Objective: To assess the benefits in terms of sound localization, to evaluate speech discrimination in noise, to appraise the prosthesis benefit and to identify outcome in right and left handed patients when BAHA are implanted on the right or on the left deaf side.

Methods: Two years prospective study in a tertiary referral center. Tests consist on Hearing in Noise Test (HINT) and sound localization after 6 months of BAHA use. Quality of life was assessed by the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire. The paired T-test and the analysis of variance were used for the statistical measures.

Results: Twenty-one subjects participated in this study. HINT: patients score better when speech and noise are spatially separated and noise is not presented to the healthy ear. In the right-handed group (left dominant brain), unaided left-implanted patients performed better than right-implanted patient when speech is in front and noise to the good ear; when speech is presented to the good ear and noise to the front, aided right-implanted patients performed better than aided left-implanted patients. Sound localization: correct answers attain 35% at best. No statistical difference between the frequencies was found, neither between the left and right implanted patients. APHAB: the score improvement is statistically significant for the global score, the background noise subscale at 5 weeks and for the reverberation subscale at 6 months.

Conclusion: It seems that left dominant hemisphere is able to filter crossed noise better than the right hemisphere. Results of uncrossed speech to the dominant left brain are better than the uncrossed speech to the non-dominant right brain.

Keywords: BAHA; Single sided deafness; Sound localization; Dominant; Non-dominant; Right-handed; Acoustic neuroma; Translabyrinthine; Schwannoma; Hearing loss
Recently, the benefits offered by the BAHA to individuals with unilateral SNHL have been examined by some investigators. However, no previous data concerning the correlation between the implanted deaf side and the brain dominant side is reported. Do results of right or left-handed single sided deafness (SSD) patients implanted on the right side differ from those implanted on the left side?

Our objectives were therefore to assess the benefits in terms of sound localization, to evaluate speech discrimination in noise, to appraise the prosthesis benefit and to identify outcome in right handed patients when BAHA are implanted on the right or on the left deaf side.

2. Materials and methods

2.1. Patients

This prospective investigation was approved by our institutional review board. It started in 2007 and ended in 2009. The inclusion criteria were as follows: (1) age 18 or above, (2) profound unilateral SNHL with BAHA implanted on the deaf side, (3) class A or B hearing (AAO-HNS classification) for the contralateral healthy ear and (4) duration of BAHA use for at least 6 months. Tests consist on Hearing in Noise Test and sound localization test. All tests were done using the omnidirectional microphone of the DIVINO transducer model. After 6 months of BAHA use, the subjects returned for testing. Information about right and left handed patients are collected as well as the side of implantation. Benefit of hearing aid system was assessed by the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire.

Because the majority of our patients are right-handed, we studied this group to assess how dominant versus non-dominant contralateral implantation outcomes differ.

2.2. Hearing in Noise Test (HINT)

The objective assessment of speech discrimination in noise was performed using the HINT. Two speakers were placed in a sound-proof cabin. The subjects were tested in five conditions, with and without BAHA. The masking evaluation conditions were: (1) both noise and speech source were in front of the patient, (2) speech source is in front and noise source is lateral to the healthy ear, (3) speech source is in front and noise source is lateral to the deaf ear, (4) noise source is in front and speech source is lateral to the deaf ear and (5) noise source is in front and speech source is lateral to the healthy ear.

The French version of the test was used [9]. It consists of 12 lists of 20 sentences that are phonetically balanced and of equal intelligibility. Noise is presented at fixed 65 dB intensity while the speech intensity varies until a 50% successful task rate completion is obtained, which corresponds to the intelligibility threshold. The results are expressed as Signal to Noise Ratio (SNR), which is computed by subtracting the 65 dB noise level from the measured speech threshold. Therefore, a lower SNR corresponds to better speech discrimination.

2.3. Sound localization

Sound localization testing was performed according to a protocol developed and normalized by the Acoustics Department of our institution [10]. The set-up consisted of 10 speakers placed in a circle at 36° from each other. The stimuli were presented randomly by one speaker at 65 dB sound pressure level (SPL) with duration of 250 ms to bypass the patient’s reflex and to prevent patient from turning his head for localization of target stimuli. To evaluate the two factors that contribute to sound localization, namely interaural phase difference and interaural intensity difference testing was performed using stimuli at 500 Hz and 3000 Hz. Therefore, sound localization measurements were tested with low-frequency (500 Hz) and high-frequency (3000 Hz) under five conditions: (1) in quiet, (2) with noise source lateral to the deaf ear, (3) with noise source lateral to the healthy ear, (4) with noise source in front of the patient and (5) with noise source behind the patient. After each stimulus presentation, the subjects were asked to identify the speaker that had emitted the sound. The percentage of correct answers was obtained by grouping the speakers into four quadrants: in front, behind and the 2 lateral sides. Results were compared to the chance level of 25% because there is a one arbitrary good response out of four possibilities. Fig. 2 represents the sound localization setup. The subjects were taken through a familiarization of each of these positions before formal testing and were not given additional feedback or training.
2.4. Benefit of hearing aid system

