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Long-term follow-up and review of the Bone Conduction Implant

Sabine Reinfeldt[a,*], Måns Eeg-Olofsson[b], Karl-Johan Fredén Jansson[a], Ann-Charlotte Persson[b,c], Bo Håkansson[a]

[a] Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden
[b] Department of Otorhinolaryngology Head and Neck Surgery, Institute of Clinical Sciences, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden
[c] Region Västra Götaland, Habilitation & Health, Hearing Organization, Gothenburg, Sweden

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ABSTRACT

Active transcutaneous bone conduction devices are a type of bone conduction device developed to keep the skin intact and provide direct bone conduction stimulation. The Bone Conduction Implant (BCI) is such a device and has been implanted in 16 patients. The objective of this paper is to give a broad overview of the BCI development to the final results of 13 patients at 5-year follow-up.

Follow-up of these patients included audiological performance investigations, questionnaires, as well as safety evaluation and objective functionality testing of the device. Among those audiological measurements were sound field warble tone thresholds, speech recognition threshold (SRT), speech recognition score (SRS) and signal to noise ratio threshold (SNR-threshold).

The accumulated implant time for all 16 patients was 113 years in February 2022. During this time, no serious adverse events have occurred. The functional improvement for the 13 patients reported in this paper was on average 29.5 dB (average over 0.5, 1, 2 and 4 kHz), while the corresponding effective gain was -12.4 dB. The SRT improvement was 24.5 dB and the SRS improvement was 38.1%, while the aided SNR-threshold was on average –6.4 dB.

It was found that the BCI can give effective and safe hearing rehabilitation for patients with conductive and mild-to-moderate mixed hearing loss.

1. Introduction

Bone conduction devices (BCD) have been developed considerably during the last 10–15 years, and several new devices have appeared on the market. A BCD is an important rehabilitation option for patients with conductive or mixed hearing loss and for patients with single-sided deafness. Common for all types of BCDs is the underlying principle of amplifying airborne sound into mechanical vibrations induced in the skull bone and transmitted to the cochleae, which can be achieved in different ways. A categorization of these devices is illustrated in Fig. 1, as a result of merging the categorizing figures in Reinfeldt et al. (2015a) and Håkansson et al. (2019). The first separation is between direct drive BCDs and skin drive BCDs. “Direct drive” means stimulation with direct bone contact, while “skin drive” refers to stimulation with skin between the transducer and the bone. All non-invasive BCDs are in the skin drive category as the vibrations are mechanically transmitted through the skin and not directly into the skull bone (Stenfelt and Goode, 2005a). These transducers are attached either with pressure, using a softband, a steel spring headband, or the Baha® SoundArc from Cochlear Bone Anchored Solutions (Mölnlycke, Sweden), or with adhesive, as Adhear from MED-EL (Innsbruck, Austria).

There were several disadvantages with the early version of non-invasive conventional BCDs, such as pain and circulation problems from the high static pressure, feedback issues (requiring the microphone and the transducer to be separated and e.g. be placed on opposite sides of the head), and sound quality issues because of the attenuation through the skin. These drawbacks remain to some extent with several of today’s non-invasive BCDs. To overcome these drawbacks, the direct drive percutaneous solution was developed in the late 1970s (Håkansson et al., 1985). This solution was early generically named the bone-anchored hearing aid (BAHA) and has become the golden standard with more than 300 000 patients over the world. The BAHA sound processor is attached to a skin-penetrating titanium implant in the skull bone and is now

* Corresponding author: Sabine Reinfeldt, Dept of Electrical Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden.
E-mail address: sabine.reinfeldt@chalmers.se (S. Reinfeldt).

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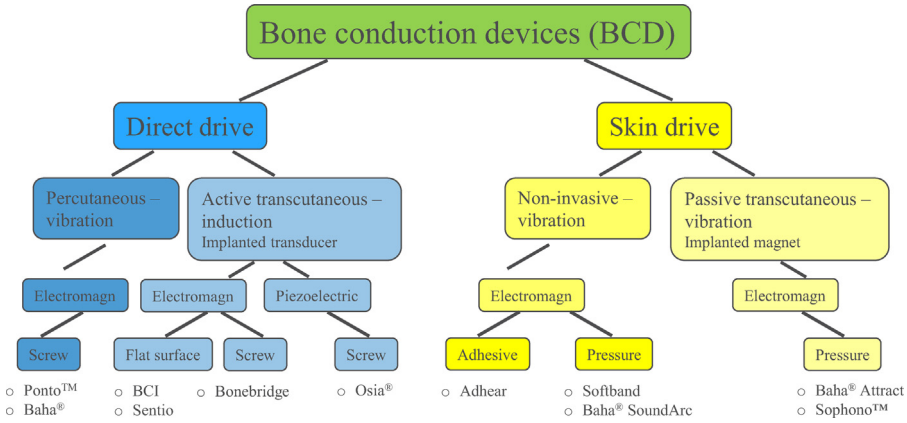

Fig. 1. Categorization of bone conduction devices (BCD) into two main categories; direct drive and skin drive. The vibration mechanism of the BCDs is either percutaneous, active transcutaneous, non-invasive or passive transcutaneous. Both electromagnetic or piezoelectric transducer solutions exists, as well as different attachment alternatives such as -titanium implant, flat surface, adhesive or static pressure. All devices mentioned are on the market, except for BCI and Sentio which are still in clinical studies.

commercially available from Oticon Medical (Askim, Sweden) manufacturing the Ponto™ system and from Cochlear Bone Anchored Solutions (Mölnlycke, Sweden) manufacturing the Baha® system.

Skin-penetration has been regarded as a source of complication for the BAHA, and substantial efforts have been made to reduce the number and the extent of the complications, such as changing the coating of the implant (Dun et al., 2011; Ivanoff et al., 1997; Palmquist et al., 2010) and the surgical technique (Hultcrantz, 2011; Hultcrantz and Lanis, 2014; van de Berg et al., 2010). In a systematic review of ten years of Ponto devices on 1146 patients conducted by Lagerkvist et al. (2020), it is shown that the number of skin complications is the most common type of complication and that one in seven patients can expect a skin complication requiring treatment.

The goal to have intact skin instead of a percutaneous implant has triggered the development of transcutaneous devices, and there are now solutions available of both skin drive and direct drive types. All solutions use retention magnets to keep an external audio processor in place. For the skin drive solutions, also called passive transcutaneous BCDs, one or two magnets are implanted during surgery, and the transducer is placed in the same housing as the externally worn audio processor. For the direct drive solutions, also called active transcutaneous BCDs, the transducer is implanted in direct contact to the skull bone underneath the skin, and the signal is transmitted over the skin via an induction link.

