Evaluation of a New Bone Conduction Device for the Rehabilitation of Single-Sided Deafness: Effects on Speech Understanding in Noise

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Introduction: A new external, adhesive, no-pressure bone-conduction device provides rehabilitation for conductive hearing loss and single-sided deafness (SSD). The purpose of the study is to evaluate speech recognition performance with the bone-conduction contralateral routing of signal (aBC-CROS) and compare it to an air-conduction CROS (AC-CROS) used by subjects for at least 1 year.

Methods: Ten SSD patients underwent speech understanding in noise tests with their AC-CROS, the aBC-CROS, and unaided. The 1st test session took place the day the aBC-CROS was fitted, with the second session after 2 weeks of aBC-CROS use. Two configurations were used: speech presented on the deaf side and noise on the normal side and the reverse.

Results: The speech recognition threshold (SRT) improved with both devices when speech was presented to the deaf side. Nine patients showed significant improvement ($p < 0.016$) with the AC-CROS (mean: 2.8 dB) and the aBC-CROS (mean: 3.0 dB). Mean difference of improvement was significant between unaided and aBC-CROS ($p = 0.001$) or AC-CROS ($p = 0.006$). The SRT deteriorated by an average of 2.3 dB with the AC-CROS with noise presented on the deaf side, with significance found for six patients ($p < 0.016$). The aBC-CROS did not affect performance in this configuration (mean improvement: 0.3 dB) and only one patient had a significant SRT degradation ($p < 0.016$). Mean difference of improvement was significant between the AC-CROS and aBC-CROS ($p = 0.021$) or unaided ($p = 0.05$).

Discussion: The aBC-CROS is a good alternative to the existing CROS devices for SSD rehabilitation, as it offers the same benefit with none of the drawbacks when noise is on the patient's deaf side. **Key Words:** Adhesive device—Audiology—Bone conduction—Contralateral routing of signal—Speech in noise.

Otol Neurotol **43:**105–112, 2022.

Single-sided deafness (SSD) has an estimated prevalence of 12 to 27 patients per 100,000 people (1). Patients with SSD have monaural hearing that prevents them from benefitting from binaural advantages. Although speech understanding in quiet is not problematic (2), difficulties become apparent in noisy environments (3,4). These difficulties are explained by the following three effects, underscored by the inability to combine acoustic cues as interaural level differences and interaural time differences (5,6). First, due to the head-shadow effect, sound coming from a source on the deaf side of a subject reaches the normal ear later than the deaf ear with a lower intensity contributing to a 4 to 7 dB hearing loss in noise (7,8).

The head-shadow attenuates the high frequencies (by 20 dB) more than the low frequencies (by 3–6 dB). Then, Squelch effect, based on combining information in the brain from the two ears, is absent for SSD patient. It refers to the segregation of speech relative to background noise when both stimuli are on a horizontal plane (4,9,10). In normal-hearing listeners it results in a benefit of about 3 dB (4,11,12). Finally, the summation effect which results from the addition of the signal presented to both ears, is absent in SSD patient. In normal hearing listeners it provides a moderate benefit of 1.5 to 2.9 dB (4,11,12).

SSD patients can also have socio-behavioral issues, difficulties in everyday activities and decreased quality of life or social interactions (13–17). Tinnitus, spatialization problems and balance or posture disorders are further problems that may arise (18).

SSD patients can be rehabilitated using contralateral routing of signal (CROS) by air conduction (AC-CROS) or bone conduction (BC-CROS) to capture the sound signal on the impaired ear and transfer it to the contralateral healthy cochlea. BC-CROS uses the principle of transcranial transfer; the sound is transmitted both to the ipsilateral cochlea as well as to the contralateral inner ear through the vibration of the skull bones. This results in

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The authors disclose no conflicts of interest.

DOI: 10.1097/MAO.0000000000003364

attenuation that depends on the sound frequency, the transducer, and the type of conduction (on average 50–60 dB with AC and 0–5 dB with BC). The advantage of BC-CROS over AC-CROS is that the hearing ear's external auditory canal is not obstructed. CROS does not restore stereophony which requires two functional ears to process information in the brain (19).

Many patients who are good CROS candidates end up rejecting the system. In a literature review, Wendrich et al. (20) found that 32 to 69.6% of patients refused implantation of a BC-CROS after a trial period, mainly due to limited benefit. Hill et al. (21) reported that 72.5% of users of an AC-CROS system chose to keep it after a 30-day trial, while Linnebjerg and Wetke (22) showed that only 42.5% of users wore it more than 4 hours a day. These issues may be explained by problems with gain (23).

Results with CROS systems can vary depending on the testing configuration (24–26). If the speech is presented on the deaf side and noise on the hearing side ($S_{SSD}N_{NH}$), CROS provides better results since it improves the signal-to-noise ratio (SNR) on the hearing ear. However, when the noise is on the deaf side and speech on the hearing side ($S_{NH}N_{SSD}$) or from the front ($S0N_{SSD}$), the SNR is impaired and performance subsequently declines compared with unaided performance (26–39). In a meta-analysis, Kitterick et al. (25) found a 2.5 dB benefit with CROS in the $S_{SSD}N_{NH}$ configuration; however, this led to a 3.9 dB (AC-CROS) or 2.3 dB (BC-CROS) degradation of the SNR in the $S_{NH}N_{SSD}$ test condition.