It was assessed using a French version of the APHAB questionnaire [11]. APHAB includes 24 items to evaluate the effectiveness of hearing aids for speech understanding in everyday listening contexts through three speech communication subscales: ease of conversation (EC), listening with background noise (BN) and listening under reverberant conditions (RV). An additional subscale which evaluates a listening comfort domain, characterizes aversion to loud sounds. Aversiveness (AV) is related to loudness recruitment and hyperacusis. The scoring of the APHAB is completed by having patients fill out the 24 items. The questionnaire was completed before the BAHA use, 5 weeks and 6 months after the BAHA use. Scores were expressed as percentages, with lower scores representing better results. The difference between scores is used to calculate the benefit for each subscale. At least 5% difference between mean aided scores and mean unaided scores was deemed clinically significant. A difference of 5% or more for all three speech communication subscales approaches the 90% level of certainty [11]. A global score was also computed, which corresponds to the mean of the items of all the domains except AV.

2.5. Statistical analysis

Data obtained from the HINT was analyzed using the T-test. Results of sound localization testing were compared to chance by computing confidence intervals. Two-factor ANOVA with replication was used to examine the effects of the 5 different conditions and the effect of the 2 frequencies on results.

The paired T-test was used to compare outcome measures obtained from the APHAB questionnaire.

A subgroup analysis was performed for all these objective and subjective measures among the right-handed subjects, comparing results of BAHA on the right side with those on the left side. This analysis was completed using the T-test. A p-value <0.05 was considered statistically significant.

3. Results

3.1. Patients’ characteristics

Twenty-one subjects participated in this study. The etiologies of SNHL included one cerebello-pontine angle meningioma and 20 vestibular schwannoma where BAHA were implanted at the end of the translabyrinthine approach for tumor excision. Abutment was covered by the musculo-cutaneous flap at the end of the surgery. There was no need to use the cover screw for the fixture. Four months after the implantation, allowing osseointegration of the 4 mm titanium fixture and where the risk of cerebrospinal fluid leak is minor, the abutment was exposed under local anesthesia in the outpatient department. No fibrosis or scar tissues were developed in the abutment holes and dissection was very soft. The mean hearing threshold of the healthy ear was 17 dB for the frequencies 500, 1000, 2000 and 4000 Hz. The mean speech discrimination of the healthy ears was 99%. All patients have a class A hearing of the healthy ear (AAO-HNS). There were 19 right-handed patients. Twelve of them (63%) were implanted on the right and seven on the left (47%). The two remaining patients were left-handed. No subjects have evidence of brainstem or cortical dysfunction.

3.2. Hearing in Noise Test

Each patient performed ten tests. Fig. 3 displays the SNR obtained for each HINT conditions with and without BAHA for the five conditions. Patients benefit the most from the BAHA when the speech is presented to the deaf side while the noise is emitted in the front. The mean decrease in SNR ratio was 2.1 dB SPL when the BAHA was turned on compared to when it was turned off (p = 0.0005). In the condition where the noise is presented towards the deaf ear and the speech is presented in the front, the SNR are significantly better when the BAHA was turned off (p < 0.0001). There was a statistically significant increase of SNR ratio of 3.15 dB SPL when the BAHA was turned on compared to when it was turned off. In the three other conditions, the BAHA does not offer any improvement.

In the right-handed patients group HINT results were compared between right-implanted and left-implanted patients for each testing conditions and the SNR difference between the aided and unaided conditions was analyzed. Our
data show that for the condition 2 unaided left-implanted patients performed better \( p = 0.003 \) than unaided right-implanted patient while for the condition 5, aided right-implanted patients had better results \( p = 0.04 \) than aided left-implanted patients. However, for the remaining conditions no statistically significant difference was observed. For the global result, our data show that patients’ handedness does not have consistent impact on the results of the HINT.

3.3. Sound localization

Fig. 4 displays the percentage of correct answers for the sound localization testing for each condition and frequency. Sound localization after six months of BAHA use was found to be better than chance in 5 situations. When 25% of chances are out of the confidence interval (CI), the difference is statistically significant. At the 500 Hz stimulus level, localization performance was better than the chance when noise source was in the BAHA side (CI: 29.15–38.47) or in the healthy ear side (CI: 28.70–41.77). At 3000 Hz stimulus level, localization performance was better than the chance in the quiet condition (CI: 28.43–40.15), when noise source was in the healthy ear side (CI: 28.60–39.97) and when noise source was in front of the patient (CI: 26.29–38.47). However, the percentage difference (percentage of correct answer using BAHA minus chance percentage) in any of these situations was never above 10%. In the remaining condition localization performance was essentially without difference from the chance at both 500 and 3000 Hz stimuli levels. The ANOVA testing revealed no statistical difference between the conditions \( p = 0.544 \) or between the frequencies \( p = 0.416 \) used for the localization. That’s mean neither the conditions and nor the frequencies affect the results. Similarly, there were no differences between the left and right implanted side for the right-handed patients.

