European Archives of Oto-Rhino-Laryngology (2019) 276:2729–2737
https://doi.org/10.1007/s00405-019-05516-3

OTOLOGY

Evaluation of wireless Bluetooth devices to improve recognition of speech and sentences when using a mobile phone in bone conduction device recipients

Tae Hoon Kong[1] · Chanbeom Kwak[2] · Woojae Han[2,3] · Young Joon Seo[1]

Received: 11 February 2019 / Accepted: 13 June 2019 / Published online: 19 June 2019

Abstract

Objective To evaluate the effect of a wireless Bluetooth device (WBD) in word and sentence recognition in patients with bone conduction devices (BCDs) while using mobile phones.

Methods We performed a prospective study evaluating speech and sentence recognition in both quiet and noised conditions. A total of nine patients, audiologically eligible for BCDs, were included. Based on their hearing impairment type and severity, subjects were divided into "BCD only" and "BCD with HA" groups. The speech and sentence recognition scores of each condition were compared by nonparametric methods.

Results Both the "BCD only" and "BCD with HA" groups had higher scores in the quiet condition than in the noised condition in word and sentence recognition tests, irrespective of whether the WBD was used. The benefit from using a WBD was greater in the noised condition. There were significant differences in the word recognition test results before and after using the WBD in the "BCD only" group, and in both the word and sentence recognition tests results before and after using the WBD bimodally in the noised condition in the "BCD with HA" group.

Conclusion WBDs improve word and sentence recognition in adult BCD bone recipients when they use mobile phones. WBD use provides additional benefits in "BCD with HA" patients in a bimodal situation.

Keywords Bone conduction device · Bone-anchored hearing aid · Wireless Bluetooth device · Speech in noise · Hearing aid

Introduction

Bone conduction devices (BCDs) are very useful alternative tools for the rehabilitation of patients who cannot adapt to conventional hearing aids (HAs), or if HAs are unacceptable to them, such as in cases of single-sided deafness (SSD) and conductive hearing loss (CHL)/mixed hearing loss (MHL) [1]. The principle is that sound can be transferred to the inner ear by skull vibrations, bypassing the external and middle ear. Since the successful placement of the first implant was reported in 1977, more than 10,000 patients worldwide have received a BCD [2, 3]. Regardless of the type of hearing loss, BCDs improved the mean pure tone hearing threshold, the speech discrimination score, as well as the speech reception threshold noise in recipients [4].

Despite these benefits of BCDs, some audiological limitations have also been reported. In a long-term follow-up study and systematic review of patients with SSD and a BCD, despite the benefits in speech discrimination in noise

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00405-019-05516-3) contains supplementary material, which is available to authorized users.

✉ Young Joon Seo
okas2000@hanmail.net

[1] Department of Otorhinolaryngology-Head and Neck Surgery, Yonsei University Wonju College of Medicine, 20 Ilsanro Wonju, Gangwon, South Korea

[2] Laboratory of Hearing Technology, Department of Speech Pathology and Audiology, Graduate School, Hallym University, Chuncheon, South Korea

[3] Division of Speech Pathology and Audiology, College of Natural Sciences, Hallym University, Chuncheon, South Korea

conditions, subjective outcomes, and improvement of quality of life, there was no significant improvement in sound localization [5, 6]. Furthermore, hearing improvement using BCDs was not satisfactory to the patients. Among patients for whom a BCD was considered suitable, about 61.2% refused the implant. Forty percent of patients who refused the BCD perceived limited benefits from the device or preferred conventional hearing aids [7].

The limitations to the benefits of implantable devices, including BCDs, are further exacerbated when a telephone (landline or mobile) is used [8]. Many factors may affect the difficulties experienced by users on the telephone [9–11]. They cannot make use of visual cues in the telephone environment and that the limited frequency (300–3000 Hz) of the telephone makes speech recognition difficult.

To overcome the limited benefits of implantable hearing devices, including BCDs, wireless accessory devices using Bluetooth technology (hereafter referred to as wireless Bluetooth devices or WBDs) have been developed [9]. WBDs can transmit sound from a microphone to the sound processor of implants, as well as to HAs. The usefulness of WBDs in HA users has already been studied [12]. The benefits of WBDs in cochlear implant (CI) users or CI and HA bimodal users has also already been studied. It has been reported that using a WBD results in a high score in speech recognition in both quiet and noised conditions [9, 13]. In particular, CI and HA bimodal users reported that it is more effective to apply a WBD to CI with an HA than in CI only [13].

With the same principle, a WBD could be connected to the sound processor of BCDs. We performed this study to assess the usefulness of WBDs in patients using a BCD as well as those using a BCD and an HA bimodal users.

Materials and methods

Participants

Nine patients who were deemed audiologically suitable to use a BCD were included in our study. Table 1 shows the demographic characteristics of the participants, including the details of hearing impairment. Patients were allotted to the "BCD only" group or the "BCD with HA" group, taking into account the type and severity of the patients' hearing impairment on both sides.