Recently, a new external bone conduction device for the rehabilitation of conductive hearing loss and SSD entered the market. It is composed of a BC audio-processor, which is clipped via a connector to an adhesive adapter. It is then stuck to the smooth part on the tip of the mastoid, but it can also be adapted on a headband. The transmitting principle is the same as other skin-driven BC devices and the effectiveness and advantages seem to be comparable (40). Moreover, the adhesive component avoids pressure on the mastoid that other systems require to transmit the vibrations through the skin. This could limit the amount of pressure and soft tissue reaction or other adverse events frequently found with BC devices (41).

We wondered whether the absence of mastoid pressure might compromise the efficiency of the non-implantable BC device in our study, and sought to determine whether or not the device was able to provide results equivalent to or better than other prosthetic solutions. We aimed to evaluate the new BC device (aBC-CROS) in SSD patients already fitted with an AC-CROS. We compared speech understanding in noise in the aided and unaided conditions. These devices have already been evaluated in a similar population (42,43), with no significant differences found between aBC-CROS and the unaided condition for speech understanding in noise. However, Mertens et al. (42) used the testing configurations S0N0, $S0N_{SSD}$, and $S_{SSD}N_{NH}$ (0 = in front of the patient; SSD = impaired ear; NH = normal ear). We limited our study to the head shadow effect, using the $S_{NH}N_{SSD}$ condition (as in Cho et al. (43)) to place the patients in a complex situation in which performance has been shown to be the most affected. According to the literature, scores for the CROS system are expected to have the greatest variations in this condition. We decided to limit the study to this condition because adding further tests in noise could have caused the patient to become fatigued.

MATERIAL AND METHODS

Aim of the Study

Speech recognition performance with the aBC-CROS (ADHEAR, MED-EL, Innsbruck, Austria) was compared with an AC-CROS that the patient had used on a daily basis for at least 1 year. Study participants tested the aBC-CROS for a minimum duration of 15 days, after which period the speech recognition tests with both devices were performed. In accordance with the declaration of Helsinki, written informed consent was obtained from the participants before their inclusion into the study. The protocol of this clinical study was approved on May 23, 2019 by the ''Comité de Protection des Personnes Ouest 6'' (n° CPP 1155 DM2) ethics committee.

Population

Ten subjects were recruited in the Audition Conseil laboratories in Villeurbanne Gratte-Ciel and enrolled in the study (seven females, three males), ranging in age from 18 to 63 years (mean: 42.9 yr). All the subjects (six left ears and four right) suffered from long-standing SSD ($PTA_{0.5,1,2,4kHz} \geq 70$ dB HL and $PTA_{0.5,1,2,4kHz}$ better ear $\leq$30 dB HL, as defined by Van de Heyning et al. (44)). The mean auditory thresholds of the contralateral normal ear are represented in Figure 1. Etiologies were seven acoustic schwannomas (one intra-cochlear), one meningioma, and two unknown (congenital or acquired during

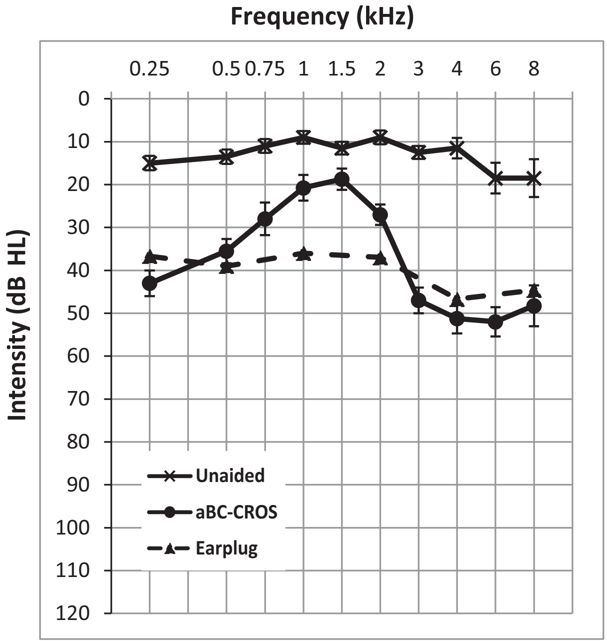

FIG. 1. Mean pure-tone threshold, measured with headphone, of the contralateral ears (unaided) and mean pure-tone threshold in free-field with the ADHEAR. Error bars indicate the standard error. The dashed curve represents the mean attenuation of the earplug, according to the data provided by the manufacturer Quies.

childhood). Before the study began, all patients were regular users of an AC-CROS (RITE Audéo by Phonak) for more than 1 year.

Material

Tests were performed using a Madsen Astera audiometer, a TDH 39 headphone, a BC vibrator (Radioear B71), and a pair of Triangle loudspeakers. The speech intelligibility tests in noise consisted of 40 lists of 10 dissyllabic words (45) uttered by a male talker (20 syllables for each list). For better precision, performance was measured by the percentage of syllables correctly repeated (this test normally counts the number of correct words). Cocktail-party noise, which is more representative of real-life situations than the white noise, was used. All the tests were carried out in an audiologic test room with very low reverberation (T60 $<$ 0.5 s at 500 Hz).

Procedure

During the first session (D0), AC and BC thresholds were measured after an otoscopy to confirm SSD, exclude deafness of the hearing ear, and avoid any conductive component. This first session also allowed for adaptation of the aBC-CROS and for the examiner to provide explanations and instructions regarding the usage and care of the device. Subsequently, tests in noise were performed. The aBC-CROS was then loaned to the patient for a trial of at least 15 days, after which point tests in noise were performed during a second session (D15).

