioned at a distance of 1m from the listener’s head.

E. Statistical Analysis

Results were analyzed using InStat 3.10 (GraphPad Inc., La Jolla, CA, USA). Before using t-tests (paired, two-sided) normality of the distributions was confirmed with the Kolmogorov-Smirnov test.

III. Results

A. Speech Understanding in Quiet

Figs. 4 (a) and (b) show the unaided and aided speech reception thresholds of two-digit numbers for all 8 combinations of CR and MPO.

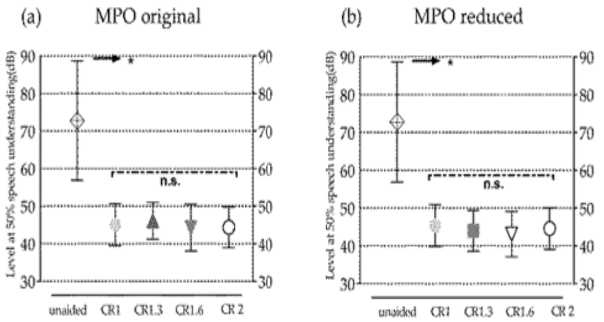

Fig. 4 Aided and unaided speech reception thresholds in quiet measured with the two-digit number test (German Freiburg numbers test). Data points denote average levels for 50% correctly repeated numbers over all subjects, error bars show standard deviations (* p<0.05; N.S. not significant)

All tested combinations of CR and MPO provide a significant benefit (mean: 25.9 - 28.5 dB; SD: 1.6 - 1.8; p<0.0001) compared to the unaided condition (mean: 72.8 dB; SD: 15.8 dB) However, no statistically significant difference could be found between any 2 combinations (p= 0.33 - 0.53).

Figs. 5 (a) and (b) show the results for the understanding of monosyllabic words in quiet. As with the two-digit numbers in Figs. 4 (a) and (b), statistically highly significant (p<0.0007) benefit of 34.1 to 77.9 % points was found when comparing unaided versus aided condition for any of the CR ratio / MPO configuration.

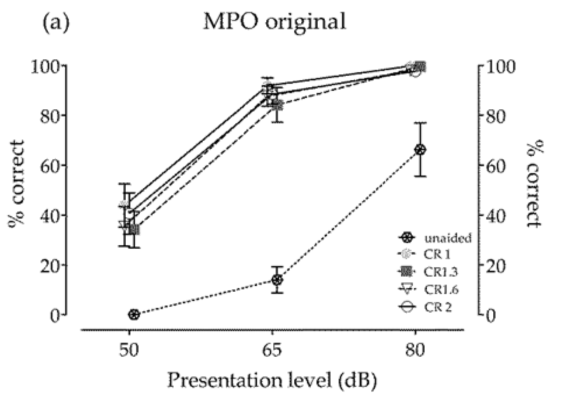

Fig. 5 (a) Speech understanding in quiet for monosyllabic words from the German Freiburg word list at 50, 65, and 80 dB SPL. Averages of correctly repeated words over all subjects with the original MPO; Mean values and standard errors of the mean are shown

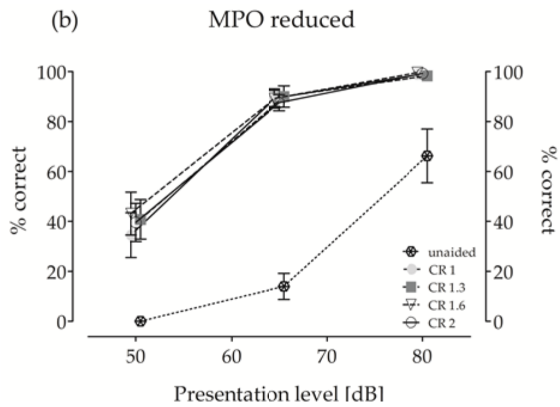

Fig. 5 (b) Speech understanding in quiet for monosyllabic words from the German Freiburg word list at 50, 65, and 80 dB SPL. Averages of correctly repeated words over all subjects with the MPO reduced by 5 dB as well as standard errors of the mean are shown

In Fig. 5 (a) word understanding with the original, non-reduced MPO), the aided scores at 50 dB input range from 34.2 to 43.8% (SD: 25.2 – 30.9). At 65 dB aided scores improve to 84.2 – 91.8% (SD: 11.8 – 23.9) and at 80 dB input, mean scores are between 96.8 and 99.6% (SD: 0.5 – 4.3). None of the differences between any two CR-settings are statistically different (p=0.13 - 0.67).

