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What is This?
Long-Term Performance of Cochlear Implants in Postlingually Deafened Adults

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Abstract

Objective. To evaluate the stability of long-term hearing performance after cochlear implantation (CI) in postlingually deafened adults and to explore the boundaries and limitations of the present test batteries for adult CI patients.

Study Design. Case series with chart review.

Setting. Tertiary referral center.

Subjects and Methods. A cohort of 1005 postlingually deafened adult cochlear implantees, who received their implants after age 18 years, was unilaterally implanted and had no inner ear malformations or cochlear ossification. Hearing performance with cochlear implant was evaluated with the help of 5 standard German speech tests.

Results. The average performance improved significantly during the first 6 months in all tests (learning phase) and afterward entered a plateau phase in which no statistically significant improvements or deteriorations were observed for more than 20 years of follow-up. For each test, the average performance of the cohort, the ceiling effect, and the average results for high and low performers are presented.

Conclusions. In this study, postlingually deafened adults required about 6 months to learn how to process the artificial signals delivered by the cochlear implant. After this learning phase, the hearing performance entered a stable plateau phase for more than 20 years. This stability reveals the long-term reliability of the technology and the biological stability of the electrode-nerve interface over years. In this study, the authors also evaluated the "ceiling effect" with 5 standard German speech tests, used for evaluation of postlingually deafened adult CI patients.

Keywords

cochlear implant, adult, performance

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In the past 4 decades, more than 150,000 deaf individuals have received a cochlear implant worldwide. Forty years ago, single-channel cochlear implants provided recognition of environmental sounds and improved the speech perception only in combination with lip reading.¹ As a result of the improvements in implant design and speech-processing strategies, most postlingually deafened adults who receive a multi-channel cochlear implant develop within a short period open-set speech perception and can converse on the phone.²⁻⁴ Nowadays, the indicators for high performance in adult cochlear implantees are speech perception in noise and even music perception and enjoyment. Because of this continuous improvement in hearing performance, the standard test batteries for evaluation of patients’ performance must also be reevaluated and modified. Large cochlear implant centers with systematic postoperative follow-up programs can contribute significantly to the development of a standardized test battery for evaluation of performance in cochlear implant patients. Not only the short-term evaluation but also evaluation of performance over long periods of follow-up should be considered.

The Hannover cochlear implant program started in 1984 and, with more than 4500 implantations by the end of 2009, is the largest cochlear implant program worldwide. With the systematic rehabilitation and follow-up program in Hannover, it is possible to evaluate the performance in large cohorts of cochlear implant patients.

Here we present a longitudinal retrospective study on the performance of a cohort of 1005 postlingually deafened adult subjects who were implanted from July 1984 to January 2008 in the Ear, Nose, and Throat (ENT) Department of the Medical University of Hannover. Our goal is to evaluate the stability of long-term hearing performance after cochlear implantation in postlingually deafened adults and to explore the boundaries and limitations of the present test batteries for adult cochlear implant (CI) patients.

Material and Methods

More than 3960 cochlear implantations were performed from July 1984 to January 2008 in the ENT Department of

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the Medical University of Hannover. Of these implantations, 1761 were performed in postlingually deafened adults (age >18 years at the time of implantation). A cohort of 1005 of these adults was selected for a retrospective evaluation of their long-term hearing performance with cochlear implants. In this study, the results of 5 different standard German speech tests performed from August 1984 to October 2008 (up to 24 years of follow-up) were analyzed. The test battery was composed of Freiburger numbers and monosyllabic tests, speech tracking, and the Hochmair-Schulz-Moser (HSM) sentence test in quiet and with 10-dB signal-to-noise ratio (SNR). The study was performed with approval of the ethics committee of the Medical University of Hannover (Nr. 1227-2011).

Patient Selection Criteria
All subjects were postlingually deafened adults who were 18 years or older at the time of implantation. To select a homogeneous cohort, subjects with additional handicaps, cochlear ossification, and inner ear malformations were excluded from this study. Also, adults who received special types of cochlear implants (hybrid or double array) were not included. In patients who underwent reimplantation or received an implant on the contralateral side, only the test results up to revision or contralateral implantation were included in the study. All the subjects were traditional cochlear implant candidates with an average preoperative best-aided hearing performance of 13 ± 18 words/min in the speech-tracking test (normal-hearing adults perform with 80-100 words/min in this test). To provide equal test conditions, one selection criterion was German as a native language.