Patients with SSD whose contralateral hearing function is normal, or mild impairment (participants #2 and #3 in Table 1) were allotted to the "BCD only" group. Patients with bilateral CHL or MHL, a normal or mildly impaired bone conduction hearing threshold, and similar bilaterally (participants #1, #4, and #5 in Table 1), were also included in the "BCD only" group. If the patients with SSD or MHL had an opposite side ear having sensorineural hearing loss (SNHL), and if they were considered to have sufficient benefit with an HA (participants #6, #8, and #9 in Table 2), they were included in the "BCD with HA group". If the patients with MHL had an opposite ear with CHL, the BCD was implanted on the MHL side to maintain normal bone conduction hearing function on the CHL side. In one patient, impaired air conduction of CHL was supported with an HA (participant #7 in Table 2), and hence, that patient was allotted to the "BCD with HA group".

In addition, all patients met the following conditions: (1) at least 18 years of age; (2) at least a year since hearing

Table 1 Participant demographics, including details of hearing impairment

	Participants	Age (years)	Sex	Duration HI (year)	Etiology	HA experience non-implanted ear (years)	HI type[a]	Implanted ear[b]	BCD duration (days)[c]
BCD group	1	75	M	30	COM	20	MHL	Right	153
	2	55	F	50	Congenital	0	SSD	Left	127
	3	57	F	2	ISSNHL	0	SSD	Right	22
	4	53	F	10	Trauma	4	MHL	Left	13
	5	33	M	34	Congenital	0	CHL	Right	13
BCD with HA group	6	56	M	50	Congenital	17	SNHL + deaf	Left	321
	7	59	M	40	COM	8	MHL + CHL	Right	321
	8	62	F	1	Trauma	0	SNHL + MHL	Left	286
	9	57	M	2	COM	1	MHL + SNHL	Right	48

HI hearing impairment, *BCD* bone conduction implants, *HA* hearing aid, *COM* chronic otitis media, *ISSNHL* idiopathic sudden sensorineural hearing loss, *SSD* single-sided deafness, *CHL* conductive hearing loss, *SNHL* sensorineural hearing loss, *MHL* mixed hearing loss

[a]The type of hearing loss is indicated as BCD implanted in the BCD group, and in the order of right and left in the BCD with HA group

[b]Where the BCD was implanted. In case of BCD with HA group, HA was applied the opposite side of implanted ear

[c]BCD duration is defined as the time from the day when the BCD was first fitted to the day the patient performed the test

Table 2 Korean sentences for measuring sentence clarity test (translated to English)

	Sentences (translated from Korean to English)[a]
1	I fell asleep on the subway and passed the station
2	A man ate at the restaurant and drank coffee
3	I bought a watch for my friend 's birthday present and received a gift
4	I wanted to hear from my parents, so I called first
5	The weather was good, so I went out for a walk
6	As I walked across the crosswalk, I lost important photos
7	I went to the bookstore, but there was no book I wanted
8	It was raining when I came out to go home after the test
9	The person who was standing at the last in the line just walked away
10	I bought one because I wanted to plant a pretty flower in the front yard

[a]In our study, we conducted tests with commonly used, structured Korean sentences. This table only suggests English translations to show that daily sentences were used

loss occurred irreversibly; and (3) use of spoken language as the primary mode of communication, with Korean as their native tongue.

All participants signed an informed consent form before participating in the study. Approval of the Institutional Review Board (IRB) in our institute was obtained (Protocol No. CR316089). All methods were performed in accordance with the relevant guidelines and regulations of the IRB.

Devices

All patients were fixed with the Baha® Attract System (Baha®, Cochlear Ltd., Sydney, Australia). The Baha® Attract System is a highly effective bone conduction hearing system designed to leave the skin intact. It uses a magnetic connection to attach the sound processor to the implant, sending the sound to the inner ear without breakage of the skin [14].

Mobile phone performance was assessed while the subjects used the Baha® 5 sound processor. The wireless digital radio frequency (RF) Cochlear Wireless Phone Clip device was used in the "BCD only" group and the Cochlear Wireless Mini Microphone was used in the "BCD with HA" group. The WBD was paired to the Baha® 5 sound processor of the participant and was also connected via Bluetooth to his/her own mobile phone. For the "BCD with HA" group, the WBD was also paired with a ReSound LiNX 5 hearing aid. The mixing ratio between WBD and BCD or HA was 0 dB as default value, which means the microphone and WBD were balanced equally (i.e., 50% mixing ratio). Figure 1 shows the equipment and how the devices were connected. The WBD receives and transmits signals to the mobile phone via Bluetooth RF transmission; the audio signal from the mobile phone is then transmitted to the recipient's Baha® 5 sound processor and HA via a 2.4 GHz digital radio frequency transmission. The WBD allows recipients to answer calls on the mobile phone and to deliver his/her voice back to the phone via a microphone, which is typically clipped to the recipient at the level of the second or third shirt button. Pairing of the equipment was confirmed by asking the participant to acknowledge the presence of practice words dictated via the mobile phone.