The aBC-CROS's default program was selected (omnidirectional microphone with ambient noise reduction and anti-feedback algorithms) for all tests. The processing time of the aBC-CROS is 8 ms. The anti-feedback algorithm is a phase cancellation algorithm which operates by subtracting an internal estimate of the hearing-aid feedback signal from the microphone signal. The noise reduction algorithm is built upon a high-resolution 128-band filter bank. The signal-to-noise ratio (SNR) in each band determines the maximum amount of attenuation to be applied to the band; the poorer the SNR, the greater the amount of attenuation. Simultaneously, in each band, the masking threshold variations resulting from the energy in other adjacent bands is taken into account. Finally, the noise reduction gain is also adjusted to take advantage of the natural masking of ''noisy'' bands by speech bands over time.

For the AC-CROS tests, the patient's usual fitting was used (omnidirectional microphone, noise reduction, and anti-feedback algorithms). Pure-tone, free-field audiometry with the aBC-CROS was carried out to measure the threshold in the deaf ear with the normal ear obstructed with an earplug. The intelligibility test in noise was carried out in three conditions (unaided, patient's own AC-CROS, aBC-CROS). Two loudspeakers were placed at ear height 1 m away from the patient's head. One of the loudspeakers played a list of 10 dissyllabic words while the other played a cocktail party noise. The three conditions were tested in two configurations: 1) $S_{SSD}N_{NH}$: five lists; speech at 55 dB SPL on the deaf side; noise on the hearing side varying from 45 to 65 dB SPL (signal to noise ratio [SNR]: from +10 to −10 dB-SNR); 2) $S_{NH}N_{SSD}$: five lists; speech at 55 dB SPL on the hearing side; noise on the deaf side varying from 50 to 70 dB SPL (SNR: from +5 to −15 dB-SNR).

Statistics

For each testing configuration, the following effects were evaluated: intensity, time, and tested condition (Unaided, AC-CROS, or ADHEAR). Logistic regression analysis (logit model with likelihood maximization) was applied with score as dependent binary variable and intensity, time and tested condition as predictor variables. The Wald chi-squared test was used to test the significance of the predictor variables and to compare the quantitative variables 2-by-2.

Significance level was fixed to 0.05. When systems were compared 2-by-2, Bonferroni correction was applied to fix the significance level to 0.016.

For each patient, the SNR at which the subject had 50% intelligibility (SRT50) was evaluated from the logistic regression model.

For all the patients and for each testing configuration, mean SRT50 were compared between the tested conditions with a Friedman test and post-hoc Nemenyi tests. Significance level was fixed to 0.05.

RESULTS

Figure 1 shows the mean unaided pure-tone threshold of the contralateral healthy ears (measured with earphone), together with the mean aBC-CROS-aided pure-tone threshold measured in free-field with an earplug in the normal ear. The mean attenuation of the earplug is between 36 and 47 dB. The mean aBC-CROS-aided thresholds were poor at 250 Hz and above 3000 Hz. This was not due to the noise reduction or feedback algorithm, as due to the nature of the signal (warble tone) they were not working during the audiometry test. Poor thresholds could be due to the transcranial and transcutaneous attenuation (46).

Speech in Noise Tests

$S_{SSD}N_{NH}$ Configuration

Figure 2 represents the SRT50 obtained for the AC-CROS and aBC-CROS as a function of the SRT50 obtained in the unaided condition with speech presented to the deaf ear and noise to the normal-hearing ear ($S_{SSD}N_{NH}$). Nine patients showed significant improvement with the AC-CROS (one $p < 0.016$, $\text{Khi}^2 = 6.97$; four $p < 0.003$, $\text{Khi}^2 = 8.64$, 10.51, 11.36, 12.27; four $p < 0.0003$, $\text{Khi}^2 = 15.99$, 15.76, 27.14, 33.99) as well as the aBC-CROS (three $p < 0.003$, $\text{Khi}^2 = 8.64$, 10.11, 11.36; six $p < 0.0003$, $\text{Khi}^2 = 13.40$, 14.15, 16.74, 19.69, 18.03, 52.66). The linear regression lines show a significant correlation between the SRT50 obtained in unaided and aided conditions (AC-CROS: $R^2 = 0.62$, $p < 0.01$; aBC-CROS: $R^2 = 0.57$, $p < 0.05$). Both the AC-CROS and aBC-CROS provided a mean improvement of about 2 to 3 dB-SNR (AC-CROS: $y = 0.87x - 2.5$; aBC-CROS: $y = 1.09x - 3.2$).

Figure 3 compares the SRT50 with the aBC-CROS versus the AC-CROS. One patient scored significantly better with the aBC-CROS than with the AC-CROS ($p < 0.003$, $\text{Khi}^2 = 8.79$), while one subject's AC-CROS score was significantly better than aBC-CROS ($p < 0.016$, $\text{Khi}^2 = 6.93$). All subjects showed a statistically significant deterioration in performance when the noise level was increased ($p < 0.001$). Only one patient had a statistically significant effect of time in this

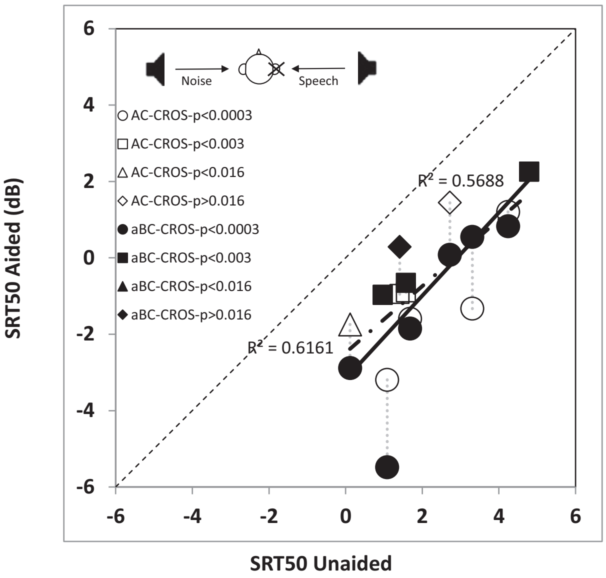

FIG. 2. SRT50 in aided condition AC-CROS (*empty symbols*) or aBC-CROS (*filled symbols*), versus unaided condition, in $S_{SSD}N_{NH}$ configuration, for the 10 patients. The various symbols represent the various degrees of significance, between aided and unaided condition. Dash-dotted line represents the linear regression for the AC-CROS, solid line represents the linear regression for the aBC-CROS. Vertical dotted lines link the results for the same patient.