The number of active transcutaneous BCD solutions are increasing and have slightly different design principles. Bonebridge™ from MED-EL (Innsbruck, Austria) uses an analog induction link for sound transmission through the skin and the electromagnetic transducer is placed subcutaneously in a predrilled hole and attached to the skull bone using two stationary screws on opposite sides of the transducer, transmitting the vibrations to the bone. Osia® from Cochlear Bone Anchored Solutions has a digital induction link and the transducer is attached to a titanium screw (which is also used in their Baha® solutions) which in turn is anchored in the skull bone and transmits the vibrations. Osia®'s transducer is of piezoelectric type, unlike the other BCDs, to improve the magnetic resonance (MR) compatibility. The Bone Conduction Implant (BCI) is in a clinical trial and has been developed in a collaboration between Chalmers University of Technology and Sahlgrenska University Hospital in Gothenburg, Sweden. The implanted transducer in the BCI is wirelessly driven via an analog induction transmission link and attached to the skull bone with a flat surface in a predrilled hole with a small static pressure obtained by a titanium wire. Sentio from Oticon Medical is in the final clinical phase and is based on the BCI and adapted to their transducer and audio processor platforms. Sentio achieves its power transmission via an analog amplitude modulated induction link to an implanted titanium-cased electromagnetic transducer with a flat surface attachment that transmits the vibrations. The transducer casing is fixed by a thin silicone covered titanium band and secured in the bone using self-drilling screws on each side of the band.

This article is focusing on the BCI to give a review over preclinical and clinical studies, and to give the latest updates for the long-term clinical study including the 5-year follow-up results.

There are several stages in the developing process of an implantable device before it can be used in clinical studies. For the BCI, all these stages were investigated in separate preclinical studies, divided into different categories: transducer design, implant position, attachment method, biocompatibility, induction link, feedback stability, MR compatibility and robustness. Among the clinical studies, there have been several investigations within the main clinical trial with audiometric tests and questionnaires, the functionality of the implant, and further clinical studies about localization and spatial abilities.

Transducer design: The balanced electromagnetic separation transducer (BEST) was developed by Professor Bo Håkansson at Chalmers, being smaller, more efficient and having lower total harmonic distortion than the previous BAHA transducers of variable reluctance type (Håkansson, 2003). The reduction in size made it suitable for implantation in the temporal bone. Consequences of different transducer sizes were investigated in a study using computer tomography images of temporal bones from 22 subjects virtually reconstructed in a 3D model, inserting a virtual implant of varying diameter and height (Reinfeldt et al., 2015b). It was demonstrated that a transducer casing of diameter 15.5 mm and height 6.4 mm, close to the present BCI transducer size, fits in more than 95% of normal size temporal bones.

Implant position: Studies have shown that the transmission to the cochlea is more efficient the closer to the cochlea the transducer is positioned. This has been investigated by stimulating at different skull positions, measuring the resulting vibration velocity of the promontory with a laser Doppler vibrometer (LDV) in cadavers (Eeg-Olofsson et al., 2008; Håkansson et al., 2008, 2010; Stenfelt and Goode, 2005b), in BAHA patients (Eeg-Olofsson et al., 2013) and in normal hearing subjects measuring thresholds and ear-canal sound pressure (Reinfeldt et al., 2014). Eeg-Olofsson et al. (2008) used LDV measurements on seven human cadavers, stimulating at eight positions on each side, and found that the velocity of the cochlear promontory increases with closer stimulation to the cochlea. Above 500 Hz, the average vibrational response at the cochlea was 10–20 dB

higher close to the cochlea as compared with the normal BAHA position. LDV measurements on three cadaver heads by Håkansson et al. (2010) showed that stimulation from the BCI position produces 0–10 dB higher maximum output acceleration level at the ipsilateral promontory than stimulation from the BAHA position at speech frequencies. Eeg-Olofsson et al. (2013) measured the vibration velocity of the lateral semicircular canal and the cochlear promontory with LDV on 16 BAHA patients with a unilateral middle ear common cavity, using four stimulation positions. Also masked BC thresholds were measured from the same stimulation positions. Similar trends were seen for vibration and threshold data, but with low correlation at the individual level. The average difference between a position close to the BCI position and the BAHA position in thresholds and LDV measures was -3–7 dB in 0.5–3 kHz. Reinfeldt et al. (2014) measured BC thresholds and ear-canal sound pressure (ECSP) on 20 normal hearing subjects for stimulation at the BAHA and the BCI positions. The difference between the BCI and the BAHA positions were around 2–14 dB in average for both measures, and the relative ECSP and the relative thresholds showed similar frequency dependence. It was also discovered that the improved sensitivity below 500 Hz measured by thresholds and ECSP was not shown by LDV measurements in previous studies.

Attachment method: Rigato et al. (2018, 2019) investigated if and how the transducer-to-bone attachment influences vibration transmission to the cochlea. With BC stimulation from three different attachment methods in the same position on four cadaver heads the transmission efficiency was measured as velocity with LDV at the cochlear promontory and ECSP on both ipsilateral and contralateral sides. The attachment method seems to affect the transmission mainly at frequencies above 5 kHz, and a smaller contact surface might perform better at mid and high frequencies. As an average over the whole frequency range, the results are comparable from the different attachment methods. Rigato et al. (2019) also showed that the same trends were seen ipsilaterally and contralaterally, and furthermore that the transcranial attenuation mainly differed between different positions, and not between different attachment methods at the same position.

Biocompatibility: In an animal study with three sheep, the vibration transmission characteristics were studied over time (Taghavi et al., 2013), measuring the mechanical point impedances and vibration transfer response functions of BCI implants at time of surgery and after 8 months. The results indicated that the BCI implants osseointegrate and that the transmission conditions remain stable over time. Eeg-Olofsson et al. (2014) assessed the osseointegration of the same implants using quantitative and qualitative histology as well as cone beam computed tomography and computed tomography. The histology sections of the bone close to the implant showed bone remodeling, compact bone and osseointegration. It was shown that to use a flat surface contact between the implant and the bone can be a feasible method for efficient vibration transmission to the skull bone.

