The impairments caused by unilateral deafness have been studied by many researchers since the mid 20th century (1–3). Patients report difficulties in sound localization and with speech comprehension when the speaker is talking on the deaf side, especially in a noisy environment. The advantages of binaural hearing over the unilateral situation have been shown by several research groups (4–7). Three effects are responsible for the advantages of binaural hearing. The 2 effects suggesting true binaural processing of auditory information arriving at each ear are binaural summation and binaural squelch.

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Although the head shadow effect is not based on binaural sound processing, it is a consequence of hearing on both sides, which permits the subject to take advantage of 2 different signal-to-noise ratios, subsequently leading to improved speech comprehension. Up to now, treatment modalities of unilateral deafness consist of no treatment, contralateral routing of signal (CROS) treatment with CROS hearing aids and the Bone-Anchored Hearing Aid (BAHA) treatment based on bone conduction. The last 2 methods do not allow for real binaural hearing because the brain only receives and processes auditory input from one side. However, for patients deafened because of cochlear ossification, or after acoustic neuroma surgery in which the auditory nerve function is compromised, conventional treatment with BAHA or CROS hearing aid represents the therapy of choice.

A single-center trial to investigate the potential clinical application of unilateral electrical stimulation with cochlear implantation in patients with single-sided deafness and tinnitus was assessed and approved by the ethics committee of the University of Freiburg (No. 69/2009/Arndt). The effect of electrical stimulation of the implanted side with normal hearing on the other side was evaluated after a period of 6 months and compared with the unaided situation, with BAHA and conventional CROS hearing aids. The data presented in this article reflect the results of speech comprehension in noise, sound localization ability, and subjective self-assessment of the patients.

MATERIALS AND METHODS

Subjects/Study Design

Eleven adult German native speakers with acquired unilateral deafness were enrolled in the study (Table 1). The mean duration of deafness was 25 months. They presented with a pure-tone average of more than 70 dB HL and a word score on the Freiburg monosyllabic word test of maximum 30% at 70 dB SPL. The hearing on the better ear was limited to pure-tone average at maximum 30 dB HL in air conduction and a minimum word score of 80% in the Freiburg word test at 65 dB SPL. Only those patients were included in whom therapy with CROS hearing aid or BAHA was not successful and in whom the auditory nerve was found to be intact and the cochlea patent. Another selection criterion was a short duration of deafness with a maximum of approximately 10 years. Before cochlear implantation, all subjects were informed about the implications involved in the study and granted written informed consent. In particular, the information included the known risks of cochlear implant (CI) surgery, such as facial nerve paralysis and loss of taste. Additionally, the patients were informed about the postoperative rehabilitation time. The anticipated benefit is improvement of speech comprehension in noise and improvement of sound localization. All subjects received the Nucleus Freedom Implant (CI24RE; Cochlear Ltd., Lane Cove, Australia) and use the Nucleus Freedom speech processor.

Repeated single subject measures were performed for each subject, with each subject serving as his/her own control. Objective and subjective data of speech comprehension and localization were obtained to compare performance for the unaided condition and the aided conditions with BAHA, CROS, or CI. Subsequently, all subjects were fitted in random order with a BAHA Intenso mounted on the headband or with CROS hearing aid (Phonak Una M). After test periods with both devices, the subjects received a CI. Speech comprehension in noise and localization abilities were measured 3 weeks after fitting of each device and 6 months after the first fitting of CI.