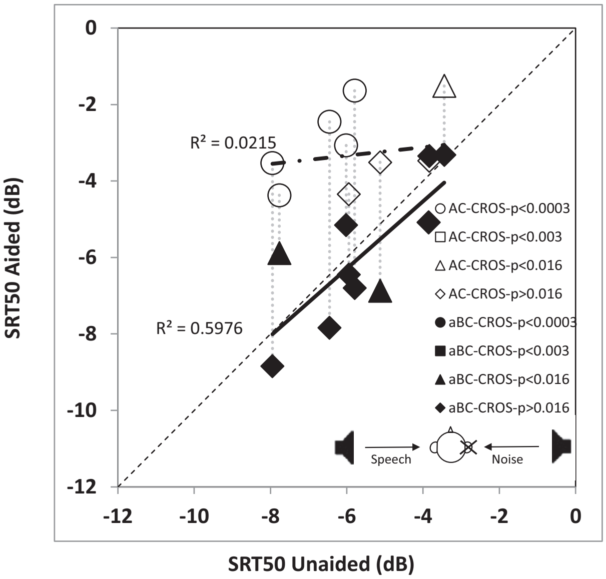

FIG. 4. SRT50 in aided condition AC-CROS (*empty symbols*) or aBC-CROS (*filled symbols*), versus unaided condition, in $S_{NH}N_{SSD}$ configuration, for the 10 patients. The various symbols represent the various degrees of significance, between aided and unaided condition. Dash-dotted line represents the linear regression for the AC-CROS, solid line represents the.

configuration (improvement between D0 and D15, $p < 0.01$, $\text{Khi}^2 = 7.42$).

$S_{NH}N_{SSD}$ Configuration

Figure 4 represents the SRT50 obtained for the AC-CROS and aBC-CROS as a function of the SRT50 obtained in the unaided condition with speech presented to the normal-hearing ear and noise to the deaf ear ($S_{NH}N_{SSD}$).

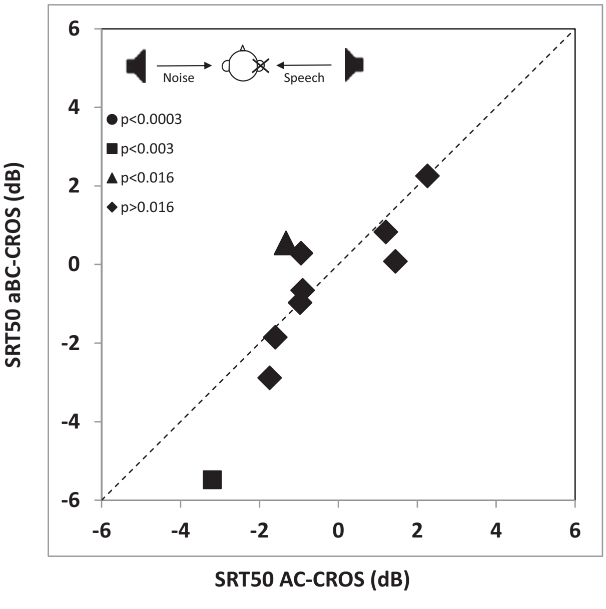

FIG. 3. SRT50 obtained with aBC-CROS versus SRT50 obtained with AC-CROS, in $S_{SSD}N_{NH}$ configuration, for the 10 patients. The various symbols represent the various degrees of significance, between aided and unaided condition.

Six subjects' performance deteriorated significantly with the AC-CROS (one $p < 0.016$, $\text{Khi}^2 = 8.03$; five $p < 0.0003$, $\text{Khi}^2 = 18.20$, 18.76, 25.95, 27.50, 28.45). One subject had significantly worse scores with the aBC-CROS than in the unaided condition ($p < 0.016$, $\text{Khi}^2 = 6.28$), while one patient improved significantly ($p < 0.016$, $\text{Khi}^2 = 6.09$). A significant correlation was found between the unaided and aBC-CROS-aided SRT50 ($R^2 = 0.60$; $p < 0.01$), but not the AC-CROS-aided SRT50 ($R^2 = 0.02$; $p > 0.05$). The regression line for the aBC-CROS is on the diagonal; i.e., the auditory performance was not affected by the aBC-CROS (the SRT was the same unaided and with the aBC-CROS). However, for the AC-CROS condition, the regression line indicates that performance in the aided condition is independent of the performance in the unaided condition.

Figure 5 compares the SRT50 with the aBC-CROS versus AC-CROS. For seven patients, the aBC-CROS was significantly better than the AC-CROS (one $p < 0.016$, $\text{Khi}^2 = 7.06$; two $p < 0.003$, $\text{Khi}^2 = 9.05$, 9.8; four $p < 0.0003$, $\text{Khi}^2 = 20.35$, 36.88, 37.17, 43.68). All subjects showed a statistically significant deterioration in performance when the noise level was increased ($p < 0.001$). The effect of time was significant for three patients, with one improvement ($p < 0.05$, $\text{Khi}^2 = 5.09$) and two deteriorations ($p < 0.05$, $\text{Khi}^2 = 5.09$; $p < 0.001$, $\text{Khi}^2 = 15.76$).