Test environment and procedures

Assessment of word and sentence recognition was tested in an audio booth. A word recognition test was performed with a full list of monosyllabic words in Korean (Supplement 1) [15, 16]. One of the four tables containing 50 words was selected randomly across subjects and they were used to test for word recognition. The percentage of correct recognition of each word was calculated as the speech discrimination score.

A sentence recognition test was performed with standardized and structured daily-use Korean sentences. (Supplement 2). The corresponding sentences translated into English are presented in Table 2. This table only shows English translations to indicate that these sentences are used daily. The components in the sentence were given a score from 0.5 to 2 points, so that one complete sentence resulted in 10 points.

Both speech perception and sentence recognition tests were conducted in quiet and noised conditions in a double walled single room audio booth. In the noised condition, uncorrelated and continuous presenting speech noise was presented from three loudspeakers located on the right, left, and in front of the subjects at a distance of 1.4 m (Fig. 2a). The level of competing noise was 40 dB SPL (sound pressure level), as measured at the position of the participant.

The monosyllabic words and standardized sentences were presented to subjects from an Apple iPhone 6 connected

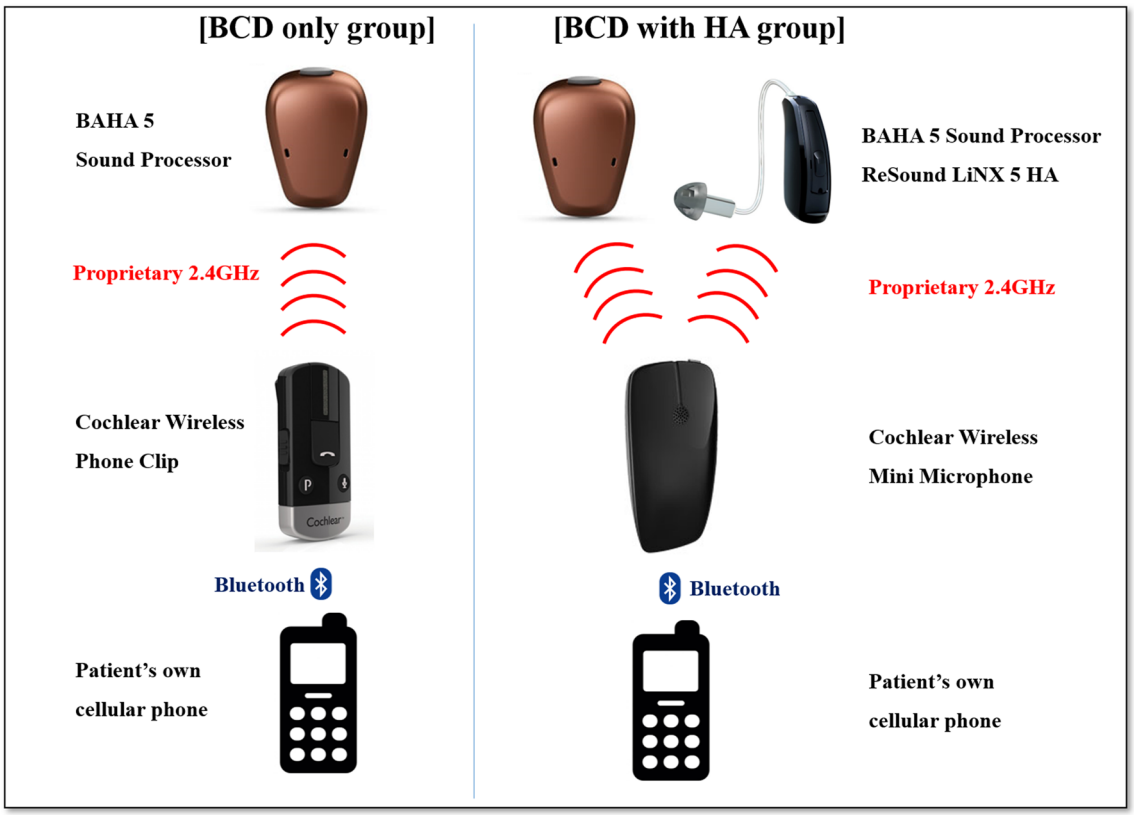

Fig. 1 A schematic diagram of a patient using a Cochlear Wireless Phone Clip and Cochlear Wireless Mini Microphone to make a telephone call to patients in the BCD only group and BCD with HA group