In Fig. 5 (b) (MPO reduced by 5 dB) the aided scores at 50 dB input range from 34.2 to 40.8% (SD: 25.2 – 30.2). At 65 dB aided scores improve to 84.2 - 91.8% (SD: 11.7 – 23.9) and at 80 dB input, mean scores are between 97.7 and 99.6% (SD: 0.7 – 5.1). None of the differences between any two CR-settings are statistically different (p=0.11 - 0.82).

B. Speech Understanding in Noise

Fig. 6 shows the results from the speech in noise test. Signal-to-noise ratios (SNR) required for 50% speech understanding are depicted. Individual results are represented by connected data points and average results by a solid black line.

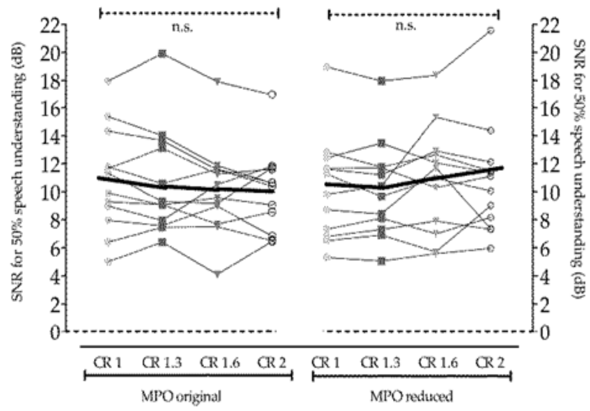

Fig. 6 Aided signal-to-noise ratios (SNRs) required for 50% speech understanding using the Oldenburg sentence test. In this test, speech was presented from the front and noise from the rear. Lower values denote better speech understanding in noise. Each data point represents the result from an individual measurement. The solid thick line connects average values

The mean SNR for all combinations of CR and MPO range between 10.1 and 10.8 dB (SD: 2.9 - 4.1 dB). They do not differ significantly from each other (two Wilcoxon matched pairs sign ranks with Bonferroni correction for multiple testing; p=0.18 - 0.85).

On the left side of the graph (MPO original), a slight, statistically non-significant trend in favour of higher compression ratios can be seen. For the “MPO reduced” condition, there is a similarly slight, non-significant trend, towards lower compression ratios.

C. Final Preferred Settings

In the final session, the participants were asked to indicate their first and second choice from the 8 programs tested. The choice was purely subjective and based on the experience of the previous 8 weeks and reflects the programs they would like to use on a daily basis. Fig. 7 (a) shows a graph bar of the first and second choice as a function of the compression ratio and Fig. 7 (b) shows first and second choices as a function of MPO.