Patient Demographics
Our cohort was composed of 565 women (56%) and 440 men (44%). The average age of the subjects at the time of implantation was 53 years (range, 18-90 years). The average age of the subjects at the time of study (October 2008) was 61.5 years, ranging from 19 to 98 years. The average duration of deafness for the implanted ear was 7 years.

Cochlear Implant Systems and Speech Processing Strategies over Time
During these 24 years, different types of cochlear implant systems and speech-processing strategies were applied in our patients. The present adult cochlear implant community benefits from a variety of implant systems and speech-processing strategies. The detailed information regarding the implant systems and speech-processing strategies over time is presented in Figure 1. In our study, we present the average performance of this mixed cohort of postlingually deafened adult cochlear implantees independent of their type of implant and speech-processing strategy.

The Speech Test Battery
The speech test battery was composed of 5 standard German tests for speech recognition: Freiburger numbers and monosyllabic tests, speech-tracking test, and the Hochmair-Schulz-Moser (HSM) sentence test in quiet and in 10-dB SNR. The HSM test was included later in the standard test battery for evaluation of cochlear implant patients in Hannover (HSM in quiet was performed since December 1999 and HSM in noise since July 2000). The speech tests were performed systematically at 3, 6, and 12 months after implantation and then at least once a year.
Principally, we would expect to have 8028 test results, if all the patients had been evaluated with the 5 speech tests in each follow-up visit and if none of the patients missed a follow-up visit over the years. Because of the later application of the HSM tests in the standard test battery, however, the first follow-up results with these 2 tests in our pioneer subjects (implanted before 1990) started 15 years after implantation, which reduces the number of the available tests to nearly half of the expected number. The Freiburger and speech-tracking tests are missing only in cases in which patients missed a follow-up session or, due to lack of time, not all the 5 speech tests were performed. Table 1 reveals the number of the available test results in our cohort for the whole duration of follow-up until October 2008.

**Definition of Poor Performers and Good Performers**

To be able to have simple categories for good and poor performers in a standard and uncomplicated way, we defined a poor performer as an individual whose performance is lower than the mean value minus the standard deviation. A good performer is defined as an individual whose performance is better than the mean value plus the standard deviation. It is evident that this definition can only be applied to the data if there are no ceiling effects.

**Definition of the Plateau and Ceiling Effect**

There is no official definition for plateau in speech tests; therefore, we use our own definition, which is as follows: a plateau in the time course of a speech test is reached between 2 test sessions, t0 and t1, when all the test results between t0 and t1 stay within ± 10% of the average of all the test results in this time interval.

A ceiling effect occurs when the speech test is not challenging enough for a group of subjects, because they have already reached the highest score that can be achieved on that test. In other words, the most highly performing individuals will score at the highest possible score. This becomes a measurement problem when you are trying to identify changes—the subject may continue to improve, but the test does not capture that improvement.

**Statistical Analysis**

The statistical analysis of the test results was performed with SPSS version 16 (SPSS, Inc, an IBM Company, Chicago, Illinois). The analysis was performed with the help of 1-way analysis of variance (ANOVA) and the least significant difference (LSD) test. The significance level was $P \leq .05$, and highly significant was defined as $P \leq .01$.

**Results**

**Freiburger Numbers Test**

In the Freiburger numbers test, the average performance of our cohort improved significantly from 73.9% ± 31.7% to 85.9% ± 26.1% during the first 6 months after implantation and remained stable thereafter for the whole period of follow-up (22 years). During this long follow-up, no statistically significant improvements or deteriorations were observed in the average performance. The slight dip in the curve at 22 years after implantation is due to the limited number of test results available at this time interval and is not statistically significant (Figure 2).

The average performance of our cohort for the Freiburger numbers test at 1 year after implantation was 87.4%. One year after implantation, 61.8% (504 of 816) of the patients had already achieved the maximum test result (100%). The strong ceiling effect makes the Freiburger numbers test inappropriate for evaluating the performance over long periods of time. According to our definition, the poor performers had a performance below 63.07% at 1 year after implantation.