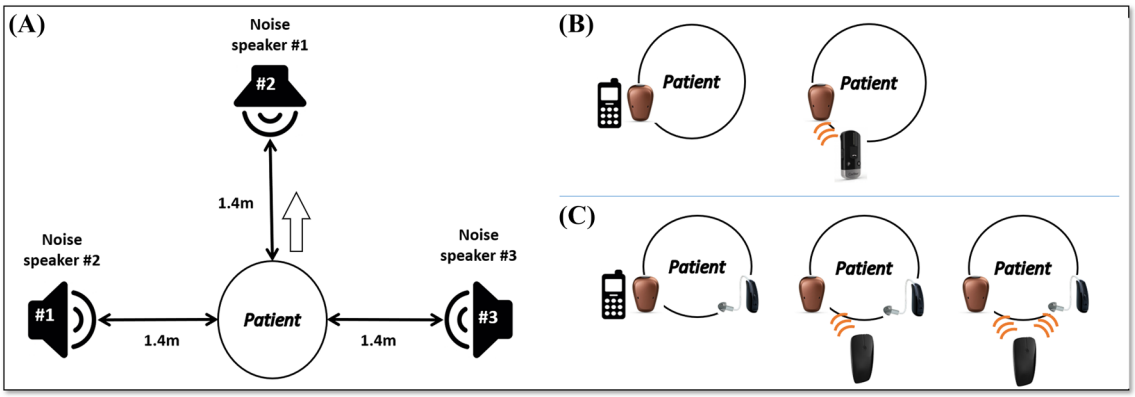

Fig. 2 Test environment for the assessment of telephone speech recognition in quiet and noised conditions. **a** A schematic of our test environment. The patient is in the middle of three loudspeakers emitting noise, all at a distance of 1.4 m. The patient sits on the chair and faces the loudspeaker #2 (white arrow). Test setup for assessment of phone speech recognition in quiet and noise conditions. **b** The BCD only group. First, patients put their mobile phone directly on the sound processor of the BCD to make a phone call. Thereafter, patients used a Cochlear Wireless Phone Clip to connect to their mobile phone via Bluetooth; the Cochlear Wireless Phone Clip was connected to the sound processor of the BCD, and tests were performed. **c** The BCD with HA group. Similar to the patients of BCD only group, patients in the BCD with HA group also put their mobile phones directly on the sound processor of the BCD to make a phone call. Thereafter, patients used a Cochlear Wireless Mini Microphone to connect to their mobile phone via Bluetooth; the Cochlear Wireless Mini Microphone was connected only to the sound processor of the BCD and tests were performed. Lastly, the Cochlear Wireless Mini Microphone was also connected to both the BCD and HA simultaneously, and the tests were performed

with EarPods with a 3.5-mm headphone jack plugged directly to the patients' own mobile phone by one audiologist. Word and sentence recognition tests were administered to participants in each condition as follows (Fig. 2b):

"BCD only" group

1. Patients put their cellular phone directly on the Baha® 5 sound processor to make a phone call to conduct both speech and sentence tests in the quiet condition.
2. Patients used the Cochlear Wireless Phone Clip to connect to their mobile phone via Bluetooth; the Cochlear Wireless Phone Clip was connected to the Baha® 5 sound processor and the patient underwent tests in the quiet condition.
3. In the noised condition, patients performed the tests (1) and (2) above in the presence of a 40 dBA SPL speech sound.

"BCD with HA" group

1. With the HA and Baha® on, patients put their mobile phone directly on the Baha® 5 sound processor to make a phone call to conduct both speech and sentence tests in the quiet condition.
2. Patients connected the Cochlear Wireless Mini Microphone to their mobile phones via Bluetooth, and the Cochlear Wireless Mini Microphone to the Baha® 5 sound processor, and underwent the tests in the quiet condition.
3. Patients connected the Cochlear Wireless Mini Microphone to their mobile phone via Bluetooth, and the Cochlear Wireless Mini Microphone to both the Baha® 5 sound processor and HA, and underwent the tests in the quiet condition.
4. In the noised condition, patients performed the tests (1), (2), and (3) above in the presence of 40 dBA SPL of speech noise.

The examiner ensured that the subjects appropriately positioned the mobile phone next to the sound processor microphone in the both quiet and noised conditions. Prior to both the quiet and noised conditions, participants adjusted the volume control of their sound processor and of the mobile phone to their preferred loudness levels while listening to a practice list of the target stimuli over the phone.

In participants in the "BCD with HA" group, the audio signal from the mobile phone was streamed to both the Baha® 5 sound processor and HA in the WBD. In both the quiet and noised mobile phone conditions, participants used the mobile phone on the BCD side ear, while the opposite ear with the HA remained active. In the "BCD only" group, the implanted ear was active during all conditions, and the non-implanted ear was not plugged.