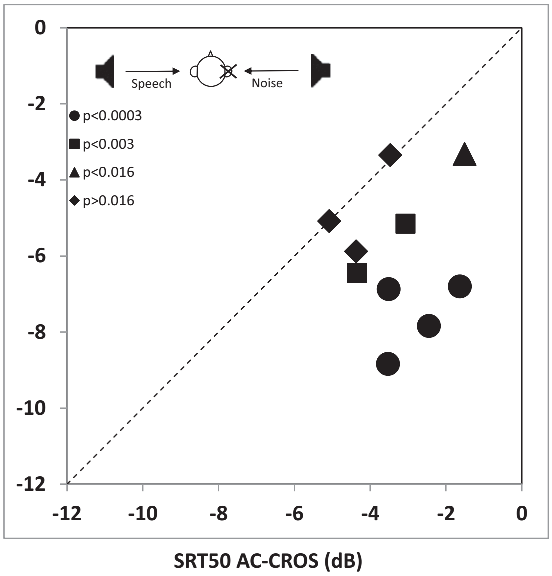

FIG. 5. SRT50 obtained with aBC-CROS versus SRT50 obtained with AC-CROS, in $S_{NH}N_{SSD}$ configuration, for the 10 patients. The various symbols represent the various degrees of significance, between aided and unaided condition.

Figure 6 shows the SRT50 in the $S_{NH}N_{SSD}$ configuration as a function of the SRT50 in $S_{SSD}N_{NH}$ configuration for the unaided, AC-CROS and aBC-CROS conditions.

Group Results

In the $S_{SSD}N_{NH}$ configuration, the mean difference in improvement of both devices over the unaided condition was significant (Friedman test $p = 0.0003$): 2.8 dB (SD = 1.1 dB; $p = 0.006$ versus unaided) for the AC-CROS and 3.0 dB (SD = 1.4 dB; $p = 0.001$ versus unaided) for the aBC-CROS. In the $S_{NH}N_{SSD}$ configuration, the AC-CROS provided a mean degradation of 2.3 dB (SD = 1.8 dB); the aBC-CROS a mean improvement of 0.3 dB (SD = 1.2 dB). Mean differences were significant (Friedman test $p = 0.012$): between AC-CROS and aBC-CROS ($p = 0.021$) or unaided ($p = 0.05$).

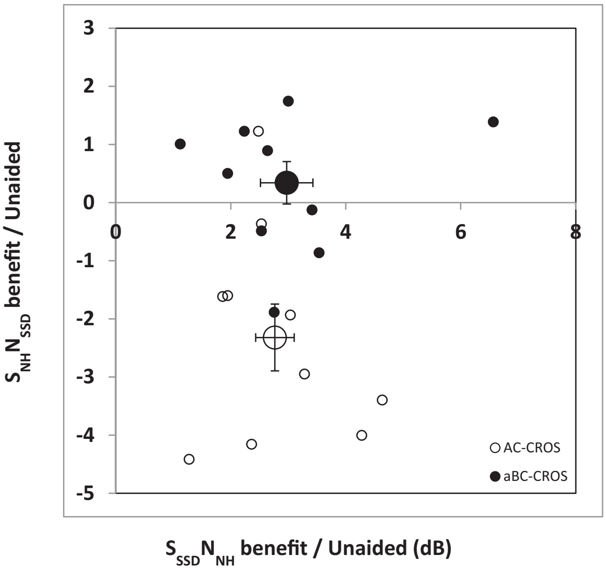

FIG. 6. SRT50 measured with AC-CROS (*empty circles*) and aBC-CROS (*filled circles*) in $S_{NH}N_{SSD}$ configuration versus in $S_{SSD}N_{NH}$ configuration. Big symbols and error bars represent mean value and standard errors. Small symbols represent individual data.

DISCUSSION

Our results show that speech recognition performance in noise with the aBC-CROS varies depending on the configuration. In the $S_{SSD}N_{NH}$ configuration, both the AC- and the aBC-CROS significantly improved the SRT50 in nine out of 10 patients compared with the unaided condition, with no significant difference between devices. Mertens et al. (42) and Cho et al. (43) compared the AC-CROS with the aBC-CROS in the same configuration, finding significant benefit over the unaided condition for only the AC-CROS device. The differences between our study and those of Mertens et al. (42) and Cho et al. (43) could be due to the type of noise used (speech-weighted noise and 8-talker babble noise, respectively).

In the $S_{NH}N_{SSD}$ condition, the AC-CROS significantly decreased intelligibility in noise in six out of 10 patients. Seven patients had significantly better results with the aBC-CROS than the AC-CROS, although the aBC-CROS was not significantly different than the unaided condition. These findings are supported by Cho et al. (43) and Mertens et al. (42). Other studies in the $S_{NH}N_{SSD}$ condition reported much poorer performance with AC-CROS than BC-CROS devices, although both were worse than the unaided condition (29–34,38). The BC-CROS's better performance could be linked either to the CROS transmission modality (BC versus AC) or to the bandwidth transmitted by the CROS, since BC systems purportedly transmit low-frequency (LF) and high-frequency (HF) sounds less efficiently than AC systems.