**Freiburger Monosyllabic Test**

The average performance of our cohort for the Freiburger monosyllabic test improved significantly from 27.1% ± 25.4% to 47.7% ± 30.7% during the first year after implantation and then remained stable over the period of 22 years. Statistically significant improvements or deteriorations were not observed after 1 year (Figure 3).

Only 1.1% (9 of 804) of our patients reached the maximum test result (100% correct) at the 1-year interval and showed a ceiling effect. According to our definition, good performers had a performance above 78.44% and poor performers had a performance below 17.06% at 1 year after implantation.

**Speech-Tracking Test**

The average performance of our cohort for the speech-tracking test showed a significant improvement from 24.5 ± 19.6 words/min at the first fitting to 36.3 ± 24 words/min 6 months after implantation. During the 22 years of follow-up, speech recognition remained stable and did not show statistically significant improvements or deteriorations. The sinking of the curve 20 years after implantation is due to the limited number of the tests evaluated at this time and is not statistically significant (Figure 4).

The average result of the speech-tracking test at a 1-year interval was 42.25 words/min. Some star performers could even reach speech recognition up to 105 words/min at the 3-month interval. Of the patients, 4.6% (36 of 785) reached a test result of 80 words/min or higher 1 year after implantation. According to our definition, good performers had a
performance above 67.08 words/min and poor performers had a performance below 17.42 words/min at 1 year after implantation. The results of this test are limited to approximately 80 words/min by the speed of normal talkers.

**HSM Sentence Test in Quiet**

The average results of the HSM sentence test in quiet improved during the first 6 months after implantation from 44.3% ± 36.7% to 69.3% ± 35.3% and then remained stable up to the seventh year after implantation. At this time, we observed a slight deterioration of the average test results from 69.5% ± 35.1% to 63.3% ± 35.8% \( (P = .043) \) and then again a stable phase up to the 22nd year after implantation in which no statistically significant improvements or deteriorations were observed. This slight deterioration in the average results at the seventh-year interval probably is due to the fact that patients who were implanted in the past 7 years had a better performance (due to recent implant and speech-processing technologies) (Figure 5).

Also, in the HSM sentence test in quiet, the star performers had already reached the maximum test result (100% correct) in the first fitting session, which is evidence for a strong ceiling effect in this speech test. The average performance at the 1-year interval was 72.5%. According to our definition, poor performers had a performance below 38.51% at 1 year after implantation. At the 1-year interval, 18.1% (99 of 548) of the patients reached the maximum test result (100%) and showed a ceiling effect.

**HSM Sentence Test in 10-dB SNR**

In the HSM sentence test in noise, the average performance improved significantly from 7% ± 13.9% to 20.8% ± 24.6%
in the first 6 months after implantation and then remained stable until the seventh year of follow-up. Similar to the HSM sentence test in quiet, a slight but statistically significant deterioration of the test results can be seen (from $15.4\% \pm 22.7\%$ to $10.4\% \pm 19.2\%$). Similar to the HSM sentence test in quiet, this deterioration may be due to a reduction of the number of subjects with recent cochlear implants and speech-processing technology at follow-up intervals longer than 7 years (Figure 6).

The average result of the HSM in noise was about $22.85\%$ one year after implantation, with the maximum result being $92.5\%$. According to our definition, good performers had a performance above $49\%$ at 1 year after implantation.

**Comparison of the Results of the 5 Speech Tests over Time**

A comparison between the average results of these 5 standard German speech tests reveals the relative degree of difficulty of these tests compared with each other. The Freiburger numbers test is the easiest, with the strongest ceiling effect, followed by the HSM in quiet test, the Freiburger monosyllabic test, the speech-tracking test, and finally the HSM sentence test in noise.

**Discussion**

The stability of the results in postlingually deafened adult CI patients over more than 22 years is evidence of reliable

![Figure 4](image1.png)

**Figure 4.** The average results of the speech-tracking test (words/min) over a period of 22 years, as well as the number of the subjects tested at each follow-up session. $**P < .01$.

![Figure 5](image2.png)

**Figure 5.** The average results of the Hochmair-Schulz-Moser (HSM) sentence test in quiet (% correct) over a period of 22 years, as well as the number of the subjects tested at each follow-up session. $^*P < .05$. $**P < .01$. 