### Tests

Speech comprehension tests were conducted in a sound-treated chamber via 2 of 3 loudspeakers, at an angle of +45°, 0°, and −45° 1 m away from the subject’s head. The 3 presentation setups S0N0, S+45N−45, and S−45N+45 were used for testing speech comprehension in background noise. In relation to the side of the subject’s deaf ear, these presentation setups are the configurations S0N0 (speech and noise from the front), SnhNssd (speech from the normal hearing side/noise from the unilateral deaf side), and SssdNnh (speech from the unilateral deaf side/noise from the normal hearing side). Speech comprehension in noise was assessed using the Hochmair-Schulz-Moser (HSM) sentence test (8) and the Oldenburg sentence test (OLSA) (9,10). Speech and background noise were presented at 65 dB SPL with a fixed signal-to-noise ratio (SNR) of 0 dB using the HSM test. Two lists of 20 sentences were used, and speech comprehension was scored as percentage correct word score. Speech comprehension in noise with the OLSA was tested using an adaptive procedure in the unaided and the aided condition with CI. The background noise was presented at 65 dB SPL, and the speech level of each sentence was adaptively adjusted depending on the subjects’ response to each test item to obtain the SNR at which the percent correct word score is 50% (critical SNR). Two lists of 30 sentences were used,

### TABLE 1. Patient demographics

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Age at surgery, yr</th>
<th>Duration of deafness, mo</th>
<th>Cause</th>
<th>Deaf side</th>
<th>Pure-tone average of the good ear, mean dB HL</th>
<th>Pure-tone average of the poor ear, mean dB HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47</td>
<td>43</td>
<td>Sudden hearing loss</td>
<td>Left</td>
<td>13</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>68</td>
<td>31</td>
<td>Sudden hearing loss</td>
<td>Left</td>
<td>18</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>4</td>
<td>Temporal bone fracture</td>
<td>Left</td>
<td>8</td>
<td>110</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>34</td>
<td>Sudden hearing loss</td>
<td>Left</td>
<td>8</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>39</td>
<td>6</td>
<td>Sudden hearing loss</td>
<td>Right</td>
<td>9</td>
<td>115</td>
</tr>
<tr>
<td>6</td>
<td>41</td>
<td>10</td>
<td>Labyrinthitis</td>
<td>Left</td>
<td>9</td>
<td>99</td>
</tr>
<tr>
<td>7</td>
<td>41</td>
<td>11</td>
<td>Labyrinthitis</td>
<td>Right</td>
<td>8</td>
<td>83</td>
</tr>
<tr>
<td>8</td>
<td>46</td>
<td>110</td>
<td>Menière’s disease</td>
<td>Left</td>
<td>17</td>
<td>117</td>
</tr>
<tr>
<td>9</td>
<td>54</td>
<td>10</td>
<td>Sudden hearing loss</td>
<td>Left</td>
<td>16</td>
<td>99</td>
</tr>
<tr>
<td>10</td>
<td>51</td>
<td>9</td>
<td>Sudden hearing loss</td>
<td>Left</td>
<td>30</td>
<td>99</td>
</tr>
<tr>
<td>11</td>
<td>31</td>
<td>4</td>
<td>After ear surgery</td>
<td>Right</td>
<td>16</td>
<td>103</td>
</tr>
</tbody>
</table>

*Otology & Neurotology, Vol. 00, No. 00, 2010*
Localization was tested using OLSA sentences as stimuli. These stimuli were chosen instead of artificial non-speech stimuli because sentences are acoustic stimuli used in human communication, and unilaterally deaf patients showed no localization ability using a Baha or CROS device when artificial short narrow band noise stimuli were applied (11). For the localization tests, 7 loudspeakers were located at intervals of 30 degrees from −90 degrees to 90 degrees in a frontal semicircle 2 m in diameter in a horizontal plane at the subject’s head level. The subjects were not allowed to search the presenting speaker by moving their heads during the stimulus presentations; this was controlled by the examiner. In each test, 10 sentences at 5 different intensity levels between 59 and 71 dB SPL and a mean level of 65 dB SPL were offered from each speaker in random sequence. For each of the 70 stimulus presentations, the speaker indicated by the subject as the sound-delivering speaker was recorded, resulting in a total of 70 responses. Localization ability was measured as the percentage of the 70 presenting speakers correctly indicated by the subject as the sound-delivering speakers. The chance level of correct speaker localization is 100% divided by the number of speakers, that is, 14.3%. For each subject and test, the localization ability also was measured as the localization deviation or error le in degrees, calculated as the mean of the magnitudes of the differences between the azimuth angle of a presenting speaker φp and the azimuth angle of the judged speaker φj across all N = 70 stimulus presentations:

$$le = \frac{1}{N} \sum_{k=1}^{N} |\phi_p - \phi_j|$$  

(1)