Induction link: The induction link is a very critical component in an implantable hearing system, and it must be optimally designed otherwise it may imply a loss of more than 10–15 dB as compared to direct drive system (Taghavi et al., 2012a). Several demands need to be considered on a well-functioning induction link for transcutaneous transmission in hearing implants. It should provide an efficient transfer of power, minimize loss of power in both driving and demodulation circuits, while delivering highest possible maximum force output from the implanted transducer. Moreover, the link should be capable to keep its performance even if the skin thickness varies between patients and over time.

A first design of an analog radio frequency (RF) data and power link was described by Taghavi et al. (2012a). It was designed to transmit maximum power to the implant using amplitude modulation (AM). In the investigation, it was found that the transmission was excellent but the tolerance to skin thickness was only 2–6 mm and that the current consumption was too high. Therefore, a new switched class E design was developed which was better in terms of skin thickness tolerance but required a high quiescent current (Taghavi et al., 2012b). Finally, a half bridge Class D design was developed, using an application specific integrated circuit (ASIC) which was found sufficiently good and is used in the present BCI system (Taghavi et al., 2015). By this design the maximum output force measured on a Skull simulator was found to be 107 dB re. 1 μN at a skin thickness of 5 mm and with a maximum change of 1.5 dB for skin thicknesses between 2 and 8 mm. After demodulation the inductive link was driving an impedance matched BEST transducer that also includes a high frequency boost at around 3–6 kHz accomplished by a special mechanical resonance arrangement.

Feedback stability: One advantage of having an implanted transducer is that stability margins increase and thus the gain can be increased without feedback problems. Another practical advantage is that the patient can use soft head wear, which is difficult, or even impossible, using a percutaneous device. In a study by Taghavi et al. (2012c) using a dry skull model, it was shown that the maximum stable gain of a BCI system could be increased by 10–30 dB depending on frequency, if compared to a percutaneous system when the output is related to the cochlear vibration measured by LDV.

MR compatibility: The magnetic resonance compatibility of the BCI has been assessed in two studies by Fredén Jansson (2015; 2014). In Fredén Jansson et al. (2014), demagnetization and torque (measured and simulated) were studied for magnets of two types of coercive fields, in a uniform static magnetic field of 1.5 Tesla. The magnet type used in the BCI implant, with the highest coercive field strength, was only demagnetized by 7.7% (average over eight magnets) and the maximum induced torque on these magnets was 0.20 Nm (while the low coercive field magnet, the demagnetization and maximum torque was 71.4% and 0.18 Nm, respectively). In Fredén Jansson et al. (2015), the MR effects was assessed on an implant worn externally on the head of a test person with a static pressure using a bandage and scanned in a 1.5 Tesla MR camera. It was shown that the MR exposure had minor effect on the maximum power output (decreased with 1.1 dB), that the total harmonic distortion was increased slightly at frequencies $<$300 Hz, and that the retention magnet was demagnetized by 5%. There was an expected image artifact, which reached a distance of 9–10 cm for the MR sequences used. These results indicate that the BCI should be approved as MR conditional at 1.5 Tesla. For MRI scanners with higher static magnetic field strengths, such as 3 Tesla, further investigations must be performed as the effect on transducer performance and patient safety risks are still unknown at those levels. At this point, the MRI conditions for the BCI implant are expected to be similar to those for Bonebridge™ which is MR conditional up to 1.5 Tesla as both implants comprise similar retention magnets and electromagnetic transducers. The Osia®, which is using a piezoelectric transducer, is MR conditional at both 1.5 and 3 Tesla, but only under the condition that the retention magnet is surgically removed prior to 3 Tesla scanning.

Robustness: Fredén Jansson et al. (2019) developed methods to test and evaluate the mechanical robustness that were used to study the BCI implant. The tests were originally developed for cochlear implants but was modified for BCDs and included a random vibration test, a shock test, a pendulum test, and an impact test. The pendulum and the impact tests had the largest effect on the electroacoustic performance, but the change in performance was within acceptable limits ($<$20%). More specific, the lower and higher resonance peaks in the frequency response were slightly shifted downwards in frequency by 13% and 18%, respectively, and

the corresponding peak magnitudes decreased by 1.1 and 2.2 dB. The BCI passed all tests, and the lifetime was estimated to be at least 26 years for an average use of 12 h per day when the study was published. This accelerated test is still ongoing, exposing an implant to high sound level (78.6 dBA) 24 h per day, creating an accelerating factor of 7. In February 2022 the device still functions normally, and the estimated lifetime is hence expected to be at least 48 years.

The BCI is in clinical trial with 16 patients, 13 in Gothenburg and three in Stockholm, Sweden. The results from the clinical trial have been presented in several publications. After one month for the first patient, results were published with focus on the surgical procedure (Eeg-Olofsson et al., 2013). It showed that the surgery was perceived easy and safe, with beneficial audiological results for the patient. The next publication presented results after the six-month use for the first six patients (Reinfeldt et al., 2015c). The focus of this publication was on audiometric results and showed a significant improvement against unaided situation, and similar or better results as compared to a reference device, a Ponto Pro Power on a softband (Oticon Medical, Askim, Sweden). The one-year results were presented for all 16 patients by Håkansson et al. (2019), giving the same main conclusion about the improvement and focused also on the audibility of the patients, showing quite good audibility and that the patients were well amplified at low and mid frequencies but likely a bit under-amplified at high frequencies. The patients in Gothenburg have been followed for a longer time, and the three-year results of the first ten patients were presented by Persson et al. (2020). This study showed the same benefit as before with stable results over time, and that the transducer performance and transmission to bone is unchanged over time, and the skin area under the audio processor remains without complications.

During surgery, after inserting the implant, an implant functionality test was performed before closing the incision. The implant was stimulated electrically, and for a fully functioning implant, vibrations are spread throughout the skull bone and radiated as sound in all cavities of the head. This sound can be heard from outside, but also measured objectively in the ipsilateral nostril, which is a non-sterile area during surgery. The nasal sound pressure (NSP) turned out to be stabile over time in each subject but varying between subjects (Reinfeldt et al., 2019). The same test has been used in all follow-up-visits to verify the functionality of the implant over time. So far in the clinical study, all implants have been working as expected, and the study also shows stable implant-to-bone transmission.