Statistical analysis

To assess statistical significance, the mean scores of the speech perception test and sentence recognition test for each procedure were compared. SPSS Statistics (SPSS 22.0 for Windows, IBM Corp., Armonk, NY, USA) was used for the analyses. The Friedman test was performed to compare three or more groups, and the Wilcoxon signed rank test was performed to compare two groups. Differences were considered statistically significant when p values were less than 0.05.

Results

"BCD only" group

Table 3 shows the raw data of the "BCD only" group, and the results of the speech and sentence recognition tests in the "BCD only" group are presented in Fig. 3. Overall, in both the word and the sentence recognition tests, the scores were higher in the quiet condition than in the noised condition, and the scores were higher in the sentence recognition test than in

Table 3 Individual data from the speech and sentence recognition conditions in BCD group patients

Participants #	Word recognition test (in %)				Sentence recognition test (in %)			
	Quiet: BCD	Noised: BCD	Quiet: BCD-B	Noised: BCD-B	Quiet: BCD	Noised: BCD	Quiet: BCD-B	Noised: BCD-B
1	32	28	40	44	39	61	50	56
2	84	60	84	72	98	97	100	95
3	72	0	76	20	100	0	100	23
4	52	28	68	60	82	42	89	76
5	80	40	82	52	100	35	95	98
Mean	64	32.7	65	44.7	81.3	47.5	83.5	70.7
SD	19.4	19.8	20.1	21.2	24.2	31.9	20.5	28.9

BCD bone conduction implants, *BCD-B* bone conduction implants with Bluetooth device connected, *SD* standard deviation

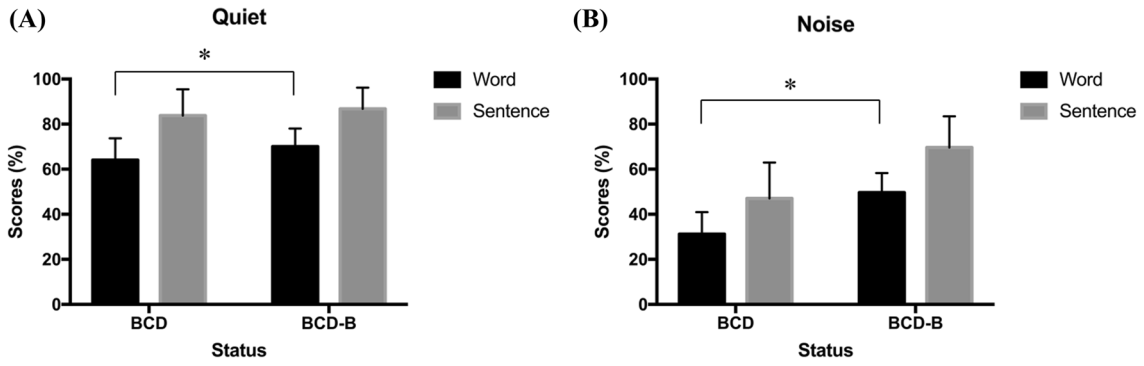

Fig. 3 The results of the word recognition test and sentence perception test in participants with a BCD only. Each test was performed with and without a wireless Bluetooth device in both quiet and noised environments. **a** Scores of the word and sentence recognition test in the quiet environment. **b** Scores of the word and sentence recognition test in the noised environment. *BCD* bone conduction implant, *BCD-B* bone conduction implant with Bluetooth device connected. *$p < 0.05$

the word recognition test (64.0% vs. 31.2% of mean value in word recognition test, 83.8% vs. 47.0% in sentence recognition test). The benefit from using the WBD was greater in the noised condition than in the quiet condition (6.0% vs. 18.4% of mean value difference in word recognition test, 3.0% vs. 22.6% of difference in sentence recognition test). However, there were statistical differences in the benefits from using the WBD only in the word recognition test ($p = 0.034$ for quiet condition, $p = 0.021$ for noised condition).

"BCD with HA" group

Table 4 shows the raw data of the "BCD with HA" group, and the results of the word and sentence recognition tests in the "BCD with HA" group are presented in Fig. 4. The overall scores of the word and sentence recognition tests of the "BCD only" group were higher in the quiet condition than in the noised condition, as well as higher in the sentence recognition test than in the word recognition test (word: 56.0%, 61.0%, and 71.0% in quiet vs. 3.0%, 38.0%, and 52.0% in noise; sentence: 68.0%, 72.8%, and 83.3% in quiet vs. 2.3%, 49.5%, and 63.5% in noise). However, statistical significance was found in the word and sentence recognition tests only in the noised condition between the cases where the WBD was not used and where the WBD was connected to both a BCD and HA ($p = 0.034$ for word and sentence recognition test). Characteristically, this group had significantly lower scores in both the word and sentence tests when the WBD was not used in the noised condition.

Discussion

This study was the first to assess the benefits of audio streaming through a WBD during a phone call in patients with BCD only or bimodal BCD with HA. Previous studies were only performed with WBDs in CI recipients or in CI and HA bimodal recipients [9, 12].