3.4. APHAB

Fig. 5 displays the outcome for each subscale of the APHAB questionnaire. Differences between unaided and aided outcomes were calculated. We noted a clinical
improvement at 5 weeks and at 6 months following BAHA use, for the global score as well as for the three speech communication subscales; progress was 7%, 8%, 9% and 11%, respectively, for the global score, EC, BN and RV. The score improvement is statistically significant for the global score ($p = 0.042$), for the BN subscale at 5 weeks ($p = 0.24$) and for the RV subscale at 6 months ($p = 0.014$).

Whereas, in the listening comfort domain we noted a 4% increase of aversiveness with BAHA. This deterioration is not clinically (less than 5%) neither statistically ($p = 0.325$) significant. There were no statistical differences for any components when comparing the results at 5 weeks with those at 6 months. No consistent differences were noted when taking into account the side on which the BAHA was implanted for the right handed patients group.

### 4. Discussion

Patients with SSD lack the advantage of interaural time and intensity differences essential for directional hearing. In terms of hearing rehabilitation with the BAHA system, the best transmission to the best working cochlea may be obtained if the skull is excited at the contralateral side [12].

#### 4.1. Hearing in Noise Test

Patients with unilateral profound SNHL express difficulties understanding speech in noisy environments especially when it is presented towards the deaf ear. The BAHA is considered to help these patients by lifting the head shadow effect. Our results showed that HINT results were significantly improved when the subjects used the BAHA while they perceived speech directed towards the deaf ear with noise presented in front of them. These findings concur with those of Hol et al. and Linstrom et al. but the latter group noted that performance of patients using the BAHA was not equivalent to that of the control group [13,14]. Our data also showed that noise presented to the healthy ear or to the BAHA side gives poor results and should be avoided. Therefore we should inform the patients of this limitation. In order to by-pass this constraint we suggest to our patients to turn off their BAHA when confronted with similar conditions or to change their position in order to be in front of the noise source. BAHA amplification benefits monaural listening when the speech and noise sources are spatially separated. The implications of this result were related to the interaural time difference and the frequency range of the critical information. Spatial separation of speech and noise creates a release from masking that often improves speech intelligibility; the threshold of intelligibility can vary as much as 10 dB in normally-hearing individuals, depending on the azimuthal difference between the sources locations [15]. Snick et al. illustrate that the binaural advantage studied with speech-in-noise tests with spatially separated speech and noise sources, proved to be comparable with that in a control group of subjects with normal hearing when they were listening monaurally versus binaurally [16].

The head shadow effect is the difference between the SNR of the poor ear and the better ear in the unaided condition. The influence of the head shadow effect increases with frequencies above 2000 Hz, and decreases with frequencies below 2000 Hz. BAHA decrease the head shadow effect when speech source is in the BAHA side and noise is in the front. When noise is presented to the BAHA side, SNR in the unaided condition was lower and therefore more favorable than in the aided conditions. This negative side issue can be explained by the transcranial transfer of noise to the healthy ear. The squelch effect, a filtering phenomenon generated by the central auditory nervous system, provides a 3–6 dB increase in speech intensity when
the speech signal is interspersed with background noise [8]. Several investigators have commented on the ability of subjects with binaural hearing to reduce (or “squelch”) the deleterious effects of background noise and reverberation on speech recognition. Although BAHA decreases the head shadow effect in SSD patients, it does nothing to restore the squelch effect or binaural summation. However, patients noted an improvement of speech understanding in background noise.