Furthermore, in a study by (Asp and Reinfeldt, 2018), the localization and spatial abilities with the BCI were investigated in aided and unaided situation using an eye-tracking setup. The sound was played from a loudspeaker and the gaze of the eyes was measured to find an error index of 0 to 1, where 0 is perfect and 1 is purely chance. Nine of eleven BCI patients experienced similar or improved localization with the BCI compared to unaided situation. In a study by Rigato et al. (2020), spatial release from masking (SRM) was measured as the difference in speech reception threshold between co-located and separated speech and competing speech sources in a setup with loudspeakers around the subject. The speech reception thresholds with the BCI were improved or maintained, while the SRM was lower for a majority of all included patients. The BCI fitted unilaterally in patients with bilateral or unilateral conductive/mixed hearing loss seems to reduce SRM.

In the main clinical study, the reference device was a BAHA on a softband, but the desired comparison is the BCI versus the percutaneous BAHA. Therefore, a matched study was performed, using the same audiometric tests and questionnaires on BAHA patients matched on an individual level based on hearing impairment, age, and gender (Rigato et al., 2016). The results were very similar to the BCI results and no statistically significant difference was detected in any of the audiological measurements, while the outcome of the questionnaires was slightly superior for the BCI in all subscales.

In a recent study (Persson et al. 2022), the aim was to measure the audibility of the individual user by objective measures. This pilot study proposes a method using a skin microphone (originally developed by Hodgetts et al. (2018)), measuring in-situ sound field thresholds, maximum power output and international speech test signal response, placing the skin microphone on the forehead. Measurements were made on normal-hearing subjects using a BAHA on a softband, and the aim for the future is to use this method in all types of BCDs.

The clinical study for the BCI is finalized and the 5-year follow-up visit has passed for all 13 Gothenburg patients, as planned. The aim in this paper is to present a broad overview of the BCI development from the initial ideas to the long-term results for BCI users with focus on the 5-year follow-up. A second aim is also to compare the BCI results to a reference device consisting of a Ponto Pro Power on a softband.

2. Material and methods

2.1. Subjects

In this long-term investigation, the 13 patients from Gothenburg are included (5 males and 8 females, ages 18–67 years, average age 32.2 years), with the following original inclusion criteria: (1) unilateral or bilateral conductive hearing loss with an air-bone gap of at least 20 dB (average over 500, 1000, 2000 and 4000 Hz); (2) pure tone average bone conduction (PTA_4BC) of 30 dB HL or better; (3) either rejecting or being unable to use conventional air conduction hearing aids; (4) to be accessible for multiple follow-up visits according to the protocol and be motivated to be one of the first subjects using the BCI. Table 1 shows the demographic and audiometric data of the 13 patients in this investigation.

2.2. Procedure

Before the surgery, all subjects were fitted with a BAHA (Ponto Pro Power, Oticon Medical, Askim, Sweden) on a softband, which from now on referred to as the reference device. It was fitted using in-situ thresholds with the algorithm NAL-NL1 in the software Genie Medical (Oticon Medical, Askim, Sweden), using omnidirectional microphones, and all automatic functions turned off (including feedback and noise manager). The reference device was used for four weeks and thereafter the subject's performance with the device was assessed with audiometric tests, described in 2.2.1, and with the two questionnaires Abbreviated Profile of Hearing Aid Benefit (APHAB) and Glasgow Benefit Inventory (GBI), described in 2.2.2.

The implantation of the internal unit of the BCI was performed under general anesthesia, using the procedure described in detail by Eeg-Olofsson et al. (2014) and Reinfeldt et al. (2015c). The transducer was placed in a 3–5 mm deep drilled recess, with 20 mm between the ear canal opening and the transducer center. A small channel for the neck of the internal unit was also drilled. After inserting the whole unit, the transducer was fixated with a small static pressure from a titanium wire in all patients except one where a flexible titanium plate was used. Before closing the incision, the functionality of the implant was verified with the NSP method, stimulating the implant electrically and measuring the NSP, according to Reinfeldt et al. (2019).

The external BCI audio processor was fitted 4–6 weeks after surgery, with linear amplification using the computer-based software ARK base (ON Semiconductor, Phoenix, AZ, USA). In this fit-

Table 1
Demographic and audiometric data. Mix = mixed hearing loss, Con = Conductive hearing loss, RC = Radical cavities, CM = Congenital malformation, Uni = Unilateral, Bi = Bilateral, ABG = Air-Bone-Gap.

	Patient characteristics				Right PTA_4 [dB]			Left PTA_4 [dB]		
Pat	Gender	Age	Etiology	Implant side	AC	BC	ABG	AC	BC	ABG
1	f	42	Uni, Mix, TS	R	65	20	45	14	13	1
2	m	48	Bi, Con, RC	L	73	16	56	53	30	23
3	m	18	Uni, Con, CM	R	54	−4	58	0	−4	4
4	f	67	Bi, Con	L	51	13	39	56	13	44
5	f	48	Bi, Mix	R	74	30	44	59	30	29
6	m	49	Bi, Con	L	41	13	29	68	15	53
7	m	20	Uni, Con	L	3	0	3	35	0	35
8	m	49	Bi, Con	L	64	20	44	69	26	43
9	f	20	Uni, Con	L	19	9	10	76	21	55
10	f	21	Bi, Mix	L	50	19	31	70	15	55
11	f	40	Uni, Con, CM	L	5	0	5	31	5	26
12	f	43	Uni, Con, CM	L	1	1	0	76	10	66
13	f	32	Bi, Mix	R	54	14	40	43	16	26

ting, no automatic features were activated, but for some of the patients, modest compression for high-level sounds was applied after interaction with the patient.

After the fitting procedure, audiometry tests described in 2.2.1 were performed, as well as the implant functionality test and the retention force to the implant magnet, described in 2.2.3.

Follow-up visits were then performed 1, 3, 6, 12, 36 and 60 months after the fitting procedure. Some of these visits have been postponed because of Covid or private reasons. All audiometric tests (2.2.1) and objective measurements (2.2.3) were performed at all visits, while the questionnaires APHAB and GBI were used at 6, 12, 36 and 60 months after fitting and International Outcome Inventory of Hearing Aids (IOI-HA) was added at 36- and 60-month visits.

2.2.1. Audiometry

The audiometric tests were performed in a sound-proof room of 16 m^3, and all equipment was calibrated according to standards (ISO 8253–1, 2010; ISO 8253–3, 2012). All measurements were controlled by an AC40 (Interacoustics A/S, Middlefart, Denmark) audiometer, and the sound field signals were presented from two loudspeakers placed 1 m in front of the subject at head level.