In both the "BCD only" and "BCD with HA" groups, the sentence recognition score was higher than the word recognition score in the same conditions. We thought that this was because, in the case of word recognition, it is necessary to recognize the Korean monosyllabic consonant–vowel–consonant words correctly. However, in sentence recognition, it is thought that the recipient can take advantage of syntactical, grammatical, linguistic, and contextual cues for a better understanding, so as to achieve a higher score [9]. Wolfe et al. reported when using WBD device, CI users showed only a mean of 66% correct from among English consonant–vowel nucleus–consonant words over a mobile phone even in the quiet condition, which is similar to our result of about 70% on average. They also mentioned that sentence recognition would be easier than word recognition.

Additionally, both the "BCD only" and "BCD with HA" groups showed higher scores in word and sentence recognition in the quiet condition than in the noised condition, irrespective of whether the WBD was connected to the mobile phone. Previous studies reported that the score of word or speech recognition test in noised condition was lower than the quiet condition [9, 13]. These findings are similar to the results of our study. The speech noise used for this study (40 dB SPL) is considered to have an adequate effect, regardless of whether the recipients used a WBD.

The benefit from using a WBD was greater in the noised condition than in the quiet condition. Wolfe et al. reported findings similar to our study in their study on CI recipients [9]. They report that in the quiet condition, there was a mean of 18.1% gain with using a WBD. In case of noised condition, there was a mean of 28.6% gain. They suggested that these findings could be explained by three aspects of direct streaming of the audio signal from the WBD to the sound processor: these are: (1) significantly reduced ambient

Table 4 Individual data from the speech and sentence recognition conditions in BCD with HA group patients

Participants #	Word recognition test (in %)						Sentence recognition test (in %)					
	Quiet: BCD/HA	Noised: BCD/HA	Quiet: BCD-B/HA	Noised: BCD-B/HA	Quiet: BCD-B/HA-B	Noised: BCD-B/HA-B	Quiet: BCD/HA	Noised: BCD/HA	Quiet: BCD-B/HA	Noised: BCD-B/HA	Quiet: BCD-B/HA-B	Noised: BCD-B/HA-B
6	40	0	48	0	52	8	56	0	64	0	71	22
7	84	8	84	80	84	80	85	9	98	98	100	100
8	24	0	36	16	60	36	38	0	36	23	81	56
9	76	4	76	56	88	84	93	0	93	77	81	76
Mean	56	3	61	38	71	52	68	2.3	72.8	49.5	83.3	63.5
SD	28.7	3.8	22.7	36.6	17.7	36.5	25.5	4.5	28.7	45.7	12.1	33

BCD bone conduction implants, *HA* hearing aid, *BCD-B* bone conduction implants with Bluetooth device connected, *HA-B* hearing aid with Bluetooth device connected, *SD* standard deviation

competing noise effect and an improvement in the SNR; (2) a more robust signal, as compared to when the receiver of the mobile phone is held next to the sound processor; and (3) use of a WBD makes it possible to avoid electromagnetic noise that may occur between the receiver of the phone and the sound processor. We thought that the above can also be applied to our study on BCD recipients. Because the difference is only an implantable device, WBD is connected to the sound processor of each implantable device. The type of implant only depends on the type of hearing loss in the patient, and the WBD is only responsible for how efficiently the sound is transmitted to the sound processor, which is the starting point of implant surgery.

In the "BCD with HA" group, an interesting finding was that the BCD and HA bimodal connection of the WBD gave an additional improvement over the WBD connection to the BCD alone. The benefit from the CI and HA bimodal connection of WBDs has already been observed in previous studies and was also observed in our study. Vroegop et al. reported that CI and HA bimodal patients showed statistically higher scores in the speech perception test when a WBD was connected to both CI and HA, rather than to CI alone [13]. It seems that the experience of using HA before BCD results in additional benefits.

On the other hand, in the noised condition, the "BCD with HA" group presented very poor scores in both word and sentence recognition tests in our study. We thought that the noise disturbance acted on both the BCD and HA devices at the same time in patients in the "BCD with HA" group, hence, they showed worse results than patients in the "BCD only" group, while the hearing function of the side opposite to the BCD ear was intact. Schwartz et al. reported significantly worse results in the speech noise (SIN) test when the noise was presented on the opposite side of the BCD in SSD patients [17]. They suggested that hearing loss in the better ear in BCD recipients seemed to perform worse in a noise condition than in that without noise [17]. They reported that when the hearing threshold of the better ear was less than 25 dBHL, the average signal-to-noise ratio was about 5.9 dB lower than that when not. Unlike CIs and HAs, BCDs are influenced by the contralateral and ipsilateral bone conduction hearing thresholds. In the "BCD with HA" group of our study, an HA was applied to improve the hearing threshold of air conduction, and a BCD was applied to the opposite site. Therefore, in cases where hearing with an HA is interrupted by noise, the negative effect of noise is higher, and the performance worsens.