The smaller the value of the localization error is, the better the localization ability. The chance level of the localization error clle is calculated as the mean of the magnitudes of the differences between the azimuth of a judged speaker φp and the azimuth of a presenting speaker φj across all N = 49 possible combinations of presenting and judged speakers yielding 68.6 degrees:

$$clle = \frac{1}{S^2} \sum_{i=1}^{S} \sum_{m=1}^{S} |\phi_{ip} - \phi_{jm}|$$

(2)

Questionnaires

For the subjective part of our study, we used the standardized Speech, Spatial and Qualities of Hearing (SSQ) questionnaire (12). This questionnaire has 3 sections and assesses speech understanding, spatial hearing, and hearing quality with a scoring system of 0 to 10 for each item, in which 0 represents unable to hear and 10 means hears perfectly. Quality of life (QoL) was evaluated by means of the Health Utilities Index 3 (HUI-3)(13). The HUI-3 is a generic, multiattribute, preference-based classification system and is administered as a measure of general health status. Responses from the HUI-3 survey were computed to a health utility index score between 0 (dead) and 1 (perfect health). Single-attribute utility scores were reported based on a scale from 0 (lack of function) to 1 (full function). The SSQ and HUI-3 were completed by the patients before any treatment, after CROS and BAHA test periods, and 6 months after CI fitting. Tinnitus distress was measured with the visual analogue scale (VAS) before and 6 months after CI activation. The patients had to mark the tinnitus strength on a scale from 0 (no tinnitus) to 10 (maximum strength). The International Outcome Inventory for Hearing Aids (IOI-HA) is a self-report

![Figure 1](image-url)  
FIG. 1. Box-whisker plots of the HSM sentence in (background) noise test percent correct scores of the 11 subjects for the presentation configurations S0N0, SnhNssd, and SssdNh in the unaided as well as the aided conditions with CROS hearing aid, BAHA, and CI after 6 months. Significant improvement using the CI compared with each of the other conditions is shown on top of their box plots: * p < 0.05; ** p < 0.01 (Wilcoxon signed-rank test).
outcome measure in rehabilitation with hearing devices and contains 7 questions (14).

**Data Analysis**

Data were analyzed with SAS 9.2. Normality of preoperative and postoperative differences could not be assumed for many of the investigated items. Therefore, comparisons of CI with preoperative conditions were performed using Wilcoxon signed-rank test for paired observations, and p values were calculated based on the exact distribution of the test statistic.

Because this is a pilot study with 11 patients, we present p values without adjustment for multiple testing.

**RESULTS**

Group HSM sentence scores for the different treatment options and presentation configurations are shown in Figure 1 and the individual and median scores in Table 2. Speech comprehension for the configuration SssdNnh with the CI is significantly improved (CI versus unaided, \( p = 0.001 \); CI versus CROS, \( p = 0.03 \); CI versus BAHA, \( p = 0.001 \)). There is no statistically significant difference in speech comprehension for the presentation configuration S0N0 (CI versus unaided, \( p = 0.75 \); CI versus CROS, \( p = 0.76 \); CI versus BAHA, \( p = 0.70 \)). For the configuration SnhNssd, there is a significant improvement of speech comprehension with the CI in comparison with CROS and BAHA (CI versus CROS, \( p = 0.031 \); CI versus BAHA, \( p = 0.023 \)), but no improvement in comparison with the unaided condition (CI versus unaided, \( p = 0.094 \)).

Group OLSA critical SNRs for the different test configurations are illustrated in Figure 2. For the SssdNnh configuration, a significant improvement of critical SNR was found when comparing the unaided (median, \(-0.6 \) dB) to the aided condition with CI (median, \(-6.2 \) dB; \( p = 0.001 \)). There is no difference in speech comprehension between the unilateral and the bilateral condition for the configurations S0N0 and SnhNssd. The S0N0 configuration, in which each ear is presented with the same SNR, allows for the computation of the summation effect, which is the difference in speech comprehension in the bilateral compared with the unilateral condition. Our patients did not show a summation effect on group median (0 dB). For the SnhNssd configuration, the median critical SNR is \(-14.1 \) dB in the unaided condition and \(-14.6 \) dB in the binaural condition (\( p = 0.15 \)). The small difference of 0.5 dB representing the binaural squelch effect is not statistically significant.