To remove the AC sound to the non-test ear, blocking was applied by inserting a foam ear-plug (E-A-R Classic Soft) as deep as possible to minimize the occlusion effect (Stenfelt and Reinfeldt, 2007) and covering the ear with an aural earmuff (Peltor™ 3M™ Svenska AB, Sollentuna, Sweden). The blocking was used in all measurements for patients with better AC hearing at the non-implanted ear than the implanted ear. Blocking was chosen instead of masking since masking would otherwise reduce the sensitivity of the bone-conducted sound transmitted from the other side of the head. This is more similar to real-life situations where both cochleae are active and contribute to hearing sensation even if there is only one device.

The audiometric tests were the following four: (1) Sound field warble tone thresholds (250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz) for unaided and aided condition; (2) Sound field speech recognition threshold (SRT) in quiet with Swedish spondees (ISO 8253–3, 2012) for unaided and aided condition; (3) Sound field speech recognition score (SRS) in noise with speech at 63 dB SPL and speech-to-noise ratio of 4 dB, using Swedish phonemically balanced words and prerecorded noise (ISO 8253–3, 2012) for unaided and aided condition; and (4) Sound field signal-to-noise ratio thresholds (SNR-thresholds) with five-word Hagerman sentences at a fixed speech level of 63 dB SPL and adaptive noise level to reach 50% speech intelligibility (Hagerman and Kinnefors, 1995) in aided condition.

To minimize any order effects, the measurement order was randomized between the follow-up visits for each patient, and also the order of the blocks unaided-aided was randomized, as were the speech lists in each speech test.

2.2.2. Questionnaires

The patient-related outcome measures were assessed in three questionnaires: APHAB, GBI and IOI-HA.

In APHAB the different questions focus on unaided and aided conditions, and the score is presented as in improvement for aided compared to unaided condition. There are four subscales: Ease of Communication (EC), Reverberation (RV), Background Noise (BN) and Aversiveness of sounds (AV) (Cox and Alexander, 1995). EC, RV and BN address speech understanding in various everyday environments, while AV quantifies negative reactions to environmental sounds.

GBI is quantifying the patient benefit in general, social support and physical health subscale scores (Robinson et al., 1996). Scores are provided on a scale of -100 to +100, where positive scores imply benefit in quality of life from the intervention.

IOI-HA has seven questions concerning aspects of hearing as daily use of the hearing aid, that focus on the wearer's experience separated from specific listening situations. The questions can be clustered in two factors, where "Use time", "Benefit", "Satisfaction" and "Quality of life" belong to Factor 1, and "Residual activity limitation", "Residual participation restriction" and "Impact on others" belong to Factor 2. The patients were answering an extra question concerning how many days a week they use their BCI. There are no normative data to support the results, but higher scores signalize successful rehabilitation and are on a scale from 1 to 5.

2.2.3. Objective measures

NSP measurements were used to verify the functionality of the implant, both at surgery and in follow-up visit. NSP was also used to provide an objective measure of the implant-to-bone transmission over time for each patient. An omni-directional microphone (EM-23346, Knowles Electronics, Itasca, IL, USA) attached to a probe tube within an E-A-R Classic ear-plug (3 M, Maplewood, MN, USA) was inserted in the ipsilateral nostril. The induction link was driven by using an Agilent 35670A (Keysight Technologies, Santa Rosa, CA, USA) as an FFT analyzer and speech frequency signal generator, and an Agilent 33220A (Keysight Technologies) as a carrier frequency and amplitude modulation signal generator. The driver stage was attached to the skin in the same way as an ordinary audio processor. For a functioning implant, vibrations are transmitted through-out the skull and radiating into all cavities, creating a sound pressure. This sound pressure was measured in the ipsilateral nostril using the Agilent 35670A in

the frequency range of 0.1–10 kHz. The procedure and results are further explained in Reinfeldt et al. (2019).

The magnetic force between the individual implant and a common customized audio processor was measured at each follow-up visit. It gives a measure of the skin compression, and if above 0.7 N, the magnet in the patient's audio processor was often changed to a weaker one.

2.3. Data analysis

The hearing improvement was calculated for each subject as the difference between the unaided and the aided condition, for the BCI and the reference device separately. The comparisons between the devices were made both at an individual level and at a group level. For the SNR-threshold test, which was done only in aided condition, comparison was done only between the devices. For the tone thresholds, both functional improvement (aided versus unaided sound field thresholds) and effective gain (BC thresholds versus aided sound field thresholds) were calculated. The unaided sound field thresholds used were based on the average unaided tone thresholds of all test occasions for each patient.

To test significant differences between unaided and aided condition (with null hypothesis of same thresholds unaided and aided), as well as between the devices (with null hypothesis of same improvement from the two devices), Wilcoxon signed rank test was used. For the warble tones, the statistical significance of the improvement at each frequency was tested at significance level $\alpha < 5\%$. No correction for multiple comparisons was deemed necessary since the tests are intended to identify at which frequencies the improvement differ from zero rather than to pairwise compare each frequency.

3. Results

The accumulated patient user time from surgery to the final submission of this paper (February 2022) is 113 years. During all this user time, there have been no serious adverse events. Two patients had transient pain where a weaker magnet led to elimination of the pain, and one patient has persistent skin sensibility loss superior to the incision line. One change of implant was conducted after eight months, because of a device deficiency, classified as not serious. The retention magnet was loose inside the titanium housing due to effective gluing, which did not create any disturbance for the patient when the audio processor was in place, only a clicking sound when attaching and removing it from its position on the head.

The audiograms (AC and BC thresholds from TDH 39 and B81) have not changed significantly for the patients since the inclusion audiogram.

Fig. 2 shows (a) the functional improvement and (b) the effective gain for the BCI (in blue) and for the reference device (in red). Please note that the effective gain is calculated for fewer frequencies as the original BC thresholds were not measured for all audiometric frequencies used in the sound field tone threshold measurements. The stars illustrate significant differences between the BCI and the reference device.