A statistically significant difference was found only in the word recognition test, irrespective of whether the noise was present in the "BCD only" group. The word and sentence recognition tests in the noise condition also showed statistical significance in the "BCD with HA" group in our study. In the BCD group, unlike the other participants, participant #5

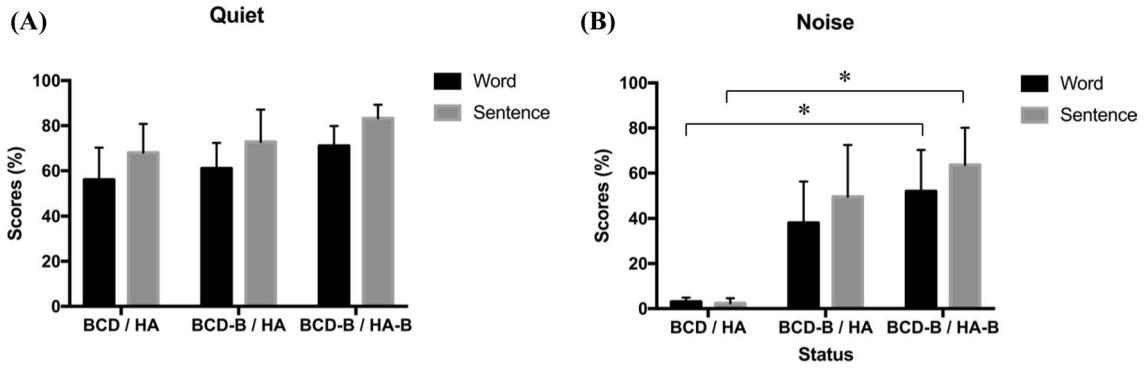

Fig. 4 The results of the word recognition test and sentence recognition test in participants in the BCD with HA group. Each test was performed with and without a wireless Bluetooth device in both the quiet and noised environments. **a** Scores of the word and sentence recognition test in the quiet environment. **b** Scores of the word and sentence recognition test in the noised environment. *BCD* bone conduction implant, *HA* hearing aid, *BCD-B* bone conduction implant with Bluetooth device connected, *HA-B* hearing aid with Bluetooth device connected. $*p < 0.05$

showed a decrease in score from 100 to 95 after using the WBD in the sentence recognition test in the quiet condition (Table 3). Similarly, in the sentence test in the noised condition, participant #2 also presented a decrease in score from 97 to 95 after using the WBD. The decrease was small and might be the result of error or fatigue from repeated testing. Because the number of participants in our study was unsatisfactory to offset these impacts, we think that it had an impact on the results of the analyses. With this small number of participants, we expected that the observed statistical significance would only be found in the comparison of some conditions in the "BCD with HA" group.

The small sample size of our study is a major limitation which made it difficult to yield general conclusions with statistical methods. Our study could show tendency towards the benefits of using WBD in BCD and BCD with HA bimodal users. Therefore, further studies with sufficient sample size should be performed to induce generalization.

Various types of hearing impairment were noted in the "BCD only" and "BCD with HA" groups. Hence, we could not assess the pattern of benefits from using the WBD in BCD and HA patients with certain types of hearing impairment. The duration of BCD use also varied from patient to patient, which may also cause a variety of benefits from the use of WBDs in each group. In general, the duration of BCD use has been reported to affect the degree of BCD adaptation and satisfaction; hence, the effect of WBDs on word and sentence recognition in BCD patients may vary depending on the duration of BCD use [18, 19].

Conclusion

This study indicated that the use of a WBD improves word and sentence recognition over the mobile phone compared to naïve mobile phones, in adult BCD bone recipients. For BCD and HA bimodal users, the use of a WBD provides additional benefits compared to using a WBD with a BCD alone. Therefore, application of a WBD to BCD patients or BCD and HA bimodal users is an effective way to deal with challenging listening conditions.

Acknowledgements This research was supported by Basic Science research program through the national research foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (NRF-2019K1A3A1A47000527) and by the Gangwon Institute for Regional Program Evaluation grant funded by the Korea government (Ministry of Trade, Industry and Energy) (No. R0005797).