Figure 3 shows the group localization errors. Localization error is significantly reduced with the CI (median, 15.0 degrees) compared with the unaided condition (median, 33.9 degrees; \( p = 0.003 \)), to CROS (median, 39.9 degrees; \( p = 0.001 \)) and to BAHA (median, 30.4 degrees; \( p = 0.002 \)).

The SSQ scores of the 3 questionnaire sections are illustrated in Figure 4. There was significant improvement with the CI in the speech section. The CI median score was 5.76 versus the unaided median score of 2.55 (\( p = 0.014 \)), the CROS median score of 3.13 (\( p = 0.014 \)), and the BAHA median score of 2.93 (\( p = 0.007 \)). In the

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**TABLE 2.** Individual and group median Hochmair-Shulz-Moser sentence test scores (% correct) for the different presentation configurations

<table>
<thead>
<tr>
<th>Patient</th>
<th>Unaided</th>
<th>CI</th>
<th>CROS</th>
<th>BAHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.42</td>
<td>7.13</td>
<td>6.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>6.13</td>
<td>6.00</td>
<td>5.80</td>
<td>5.00</td>
</tr>
<tr>
<td>4</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
</tr>
<tr>
<td>5</td>
<td>9.15</td>
<td>9.15</td>
<td>9.15</td>
<td>9.15</td>
</tr>
<tr>
<td>7</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
</tr>
<tr>
<td>8</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
</tr>
<tr>
<td>9</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
</tr>
<tr>
<td>10</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
</tr>
<tr>
<td>11</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
<td>16.35</td>
</tr>
</tbody>
</table>

Median 14.62 15.00 15.00 15.00

Range 0.00 0.00 0.00 0.00

S. ARNDT ET AL.
spatial section, the scores also were significantly better with the CI (median, 5.71) versus the unaided condition (median, 2.29; \( p = 0.001 \)), the CROS (median, 2.59; \( p = 0.027 \)), and the BAHA (median, 2.36; \( p = 0.002 \)). In the section on hearing quality, the CI median score was 7.81 versus a median score of 5.86 for the unaided group (\( p = 0.21 \)), a median score of 5.50 for the CROS group (\( p = 0.1934 \)), and a median score of 5.34 points for the BAHA group (\( p = 0.15 \)). Thus, the subjective assessment of the patients shows no significant differences in the quality of hearing. The tinnitus VAS scores are shown in Figure 5. The median tinnitus intensity before CI surgery of the 11 patients was 5. One patient had no tinnitus either before surgery or after CI implantation. Six months after CI use, the median tinnitus intensity decreased significantly to 0 when the CI was switched on (\( p = 0.0078 \)). The tinnitus intensity increased after switch-off of the speech processor to a median score of 5. Five of 10 patients showed complete suppression of tinnitus with the activated speech processor, and 3 patients reported a reduction from preoperative score of 9 to 10 to postoperative score of 2 to 3. Another patient had constant tinnitus strength of 5 before surgery and after implantation, independent of speech processor use. In 1
patient, the tinnitus did not change after implantation when using the processor but increased from 5 to 8 when the speech processor was deactivated. In the HUI-3, the overall group score for the CI condition is significantly increased compared with the CROS ($p = 0.004$) and the BAHA ($p = 0.008$). There is a tendency of preponderance with the CI compared with the unaided condition ($p = 0.051$). Closer inspection of individual subdomains in the HUI-3, especially hearing and speech, did not reveal any significant change (Table 3). The 7 domain scores of the IOI-HA are presented in Figure 6. The highest scores are obtained with the CI in all subdomains. The patients used the CI significantly longer per day than the other devices (CI versus BAHA, $p = 0.002$; CI versus CROS, $p = 0.016$). Especially the most important subdomains benefit (CI versus BAHA, $p = 0.002$; CI versus CROS, $p = 0.004$), satisfaction (CI versus BAHA, $p = 0.016$; CI versus CROS, $p = 0.008$), and QoL (CI versus BAHA, $p = 0.016$; CI versus CROS, $p = 0.016$) show significant improvement with the CI. The responses in the sub-domains residual activity limitation (RAL) and residual participation restrictions (RPR) demonstrated a significant advantage of the CI over the BAHA (RAL, $p = 0.0137$; RPR, $p = 0.0078$) but not in comparison with the CROS (RAL, $p = 0.0625$; RPR, $p = 0.1094$). There was no difference between the devices in the belief that
others are bothered by the patient’s hearing limitations (impact on others).