The average PTA_4 (500, 1000, 2000 and 4000 Hz) functional improvement is 29.5 dB (std: 7.2 dB) for the BCI and 25.2 dB (std: 10 dB) for the reference device. The functional improvement is statistically significant different from zero (aided significantly different from unaided) ($p < 0.05$) at all frequencies, except at 250 and 8000 Hz. The differences between the devices are statistically significant at 250, 500, 750, 2000 and 4000 Hz. The difference at 750 Hz is mainly related to a hard coded notch filter, suppressing the resonance peak in the reference device, whereas the difference

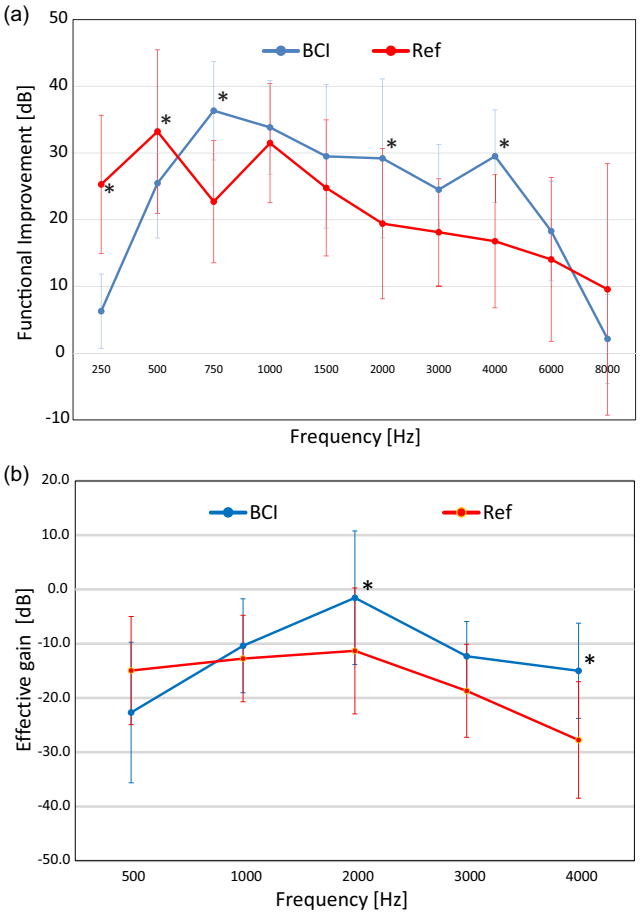

Fig. 2. (a) Functional improvement, and (b) effective gain, for BCI and reference device (Ref) from warble tone thresholds. Stars shows statistically significant differences between the devices.

between the devices in the frequency interval 2000–4000 Hz is expected due to the attenuation of vibrations in soft tissues using the reference device.

The average PTA_4 effective gain is -12.4 dB (std: 8.3 dB) for the BCI and -16.7 dB (std: 7.0 dB) for the reference device. The difference between the devices is statistically significant at 2000 and 4000 Hz.

Fig. 3 shows (a) the improvement in SRT and (b) the improvement in SRS for the BCI (in blue) and for the reference device (in red), for each patient and with the average over all the patients to the right. The standard deviation is shown for the average values. Both devices are statistically significantly better than unaided situation (SRT: BCI average improvement 24.5 dB, std 6.3 dB; Ref average improvement 24.9 dB, std 6.2 dB; SRS: BCI average improvement 38.1%, std 17.6%; Ref: average 44.1%, std 18.3 %), while there is no significant difference between the devices

Fig. 4 shows the SNR-threshold for the BCI (in blue) and for the reference device (in red), where more negative values are better and means that the patient can endure more noise with remained speech intelligibility. The SNR-threshold is in average -6.4 dB (std 2.1 dB) for the BCI and -2.9 dB (std 3.3 dB) for the reference device, and better with the BCI for ten of the 13 patients, which according to Wilcoxon signed rank test provides a statistically significant difference between the devices

The APHAB improvement for the different subscales is presented in Fig. 5a for the BCI (in blue) and for the reference device (in red), for all patients but patient 5, who is a non-user and did not answer the questionnaires. There is a statistically signifi-

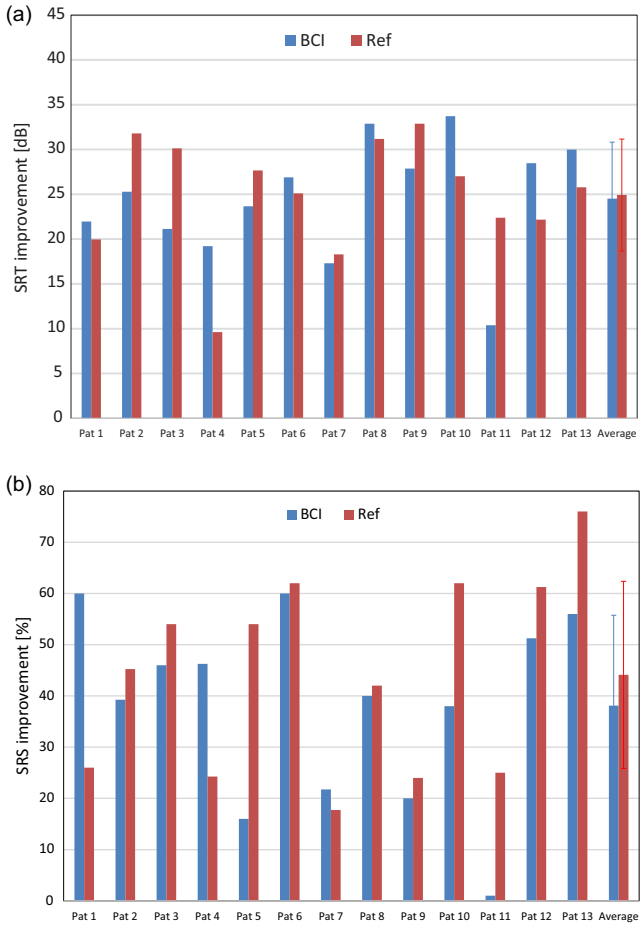

Fig. 3. (a) Speech Recognition Threshold (SRT) improvements, and (b) Speech recognition score (SRS) improvements, for BCI and reference device (Ref), for each patient and average with standard deviation.

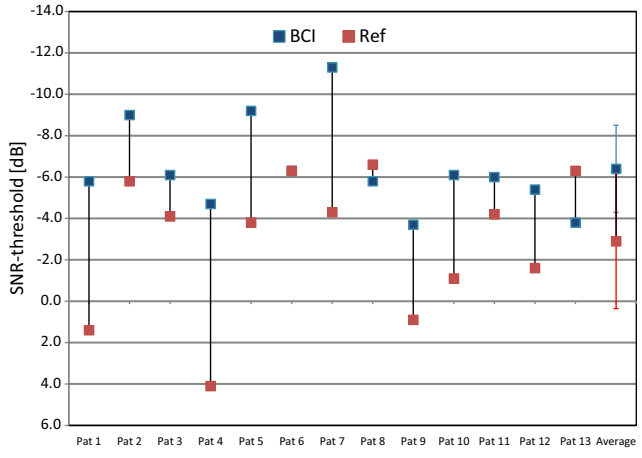

Fig. 4. Signal-to-noise ratio (SNR) threshold for BCI and reference device (Ref), for each patient and average with standard deviation. The difference between the devices is statistically significant.