Decreased performance with CROS (AC- or BC-) could be due to a comb-filtering effect that results from the combination of the direct sound and the CROS sound, which is delivered to the deaf ear with a delay corresponding to the device's processing time (47,48). The spectrum of the resulting signal undergoes distortions that manifest in an alternation of peaks separated by notches or nulls. Peaks are spaced at frequencies that are multiple integers of the reciprocal of the temporal shift. Stone and Moore (47) assume that only the first five to six peaks contain significant energy; this means that the most important distortions depend on the processing time (D) of the CROS and will occur until at least approximately ($6/D$) Hz (about 750 Hz for $D = 8$ ms). Moreover, the periodic low-frequency components at each multiple integers of $1/D$ (about 125 Hz, 250 Hz, ... for $D = 8$ ms) ms) could create a low-frequency periodic distortion that could generate a ghost perception of a pitch that would compete with that of the target voice. According to

Johansen (49), sensitivity to this phenomenon is greatest for shifts in the range of 1 to 20 ms, so to avoid it being audible, direct and delayed sounds must have a difference of more than 12 dB.

In our study, the aBC-CROS's satisfying results in noise could be explained by the efficiency of the background noise elimination algorithm, or perhaps the frequency bandwidth of the aBC-CROS makes the patient less sensitive to noise when it is presented on the deaf side. Indeed, the mean pure-tone threshold with the aBC-CROS was highest in the mid-frequencies and attenuated in the low (up to –20 dB) and high frequencies (by –25 to –30 dB). However, transcranial attenuation was lowest in the frequency region around 1000 Hz (by 7 dB), and slightly more in the low (by 8 dB) and high frequencies (by 13 dB) (50). The aBC-CROS therefore transmits low and high-frequency noise with strong attenuation to the contralateral ear in comparison to direct transmission. Due to the head shadow, direct transmission takes up to 0.7 ms and strongly attenuates high frequencies by 20 dB and low frequencies by 6 dB (51). Thus, no comb-filtering effect results from the superposition of the direct and delayed sounds because the difference between the two sounds is more than 12 dB.

AC-CROS or BAHA systems (maximum response centered around 800 Hz) have less attenuation than the BC-CROS device in the low frequencies, which could explain the negative results observed in the $S_{NH}N_{SSD}$ configuration. The low frequencies are not strongly attenuated and the comb-filtering effect results from superposition of the direct and delayed low-frequency sounds. This explanation seems consistent with literature for the AC-CROS or BAHA systems. According to Valente (52) and Valente et al. (53), the best benefit with AC-CROS occurs either in patients who have mild hearing loss in the first 1500 Hz or normal-hearing patients provided with minimal gain below 1500 Hz and significant gain above 1500 Hz.

Some studies on BAHA in SSD patients suggest that to overcome the problem of SNR deterioration when noise is presented on the deaf side, it would be sufficient to modify the processor's bandwidth by cutting the low frequencies below 1000 or 1500 Hz (54,55). Pfiffner et al. (56) validated the theory by evaluating the effect of low-frequency attenuation in SSD patients implanted with BAHA for three testing conditions corresponding to three high-pass cut-off frequencies (270, 630, and 1500 Hz) in the $S_{SSD}N0$ and $N_{SSD}S0$ configurations. They concluded that when noise is presented on the deaf side, performance remains unchanged between high-pass filtering at 1500 Hz and the unaided condition, while high-pass filtering at 270 and 630 Hz deteriorates the performance.

In our study, the AC-CROS had a mean benefit of 2.8 dB in the $S_{SSD}N_{NH}$ condition, compared with a 2.3 dB deterioration in the $S_{NH}N_{SSD}$ condition. For the aBC-CROS, we found a 3.0 dB benefit with no deterioration in these conditions. Müller et al. (28) found a 4.0 dB improvement in SRT with the BC-CROS when noise was presented on the normal-hearing side versus a 3.1 dB deterioration with noise presented to the deaf side. In a meta-analysis by Kitterick et al. (25) the average decrease in performance on the sentence in noise test (increase in SNR: AC-CROS: 3.9 dB; BC-CROS: 2.3 dB) was similar to or larger than the benefit observed when the SNR was more favorable at the impaired ear (decrease in SNR: AC-CROS: 2.6 dB; BC-CROS: 2.5 dB). Mertens et al. (42) showed no decrease in SRT when speech was presented on the deaf side with the aBC-CROS.

CROS does not restore binaurality (as squelch effect) but transfers information from the contralateral SSD side to the hearing ear as in the $S_{SSD}N_{NH}$ condition. When the noise in on the SSD side, the effect of the AC-CROS is detrimental compared with the natural head shadow effect that attenuates the noise. However, with the aBC-CROS in this study, there is no difference and the natural head shadow effect is preserved.

One limitation of the study is that patient compliance could not be assessed since the patients used the ADHEAR system for only 15 days. Future longitudinal studies should be planned over a longer time period.

In addition, the type of noise used (cocktail-party) as well as the environment (audiometric test room) could influence the results; a further study in real-world conditions would be necessary to confirm the gain observed with the aBC-CROS.

Our study suggests that the aBC-CROS seems to be a good compromise in CROS usage. In the $S_{SSD}N_{NH}$ configuration, it provides the same benefit as other CROS devices, while it outperforms in the $S_{NH}N_{SSD}$ configuration by not decreasing understanding compared with the unaided condition.

Acknowledgments: The authors would like to thank Noelani Peet (MED-EL GmbH) for her medical writing services on a version of this manuscript.