DISCUSSION

Our investigation shows that the rehabilitation of patients with unilateral deafness with a CI yields better results in speech comprehension and localization than conventional pseudobinaural hearing rehabilitation with CROS or BAHA or than in the unaided condition. The subjective self-assessments of the patients with questionnaires correlate with the objective speech comprehension and localization results.

For HSM testing, speech comprehension in noise in the most difficult configuration for patients with unilateral deafness (SssdNnh) was significantly superior with the CI. These results were confirmed by the critical SNR obtained by the OLSA test. Although Dillon (15) writes that there is no point in verifying binaural gain from the head shadow effect in the objective evaluation of hearing aids because “this advantage will occur, in some real life situations, for everyone who has a head!”, unilaterally deaf patients will profit from this purely physical effect only in patients with unilateral hearing loss, the head shadow effect still occurs but may be a detriment if speech originates on the opposite side of the head from their only hearing ear (16). It is important to offer this group of patients the opportunity of using both ears, with the CI ear receiving the sound with a better SNR, which is impossible in the pseudobinaural situation. Like Vermeire and Van de Heyning (17), we could not directly measure the acoustic head shadow effect in the free-field condition because of the difficulties in masking the normal hearing ear. Following their recommendation to use the spatial

![Box-whisker plots of the scores of the 11 subjects for each outcome domain (USE, daily use; BEN, benefit; RAL, residual activity limitation; SAT, satisfaction; RPR, residual participation restrictions; loth, impact on others; QoL, quality of life) and the overall score in the IOI-HA for CROS, BAHA, and CI after 6 months. Significant improvement using the CI compared with each of the other conditions is shown on top of their box plots: *p < 0.05; **p < 0.01 (Wilcoxon signed-rank test).](image)
configuration SciN0 where a combination of head shadow and squelch effect can be evaluated, we calculated the combined effect as the difference between the aided condition with CI and the unaided condition for the spatial configuration SssdNnh. The contribution of the head shadow effect to this combined effect remains unclear. The combined effect is 4.9 dB and represents a significant improvement with the CI. The size of this effect in the unilateral group reported by Vermeire and Van de Heyning (17) was 1.7 dB, which cannot be compared with our results because of the different presentation setups used. Although we could not prove a significant squelch effect, like Vermeire and Van de Heyning (17) in their unilaterally deaf group with a more difficult presentation configuration, it seems that binaural performance is better than the performance with pseudobinaural treatment or unaided. The only test configuration in which we could not find any advantage with the CI was the S0N0 configuration. Consequently, the summation effect obtained from this presentation configuration was not significant. Vermeire and Van de Heyning (17) even described a small deterioration of the critical SNR in this configuration with the CI 12 months after activation compared with the unaided situation. Dillon (15) voiced concern that binaural summation, similar to binaural squelch, will be affected by significant interaural asymmetries for the test measures. Our unilateral subjects have a clear interaural asymmetry in the unaided as well as in the aided condition with CI. That could explain the difficulties in detecting these 2 binaural effects.