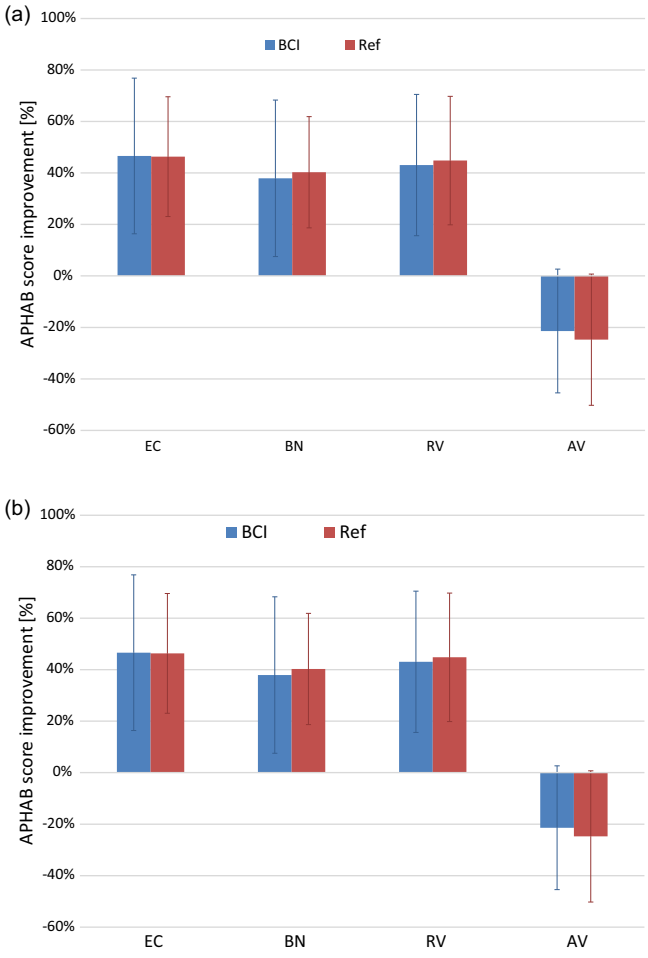

Fig. 5. (a) APHAB score improvement, and (b) GBI scores, for BCI and reference device (Ref). Average over patients 1–4 and 6–13, and standard deviations shown in error bars. EC = Ease of communication, BN = Background noise, RV = reverberant conditions, AV = Aversiveness of sound.

Table 2
IOI-HA results for five-year follow-up for patients 1–4 and 6–13. Q = Question, Use = Use time, Ben = Benefit, RAL = Residual activity limitation, Sat = Satisfaction, RPR = Residual participation restriction, Ioth = Impact on others, QoL = Quality of life.

Pat	Q1 Use	Q2 Ben	Q3 RAL	Q4 Sat	Q5 RPR	Q6 Ioth	Q7 QoL	Days/week
1	5	5	3	4	4	4	4	7
2	5	5	2	5	5	4	5	7
3	3	2	1	2	5	4	2	4
4	5	5	3	5	3	3	5	7
6	5	5	4	5	3	5	5	7
7	5	5	4	5	4	4	5	7
8	5	5	5	5	5	5	4	7
9	4	5	4	4	4	4	4	6
10	5	5	4	5	5	5	4	7
11	4	4	2	4	4	4	3	4
12	3	1	2	3	5	5	2	1
13	5	5	5	5	5	4	5	7
Average	4.5	4.3	3.3	4.3	4.3	4.3	4.0	5.9

cant difference between unaided and each device for subscales EC, BN and RV, but not for AV for the BCI. There are no significant differences between the BCI and the reference device. The GBI results are shown in Fig. 5b for the BCI (in blue) and for the reference device (in red). There is a statistically significant benefit for both devices, except in the physical health score.

The scores for the IOI-HA questions are shown in Table 2 for all patients but patient 5. The average scores for each question is included at the bottom row together with the average number of days per week of usage.

NSP has been measured at surgery and in follow-up visits as reported in Reinfeldt et al. (2019). The NPS values showed expected

normal transmission of a functioning implant at all occasions. An inter-subject comparison showed large variability, and the follow-up results showed minor variability within each subject with stable NSP over time.

No skin problems occurred related to the retention force, but some changes of magnet strengths were made. Patient 2 changed to a stronger magnet at the 3-month follow up and changed back to weaker magnets at 12 and 36 months. Patient 4 changed to a weaker magnet after 36 months. Patients 9, 11 and 12 changed to weaker magnets at the 1-month follow up, while patient 13 gradually changed to weaker magnets after 3 and 12 months. Generally, the retention force increased for all patients between the fitting and the 1-month visit with on average 0.15 N (std 0.10 N). This is expected because of compression of the skin and soft tissues between the audio processor and the implanted retention magnet, decreasing the gap between magnets resulting in increased contraction force. For the 5-year follow-up reported in this study, the average retention force was 0.72 N (std 0.26 N).

4. Discussion

In this long-term follow-up of patients with a BCI, the results are comparable with the shorter follow-up times presented in earlier publications (Eeg-Olofsson et al., 2013; Håkansson et al., 2019; Persson et al., 2020; Reinfeldt et al., 2015c). In summary for this study, the PTA_4 functional improvement was on average 29.5 dB (std: 7.2 dB) and the PTA_4 effective gain was on average -12.4 dB (std: 8.3 dB). The SRT and SRS improvements were 24.5 dB (std 6.3 dB) and 38.1% (std 17.6%), respectively, and the SNR-threshold was on average -6.4 dB (std 2.1 dB). The minor differences seen between the publications depend on how many patients that were included in each one, and variations over time, which are normal in subjective measurements.

The patients experience a significant benefit, using the BCI, shown with APHAB, GBI and IOI-HA. If comparing with previous publications of the clinical study of the BCI, a minor decrease of improvement over time in the APHAB and GBI results can be seen. Still there is no statistical difference between the BCI and the reference device. The decrease can be expected since it is normal that the patient-related outcomes of a hearing device is evaluated lower after a longer usage time. An enthusiasm bias can potentially affect shorter-term users, and in this study, it is a large difference in usage time between the reference device and the BCI. One can anticipate a similar decrease for a long usage time of the reference device, or even worse because of the disadvantages with the skin-drive feature and using a softband.