REFERENCES

1. Baguley DM, Bird J, Humphriss RL, Prevost AT. The evidence base for the application of contralateral bone anchored hearing aids in acquired unilateral sensorineural hearing loss in adults. *Clin Otolaryngol* 2006;31:6–14.
2. Sargent EW, Herrmann B, Hollenbeak CS, Bankaitis AE. The minimum speech test battery in profound unilateral hearing loss. *Otol Neurotol* 2001;22:480–6.
3. Bishop CE, Eby TL. The current status of audiologic rehabilitation for profound unilateralsensorineural hearing loss. *Laryngoscope* 2010;120:552–6.
4. Avan P, Giraudet F, Büki B. Importance of binaural hearing. *Audiol Neurootol* 2015;20 (suppl):3–6.
5. Basura GJ, Eapen R, Buchman CA. Bilateral cochlear implantation: current concepts, indications, and results. *Laryngoscope* 2009;119: 2395–401.
6. Laske RD, Veraguth D, Dillier N, Binkert A, Holzmann D, Huber AM. Subjective and objective results after bilateral cochlear implantation in adults. *Otol Neurotol* 2009;30:313–8.
7. Gantz BJ, Tyler RS, Rubinstein JT, et al. Binaural cochlear implants placed during the same operation. *Otol Neurotol* 2002;23:169–80.
8. Schoen F, Mueller J, Helms J, Nopp P. Sound localization and sensitivity to interaural cues in bilateral users of the MEDEL Combi 40/40+cochlear implant system. *Otol Neurotol* 2005;26:429–37.