Compliance with ethical standards

Conflict of interest This study was supported by Cochlear Ltd. and Resound Ltd. The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

References

1. Clamp PJ, Briggs RJ (2015) The Cochlear Baha 4 Attract System - design concepts, surgical technique and early clinical

results. Expert Rev Med Devices 12:223–230. https://doi.org/10.1586/17434440.2015.990375
2. Hakansson B, Tjellstrom A, Rosenhall U, Carlsson P (1985) The bone-anchored hearing aid: Principal design and a psychoacoustical evaluation. Acta Otolaryngol 100:229–239. https://doi.org/10.3109/00016488509104785
3. Iseri M, Orhan KS, Kara A, Durgut M, Ozturk M, Topdag M, Caliskan S (2014) A new transcutaneous bone anchored hearing device - the Baha(R) Attract System: the first experience in Turkey. Kulak Burun Bogaz Ihtis Derg 24:59–64. https://doi.org/10.5606/kbbihtisas.2014.45143
4. Hougaard DD, Boldsen SK, Jensen AM, Hansen S, Thomassen PC (2017) A multicenter study on objective and subjective benefits with a transcutaneous bone-anchored hearing aid device: first Nordic results. Eur Arch Otorhinolaryngol 274:3011–3019. https://doi.org/10.1007/s00405-017-4614-8
5. Kim G, Ju HM, Lee SH, Kim HS, Kwon JA, Seo YJ (2017) Efficacy of bone-anchored hearing aids in single-sided deafness: a systematic review. Otol Neurotol 38:473–483. https://doi.org/10.1097/MAO.0000000000001359
6. Saroul N, Akkari M, Pavier Y, Gilain L, Mom T (2013) Long-term benefit and sound localization in patients with single-sided deafness rehabilitated with an osseointegrated bone-conduction device. Otol Neurotol 34:111–114. https://doi.org/10.1097/MAO.0b013e31827a2020
7. Siau RT, Dhillon B, Siau D, Green KM (2016) Bone-anchored hearing aids in conductive and mixed hearing losses: why do patients reject them? Eur Arch Otorhinolaryngol 273:3117–3122. https://doi.org/10.1007/s00405-016-3941-5
8. Anderson I, Baumgartner WD, Boheim K, Alexander N, Arnolder C, D'Haese P (2006) Telephone use: what benefit do cochlear implant users receive? Int J Audiol 45:446–453. https://doi.org/10.1080/14992020600690969
9. Wolfe J, Morais Duke M, Schafer E, Cire G, Menapace C, O'Neill L (2016) Evaluation of a wireless audio streaming accessory to improve mobile telephone performance of cochlear implant users. Int J Audiol 55:75–82. https://doi.org/10.3109/14992027.2015.1095359
10. Hu Y, Tahmina Q, Runge C, Friedland DR (2013) The perception of telephone-processed speech by combined electric and acoustic stimulation. Trends Amplif 17:189–196. https://doi.org/10.1177/1084713813512901
11. Milchard AJ, Cullington HE (2004) An investigation into the effect of limiting the frequency bandwidth of speech on speech recognition in adult cochlear implant users. Int J Audiol 43:356–362. https://doi.org/10.1080/14992020400050045
12. Picou EM, Ricketts TA (2013) Efficacy of hearing-aid based telephone strategies for listeners with moderate-to-severe hearing loss. J Am Acad Audiol 24:59–70. https://doi.org/10.3766/jaaa.24.1.7
13. Vroegop JL, Dingemanse JG, Homans NC, Goedegebure A (2017) Evaluation of a wireless remote microphone in bimodal cochlear implant recipients. Int J Audiol 56:643–649. https://doi.org/10.1080/14992027.2017.1308565
14. Gawecki W, Stieler OM, Balcerowiak A, Komar D, Gibasiewicz R, Karlik M, Szyfter-Harris J, Wrobel M (2016) Surgical, functional and audiological evaluation of new Baha((R)) Attract system implantations. Eur Arch Otorhinolaryngol 273:3123–3130. https://doi.org/10.1007/s00405-016-3917-5
15. Byun SW, Oh SH, Chae SW, Park SN, Shim YJ, Cho KK (2007) Compromises between the frequencies of the colloquial phonemes and those of a new monosyllabic words list in Korean. Korean J Otorhinolaryngol-Head Neck Surg 50:573–578
16. Hahm TY (1986) Complementary study on construction of Korean word lists for speech audiometry. Inje Med J 7:1–19
17. Schwartz SR, Kobylk D (2016) Outcomes of bone anchored hearing aids (BAHA) for single sided deafness in nontraditional candidates. Otol Neurotol 37:1608–1613. https://doi.org/10.1097/MAO.0000000000001225
18. Faber HT, Nelissen RC, Kramer SE, Cremers CW, Snik AF, Hol MK (2015) Bone-anchored hearing implants in single-sided deafness patients: long-term use and satisfaction by gender. Laryngoscope 125:2790–2795. https://doi.org/10.1002/lary.25423
19. Nelissen RC, den Besten CA, Faber HT, Dun CA, Mylanus EA, Hol MK (2016) Loading of osseointegrated implants for bone conduction hearing at 3 weeks: 3-year stability, survival, and tolerability. Eur Arch Otorhinolaryngol 273:1731–1737. https://doi.org/10.1007/s00405-015-3746-y