All patients, except for patients 3, 5, 11, and 12, are using their BCI regularly. Patients 3, 11 and 12 are temporary users with unilateral congenital pure conduction hearing loss, which is known to be a patient group with higher degree of non-users of BCDs (Nelissen et al., 2015). The reasons are speculated in by many, and these patients are doing quite well with their normal hearing in the contralateral ear. Patient 5 is a non-user with bilateral mixed hearing loss with a PTA_4 of 30 dB HL at inclusion, which is in the inclusion borderline, and has over time developed slightly poorer sensorineural hearing. This patient still wears the implant and awaits a stronger audio processor which may come as a second generation. Present first generation only use a half bridge power amplifier but a full bridge power amplifier, theoretically giving 6 dB higher MPO, is likely to come in the future but at the expense of higher current consumption.

4.1. Comparison with other bone conduction devices

As described in the Introduction, the BCI is an active transcutaneous BCD. The skin remains intact, which provides fewer skin complications compared to percutaneous devices. Compared to passive transcutaneous BCDs, it gives direct bone stimulation, which is an advantage by not being affected by skin attenuation. Therefore, it doesn't require as strong magnetic retention force, which further decreases the risk of skin complications.

Further investigations are needed, but there are also implications that the stimulation position used for the BCI provides higher transcranial attenuation, which should be advantageous for bilateral installation, as crossover limits the sound separation and leads to decreased ability in tasks requiring binaural hearing. Rigato et al. (2019) showed that the transcranial attenuation is lower at the BAHA position related to the BCI position, and this has also been shown in previous studies (Dobrev et al., 2018; Eeg-Olofsson et al., 2011; Reinfeldt et al., 2014; Stenfelt, 2012).

4.2. Comparison with studies on other active transcutaneous bone conduction devices

In a multicenter long-term study of Bonebridge™ (MED-EL, Innsbruck, Austria) with 55 patients having conductive or mixed hearing loss, the average PTA_4 functional gain was found to be 28.9 dB after 36 months (Sprinzl et al., 2021). The corresponding word recognition score in quiet improvement was 66.5% in average over 54 patients, and the SRT improvement was 24.7 dB in average over 51 patients. Their word recognition score in quiet cannot be directly compared to the SRS improvement in this study, where a noise of 4 dB SNR was included. However, the other results are comparable with this study's functional improvement and SRT improvement. In a recent study published by Cywka et al. (2022), it was presented that 42 patients with conductive or mixed hearing loss got an average functional gain of 27 dB after a follow-up time of 12 months. This is also comparable with the results in this BCI study.

Magele et al. (2019) did a systematic review and meta-analysis of the Bonebridge™, and the results for the conductive and mixed hearing loss group (corresponding to the included patient group for the BCI) were an average functional gain of 29.08 dB (58 patients; 7 studies), and an average aided SNR-threshold ranging from +2.9 dB to −6.1 dB (54 patients; 6 studies). The results for speech in noise tests was not possible to compare within this meta-analysis, but an improvement was observed in all studies with this patient group. It should be noted that the follow-up time in all studies included were less than one year. Magele et al. (2019) is showing similar results for the Bonebridge™ as for the BCI where a comparison was possible, except that the BCI showed slightly better SNR-threshold.

Osia® from Cochlear BAS (Mölnlycke, Sweden) received FDA approval in 2019 and got CE-marked in 2021. A few studies have been published with follow-up times of no longer than six months. Pla-Gil et al. (2021) showed an average functional gain of 35.9 dB (average of 0.5, 1, 2, 3 and 4 kHz comparing with unaided AC thresholds) and an SRS improvement of 30% (using an SNR of +5 dB at 65 dB SPL) for ten patients with Osia® and follow-up time of 6 months. The average SNR-threshold was −1.3 dB. Gawecki et al. (2020) implanted four patients with bilateral mixed hearing loss with Osia®. After a follow-up time of 3 months, they got an average functional gain of 42.8 dB. This seem a bit high as from Fig. 4 in their study, it can be estimated that the SRS improvement over the unaided condition (65 dB SPL in noise, SNR +5 dB) was 28% which is a bit lower than expected. High gain setting can give apparently good threshold improvement but sacrifice dynamic range and performance at speech levels. Lau et al. (2020) reported on ten patients with Osia® after a follow-up time of 4–6 months. Five of them had mixed and three of them had conductive hearing loss. The average functional gain was 31 dB and 22 dB in the two patient groups, respectively.

Goycoolea et al. (2020) found a functional gain PTA_4 of 36.88 dB after two months on nine Osia® patients, and a SNR-threshold of −2.2 dB after six months. Due to the low number of subjects in each study, it is difficult to make any significant conclusive statement about differences between systems, but in general, the audiometric sound field results on Osia® are in the same range as the results in this long-term study of 13 BCI patients. One study with longer follow-up time has been published by Rauch et al. (2021). The average follow-up time was 30 months and the number of patients were 22, out of which 19 had conductive hearing loss. The average functional gain for these patients was 30 dB, which is similar to this study for the BCI. They also state that the Osia® provides complication free surgery and low post-operative complication rate, which complies with what we have experienced with the BCI.

5. Conclusions

The BCI has been described and investigated in several preclinical and clinical studies, presented in this paper. No serious adverse events have occurred after 113 years accumulated use among 16 patients ranging from 5 to 9 years after surgery in individual patients. Long-term audiometric measurements showed significant improved hearing ability over the unaided situation and similar or better results compared to the reference device, a skin drive Ponto Pro Power on softband. It has also been shown to give similar results as other active transcutaneous BCDs.

The BCI has shown to be safe and effective for indicated patients where the main advantage over percutaneous devices is that no permanent skin penetration is needed and that feedback oscillations rarely occurs.

Contribution to Hearing Research

Special issue “Acoustic Implant Technology” by Christof Röösli and Stefan Stenfelt.

CRediT authorship contribution statement

Sabine Reinfeldt: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration, Funding acquisition. **Måns Eeg-Olofsson:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Karl-Johan Fredén Jansson:** Methodology, Investigation, Writing – review & editing, Formal analysis, Validation. **Ann-Charlotte Persson:** Investigation, Writing – review & editing. **Bo Håkansson:** Methodology, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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