4.2. Sound localization

There were initially hopes that the BAHA could help SSD patients to achieve proper sound localization. Theoretically, the sound wave received and transmitted by the prosthesis to the healthy cochlea would have a slightly different phase and intensity compared to the stimuli perceived by the healthy ear, and the central nervous system could benefit from these differences to determine the spatial origin of the stimuli. Newman et al. studied sound localization in 8 SSD patients who had been followed for 18 months [17]. When comparing aided and unaided conditions, the authors did not discover any significant improvement with the use of the BAHA. Similarly, Hol et al. studied sound localization with the use of CROS and BAHA units in 29 patients and failed to show any difference compared to chance for either type of prosthesis [13]. Although not stated explicitly, their follow-up period before localization testing seemed to be 6 weeks. In our study, sound localization testing was performed in 21 patients after at least 6 months follow-up. Our set-up consisted of 10 speakers placed in a circle at 36° from each other to study sound localization in the different space azimuth. Subjects were asked to identify the speaker that had emitted the sound. Because 3 speakers were placed to left or to the right and 2 speakers are placed in front or behind, we considered a correct answer if it is referred to one of the grouping speakers (right, left, in front or behind). Therefore, results were compared to the arbitrary chance level of 25%. Our results showed a statistically significant difference when compared to chance in 5 out of the 10 testing situations. However, the patients still performed poorly with correct answers attaining only 35% at best. Nevertheless, in our study, no statistical difference between the conditions or between the frequencies used for the localization was found, which means neither the conditions and nor the frequencies affect the results of localization. Absence of improvement over time reflects lack of plasticity when auditory stimulation is provided through the BAHA or whether the effect size is small, requiring a larger sample for sufficient power.

4.3. APHAB

Score improvements have been noted for all the APHAB subscales except for the AV domain. The worsened results noted for the AV subscale seems logical as this domain evaluates the response of subjects to loud stimuli, which are amplified when the BAHA is turned on. However, this deterioration seems to be clinically and statistically not significant. Our results concur with those of other groups who discovered similar improved scores for all domains except AV [13,14]. APHAB data in this study and in previous reports reveal consistent listening benefit with use of the BAHA system in single sided deafness.

For a least 6 months follow-up, all patients were still using BAHA everyday: 15 patients for more than 8 h a day and 6 patients for 4–8 h a day.

4.4. Dominant versus non-dominant contralateral implantation

92% of the global population is right-handed which correspond to our sample. The auditory brainstem is a series of spatially separate nuclei that receive auditory input from the acoustic nerve and process this signal as it enters the auditory cortex [18]. The auditory system exhibits developmental plasticity, in both frequency and time domains, for sounds that are composed of acoustic elements relevant to speech. The findings are interpreted within the contexts of stimulus-related differences and experience-dependent plasticity [19]. Stimuli arriving at the ear contralateral to the dominant hemisphere were more efficiently recognized than stimuli arriving at the ipsilateral ear, that is, in the left-dominant group the right ear was more efficient. That’s mean the crossed auditory pathways are stronger than the uncrossed, and that the dominant temporal lobe is more important than the non-dominant in the perception of spoken material [20]. Each hemisphere of the brain is dominant for different behaviors. For example, it appears that the right brain is dominant for spatial abilities. Even though 47% of our right handed patients (left dominant hemisphere) were implanted on the left side, right hemisphere stimulations were not superior to the left hemisphere for the spatial abilities and sound localization. In addition, crossed stimuli to the left dominant hemisphere (left implanted BAHA) were not superior to the uncrossed stimuli to the right non-dominant hemisphere. However, upon our results, it seems that left dominant hemisphere is able to filter crossed noise better than the right non-dominant hemisphere. In addition, we thought by reason of the ipsilateral central deprivation of hearing input due to peripheral deafness, crossed fibers to the affected side lose their function; results of the uncrossed speech to the dominant left brain are better than the uncrossed speech to the non-dominant right brain. Brain plasticity refers to the brain’s ability to change throughout life. The brain has the amazing ability to reorganize itself by forming new connections between brain cells (neurons). When the brain is deprived of input from one sensory modality, it often compensates with supranormal performance in one or more of the intact sensory systems. In the absence of acoustic input, it has been proposed that cross-modal reorganization of deaf auditory cortex may provide the neural substrate mediating compensatory visual function. Results indicate that enhanced visual performance in the deaf
is caused by cross-modal reorganization of deaf auditory cortex and it is possible to localize individual visual functions in discrete portions of reorganized auditory cortex [21]. It seems that brain plasticity is not sufficient to localize sound in single sided deafness BAHA implanted patients and no differences exist between left or right deafness in right-handed patients. Sound localization needs two auditory pathways incomes.

4.5. Limitation of the study

This study is hampered by the limited number of our population. A multicenter study is considered to strengthen our conclusions regarding the efficiency of the left and right temporal lobes in processing crossed pathway signals.

5. Conclusion

BAHA prosthesis in SSD patients cannot restore sound localization even after 6 months of use. Thus patients should be well informed of this limitation and not offered unrealistic expectations. Implanted BAHA patients with unilateral SNHL express better speech understanding when speech and noise are spatially separated and when noise is in front. Left dominant hemisphere is able to filter crossed noise better than the right non-dominant hemisphere and uncrossed speech to the dominant left brain are better than the uncrossed speech to the non-dominant right brain. Finally, according to the improvement in the APHAB scores, SSD patients identify the BAHA helpfulness when they are confronted to background noise or to environments prone to reverberation.

Conflict of interest

None declared.

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