The localization results demonstrate a significant improvement in the binaural condition with CI compared with all other conditions and thus a significant binaural advantage for localization ability for the group. Even in the unaided condition, the patients showed a localization error of approximately 34 degrees on median which is approximately 34 degrees better than the chance level of 68.6 degrees. Probably, these patients benefit from 2 cues underlying monaural sound localization in the horizontal plane, head shadow, and spectral pinna cues (18,19). As in several published studies on sound localization in hearing impaired patients, for example, Laszig et al. (20), the intention of sound level roving in our study was to reduce the head shadow cue as far as possible. However, despite sound level roving, Laszig et al. (20) showed in bilateral CI patients an average horizontal localization root mean square error of 87 degrees for the left monaural CI condition and 89 degrees for the right monaural CI condition, which is better than the chance level of 105 degrees inherent to the full circle array of 12 speakers used for localization tests. Van Wanrooj and Van Opstal (19) reported that monaurally deaf listeners relied heavily on the head shadow cue when localizing sound with randomly interleaved sound levels in the horizontal plane. Until now, there are no reports on localization ability in patients with unilateral deafness after cochlear implantation. However, several studies consistently demonstrate a statistically significant improvement of localization for bilateral versus unilateral CI stimulation (20–23).

The patients scored better in all sections of the SSQ questionnaire with the CI. They scored significantly higher in the sections spatial hearing and speech comprehension. These favorable results with the CI in unilaterally deaf patients are in agreement with Vermeire and Van de Heyning (17). In contrast to them, we were able to prove a significantly better score with the CI in the speech understanding section than in the unaided situation. There was no difference between the treatment options and the unaided situation in the hearing quality section. Thus, there is no decrement in perceived speech sound quality when using the CI compared with the unaided condition, which might be expected because of the use of 2 different auditory stimulation modalities.

The initial intention of the cochlear implantation in unilaterally deaf patients, published in 2008 (24), was not binaural hearing and improvement of sound localization, but the treatment of seriously bothersome tinnitus. Van de Heyning et al. (24) report on complete tinnitus inhibition in 3 of 22 subjects after 6 months of CI use. Our tinnitus VAS results also demonstrate a significant reduction or even complete suppression of tinnitus in 8 of 10 patients. The findings of the first report and of our study represent a very encouraging side effect for patients with unilateral deafness after cochlear implantation. Although we could demonstrate a higher overall QoL score with the CI using the HUI-3 questionnaire, we did not see any significant differences in the QoL subdomains. There was a tendency to improvement with the CI in comparison with the CROS device only in the subdomains hearing and emotion. One reason for the lack of improvements in comparison with other studies with bilaterally deaf patients (25) may be that hearing impairment in unilateral deafness involves fewer complaints because of one normal hearing ear. The IOI-HA outcome in this study showed a substantial amount of benefit, satisfaction, and improvement in QoL with the CI. All but 1 patient used the CI for more than 8 hours per day; it was significant in helping them to improve their hearing, reduced the number of situations in which hearing loss was significantly problematic, and had a significant positive impact on the enjoyment of life for most of the patients.

One weakness of our study is that the BAHA was mounted on the headband. We have to keep in mind that the difference in bone conduction thresholds can vary up to 15 dB particularly in the higher frequencies compared with the use of the BAHA processor mounted to the titanium implant because of the damping of the skin and hairs (26). That may imply better results in the SssdNnh configuration after BAHA surgery. Linstrom et al. (27) demonstrated that the implanted BAHA does indeed enhance communication in unilaterally deaf patients when speech is presented on the BAHA side. They also showed poorer speech comprehension when noise was presented on the BAHA side. However, we assume that even after implantation of the titanium screw, the advantages of binaural hearing restoration are predominant with the CI. To prove this assumption, it would be necessary to perform BAHA surgery before CI surgery. Nevertheless, this procedure would not

Otology & Neurotology, Vol. 00, No. 00, 2010
CONCLUSION

The different treatment options including cochlear implantation for patients with unilateral deafness were compared for the first time. The cochlear implantation turned out to be the best option for improvement of speech comprehension in noise and localization abilities. Although we could not demonstrate a significant true binaural effect with the CI, there was a clear tendency for the existence of these effects.

REFERENCES


Otology & Neurotology, Vol. 00, No. 00, 2010