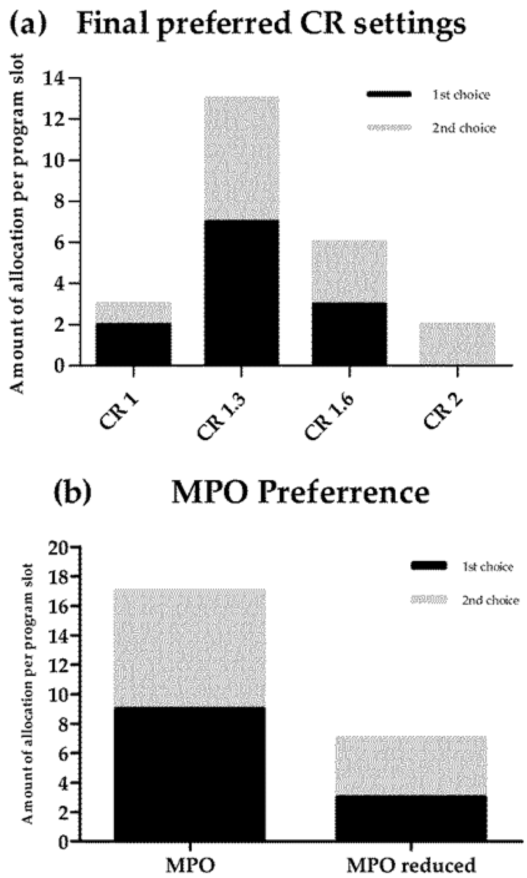

Fig. 7 Final preferred compression ratio (CR) settings patients chose at the end of the study. In both graphs, the first choice of each participant is shown in black, the second choice in grey

Regarding compression ratios (CR), most participants chose a compression ratio of 1.3 either as their first choice (7 participants) or as their 2nd choice (6 participants). 6 participants chose a CR of 1.6 either as their first or second choice. CR of 1.0 or 2.0 was chosen significantly less often. The differences between the different compression ratios is statistically significant (Kruskal-Wallis test, p=0.017).

Nine participants preferred a program with a high MPO (first choice) and 7 as their second choice. This is statistically significantly more than for settings with the lower MPO (two-tailed Mann-Whitney test, p=0.0045).

IV. Discussion

The primary aim of this study was to investigate the influence of different compression ratios and of different MPOs on speech understanding. Contrary to our expectation, we did not find any significant difference between fittings with different CR settings in the wide range between 1.0 and 2.0 or between programs with the original, maximal MPO and with MPO reduced by 5 dB.

In contrast, subjectively, participants were able to indicate their preferred settings and they chose, on average, settings with a moderate compression ratio (1.3, and a little less frequently, 1.6) and the higher of the two MPOs offered.

This phenomenon is not unknown. Already in a study of 1988, Gabrielsson et al. varied the frequency response of five electrical filters, simulating a conventional hearing aid. The electrical response of the filters varied between flat, attenuated by 6 or 12 dB/Octave between 1 kHz and 4 kHz [15]. Similar to the present study, they found that the percentage of correctly recognized words were practically identical for all transfer functions tested, despite relatively large differences. Nevertheless, subjectively, a clear preference was found. It seems that changes in signal processing influence the subjective hearing impression more than the measured scores for speech understanding either in quiet or in noise.

In our study, there was no decrease in speech understanding either in quiet or in noise, when the MPO was lowered by as much as 5 dB. Nevertheless, the reduction of the MPO was heard by the participants and generally not appreciated, as documented by their choice shown in Fig. 7 (b). It is possible that patients with a higher hearing loss than those in our investigation might be affected more by a limitation of the MPO in terms of speech understanding.

One limitation of this investigation is the limited number of participants. Patient recruitment was challenging since only few patients were willing to return for five appointments and to use different fittings, which they might potentially not like for a total of 8 weeks. It is probably due to this limited number of participants, that the data from the diaries did not show any significant trends or differences between the tested programs. Patients reported also, that they felt the diaries were challenging to fill in.

Despite the limited number of subjects, the overall benefit of the tested system with the BP110 sound processor was large and highly significant. This was found to be true for the two-digit number test (Fig. 4), the monosyllabic numbers in quiet (Figs. 5 (a) and (b)) and for speech understanding in noise (Fig. 6).

V. Conclusion

Hearing speech in quiet and in noise with a bone anchored hearing implant system (BAHI) is not significantly affected with varying compression ratios in the range of 1.0 to 2.0, in patients with mixed hearing loss. Furthermore, no substantial impact on speech understanding by the reduction of the MPO by 5 dB was found in this group. In contrast, subjectively, medium compression ratios in the order of 1.3 to 1.6 and a higher MPO were preferred.

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