9. Tyler RS, Gantz BJ, Rubinstein JT, et al. Three-month results with bilateral cochlear implants. *Ear Hear* 2002;23 (1 suppl):80S–9S.
10. Schleich P, Nopp P, D'Haese P. Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear Hear* 2004;25:197–204.
11. Laszig R, Aschendorff A, Stecker M, et al. Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-month postoperative results. *Otol Neurotol* 2004;25:958–68.
12. Buss E, Pillsbury HC, Buchman CA, et al. Multicenter U.S. bilateral MED-EL cochlear implantation study: speech perception over the first year of use. *Ear Hear* 2008;29:20–32.
13. Newman CW, Jacobson GP, Hug GA, Sandridge SA. Perceived hearing handicap of patients with unilateral or mild hearing loss. *Ann Otol Rhinol Laryngol* 1997;106:210–4.
14. Parving A, Parving I, Erlendsson A, Christensen B. Some experiences with hearing disability/handicap and quality of life measures. *Audiology* 2001;40:208–14.
15. Chisolm TH, Johnson CE, Danhauer JL, et al. A systematic review of health-related quality of life and hearing aids: final report of the American Academy of Audiology Task Force On the Health-Related Quality of Life Benefits of Amplification in Adults. *J Am Acad Audiol* 2007;18:151–83.
16. Dwyer NY, Firszt JB, Reeder RM. Effects of unilateral input and mode of hearing in the better ear: self-reported performance using the speech, spatial and qualities of hearing scale. *Ear Hear* 2014;35:126–36.
17. Giolas TG, Wark DJ. Communication problems associated with unilateral hearing loss. *J Speech Hear Disord* 1967;32:336–43.
18. Härkönen K, Kivekäs I, Rautiainen M, Kotti V, Vasama JP. Quality of life and hearing eight years after sudden sensorineural hearing loss. *Laryngoscope* 2017;127:927–31.
19. Vaneecloo FM, Ruzza I, Hanson JN, et al. The monaural pseudo-stereophonic hearing aid (BAHA) in unilateral total deafness: a study of 29 patients. *Rev Laryngol Otol Rhinol (Bord)* 2001;122:343–50.
20. Wendrich AW, Kroese TE, Peters JPM, Cattani G, Grolman W. Systematic review on the trial period for bone conduction devices in single-sided deafness: rates and reasons for rejection. *Otol Neurotol* 2017;38:632–41.
21. Hill SLJ3rd, Marcus A, Digges EN, Gillman N, Silverstein H. Assessment of patient satisfaction with various configurations of digital CROS and BiCROS hearing aids. *Ear Nose Throat J* 2006;85:427–30.
22. Linnebjerg LB, Wetke R. The benefits of CROS aids for individuals with unilateral sensorineural hearing loss. *Hearing Balance Commun* 2014;12:36–40.
23. Valente M, Valente M, Enrietto J, Layton KM. Fitting strategies for patients with unilateral hearing loss. In: Valente M, editor. *Strategies for Selecting and Verifying Hearing aid Fittings*, 2nd ed. New York: Thieme; 2002. pp. 253–71.
24. Peters JP, Smit AL, Stegeman I, Grolman W. Review: Bone conduction devices and contralateral routing of sound systems in single-sided deafness. *Laryngoscope* 2015;125:218–26.
25. Kitterick PT, Smith SN, Lucas L. Hearing instruments for unilateral severe-to-profound sensorineural hearing loss in adults: a systematic review and meta-analysis. *Ear Hear* 2016;37:495–507.
26. Lotterman SH, Kasten RN. Examination of the CROS type hearing aid. *J Speech Hear Res* 1971;14:416–20.
27. Wesarg T, Aschendorff A, Laszig R, et al. Comparison of speech discrimination in noise and directional hearing with 2 different sound processors of a bone-anchored hearing system in adults with unilateral severe or profound sensorineural hearing loss. *Otol Neurotol* 2013;34:1064–70.
28. Müller A, Hocke T, Hessel H, Mir-Salim P. Results of speech audiometry testing in case of transcranial CROS depend on duration of deafness [in German]. *Laryngorhinootologie* 2017;96:293–8.
29. Snapp HA, Hoffer ME, Liu X, Rajguru SM. Effectiveness in rehabilitation of current wireless CROS technology in experienced bone-anchored implant users. *Otol Neurotol* 2017;38:1397–404.
30. Niparko JK, Cox KM, Lustig LR. Comparison of the bone anchored hearing aid implantable hearing device with contralateral routing of offside signal amplification in the rehabilitation of unilateral deafness. *Otol Neurotol* 2003;24:73–8.
31. Wazen JJ, Spitzer JB, Ghossaini SN, et al. Transcranial contralateral cochlear stimulation in unilateral deafness. *Otolaryngol Head Neck Surg* 2003;129:248–54.
32. Hol MK, Bosman AJ, Snik AF, Mylanus EA, Cremers CW. Bone-anchored hearing aid in unilateral inner ear deafness: a study of 20 patients. *Audiol Neurootol* 2004;9:274–81.
33. Hol MK, Bosman AJ, Snik AF, Mylanus EA, Cremers CW. Bone-anchored hearing aids in unilateral inner ear deafness: an evaluation of audiometric and patient outcome measurements. *Otol Neurotol* 2005;26:999–1006.
34. Lin LM, Bowditch S, Anderson MJ, May B, Cox KM, Niparko JK. Amplification in the rehabilitation of unilateral deafness: speech in noise and directional hearing effects with bone-anchored hearing and contralateral routing of signal amplification. *Otol Neurotol* 2006;27:172–82.
35. Dumper J, Hodgetts B, Liu R, Brandner N. Indications for bone-anchored hearing AIDS: a functional outcomes study. *J Otolaryngol Head Neck Surg* 2009;38:96–105.
36. Hol MK, Kunst SJ, Snik AF, Bosman AJ, Mylanus EA, Cremers CW. Bone-anchored hearing aids in patients with acquired and congenital unilateral inner ear deafness (Baha CROS): clinical evaluation of 56 cases. *Ann Otol Rhinol Laryngol* 2010;119:447–54.
37. Saliba I, Nader ME, El Fata F, Leroux T. Bone anchored hearing aid in single sided deafness: outcome in right-handed patients. *Auris Nasus Larynx* 2011;38:570–6.
38. Finbow J, Bance M, Aiken S, Gulliver M, Verge J, Caissie R. A comparison between wireless CROS and bone-anchored hearing devices for single-sided deafness: a pilot study. *Otol Neurotol* 2015;36:819–25.
39. Ryu NG, Moon IJ, Byun H, et al. Clinical effectiveness of wireless CROS (contralateral routing of offside signals) hearing aids. *Eur Arch Otorhinolaryngol* 2015;272:2213–9.
40. Postert B, Kiesewetter K, Dejaco T. The ADHEAR system – review of clinical evidence and user satisfaction. MEDEL White Paper, Revision 1.1; 2019.
41. McDermott ALMR, Williams JS, Gill J, Child A. The ADHEAR HEARING system. A paediatric experience. Presented at Osseo 2017-6th International Congress on Bone Conduction Hearing and Related Technologies. Nijmegen, The Netherlands, May 17–20, 2017.
42. Mertens G, Gilles A, Bouzegta R, Van de Heyning P. A prospective randomized crossover study in single sided deafness on the new non-invasive adhesive bone conduction hearing system. *Otol Neurotol* 2018;39:940–9.
43. Cho YS, Park YK, Seol HY, Lim JH, Hong SH, Moon IJ. Efficacy of non-invasive treatment options for single-sided deafness: a prospective study of 20 patients. *Clin Otolaryngol* 2020;45:409–13.
44. Van de Heyning P, Távora-Vieira D, Mertens G, et al. Towards a unified testing framework for single-sided deafness studies: a consensus paper. *Audiol Neurootol* 2016;21:391–8.
45. Fournier JE. *Vocal Audiometry: intelligibility test and their applications to diagnostics, expertise and prosthetic correction of hearing loss*. Paris: Maloine Editor; 1951.
46. Mattingly JK, Banakis Hartl RM, Jenkins HA, Tollin DJ, Cass SP, Greene NT. A comparison of intracochlear pressures during ipsilateral and contralateral stimulation with a bone conduction implant. *Ear Hear* 2020;41:312–22.
47. Stone MA, Moore BC. Tolerable hearing aid delays. I. Estimation of limits imposed by the auditory path alone using simulated hearing losses. *Ear Hear* 1999;20:182–92.
48. Goehring T, Chapman JL, Bleeck S, Monaghan JJM. Tolerable delay for speech production and perception: effects of hearing ability and experience with hearing aids. *Int J Audiol* 2018;57:61–8.
49. Johansen LG. Psychoacoustics and audibility – fundamental aspects of the human hearing. Lecture note for the course TI-EAKU, University College of Aarhus; 2006.

50. Snyder JM. Interaural attenuation characteristics in audiometry. *Laryngoscope* 1973;83:1847–55.
51. Moore B. *An Introduction to the Psychology of Hearing*. London: Brill; 2013. 248–249.
52. Valente M. Fitting options for unilateral hearing loss. *Hear J* 1995;48:10–48.
53. Valente M, Potts L, Valente M, Goebel J. Wireless CROS versus transcranial CROS for unilateral hearing loss. *Am J Audiol* 1995;4:52–9.
54. Westerkull P. Hearing Aid Apparatus. US patent US 2004/0234091 A1; 2004.
55. Weste Henry P, Letowski TR. *Bone Conduction: Anatomy, Physiology and Communication (ARL-TR-4138)*. Aberdeen Proving Ground, MD: US Army Research Laboratory; 2007.
56. Pfiffner F, Kompis M, Flynn M, Asnes K, Arnold A, Stieger C. Benefits of low-frequency attenuation of baha® in single-sided sensorineural deafness. *Ear Hear* 2011;32:40–5.