![Figure 6](image3.png)
implant technology and stable biological electrode-nerve interface (long-term biocompatibility). This stability in long-term hearing performance of postlingually deafened adult CI patients may also be a clinical correlate to the findings of animal experiments that show the positive effect of chronic electrical stimulation on the survival of spiral ganglion cells in deaf cochlea.10,11

However, our data and conclusions are limited to postlingually deafened adults who have hearing loss as the only pathology with no additional morbidities.

**Good and Poor Cochlear Implant Performers**

In a retrospective study of 445 adult CI subjects in Toronto, Bodmer et al12 defined poor performance as less than a 10% score and high performance as a 90% to 100% score on the City University of New York (CUNY) or Central Institute for the Deaf (CID) test. In this population, 13% were poor performers and 44% high performers. Considering the results in our large cohort, we suggest using the mean value of each test plus standard deviation as a definition for good performance and mean value minus standard deviation as a definition for poor performance.9 This definition can be applied for different time intervals after implantation and is again necessary to have a standard definition for reporting and comparing the results between different cochlear implant centers.

**Level of Difficulty in the Standard Test Battery of Adult CI patients and the Ceiling Effect in Different Tests**

The level of performance of our cohort in this test battery showed that obviously the Freiburger numbers test is the easiest test, followed by the HSM sentence test in quiet, the Freiburger monosyllabic test, the speech-tracking test, and finally the HSM sentence test in 10-dB SNR. Most of the candidates reached relatively soon the ceiling effect in the first 2 tests (first 6 months), which makes the follow-up of improvements in performance over time difficult. The Freiburger monosyllabic test, the speech-tracking test, and the HSM test in 10-dB SNR showed a very low ceiling effect. For star performers who reached the ceiling effect even in these tests, more challenging speech tests with adaptive SNR will be required. For German-speaking countries, the Oldenburg sentence test is a well-established sentence test using the 50% speech reception threshold scheme.13

**The Learning Phase and Plateau Effect**

The postlingually deafened adult CI subjects in our cohort showed a learning phase of 6 months, in which a significant improvement in speech perception was observed, and following this primary learning phase, further improvements and deteriorations were not statistically significant. Only in the Freiburger monosyllabic test did the learning phase last for 1 year. This plateau effect was not only observed in the easier speech tests with a relatively strong ceiling effect but also in the speech test in noise, in which most of the patients were still far from the ceiling effect, and because of the difficulty of the test material, cognitive factors and the learning effect should actually play a more important role in improvement of the results over years. Also, in this test, a similar learning phase of 6 months was observed, with no statistically significant improvement in the results thereafter. It takes a relatively short time for the brain of postlingually deafened adults to learn how to process the artificial signal delivered by the cochlear implant.14 Ruffin et al,15 in a retrospective longitudinal study (10 years follow-up) of 31 Clarion 1.0 users, found the plateau at 24 months where no significant improvement or decline in speech results happened.

Herzog et al16 reported similar results for the Einsilber test for geriatric and normal adults. The plateau was reached after 2 years for both groups (55%) and remained stable up to 5 years of follow-up. In our study, in almost all of the tests, the first 6 months was obviously the learning phase. However, recent studies have shown that brain training with complex
rehabilitation tasks such as “telephone speech” and “speech in noise” can induce a significant improvement of hearing performance in postlingually deaf adult cochlear implantees who have already entered the plateau phase for several years.17

Conclusions
The stability of performance with cochlear implants after more than 20 years of device usage reveals the long-term reliability of the technology and the biological stability of the electrode-nerve interface over years. Our study revealed a learning phase in the first 6 months after implantation and thereafter the so-called plateau effect in the hearing performance of postlingually deafened adult CI patients. These 6 months may be a period when the brains of postlingually deafened adults have to learn how to process the artificial signals delivered by the cochlear implant. Exploring the results of 5 standard German speech tests for this large cohort of postlingually deafened adult CI patients revealed a relatively strong ceiling effect in 2 tests (Freiburger numbers and HSM test in quiet). The Freiburger monosyllabic test, the speech-tracking test, and the HSM test in 10-dB SNR showed a very low ceiling effect. For star performers who reached the ceiling effect even in these tests, more challenging speech tests with adaptive signal-to-noise ratios will be required.

Author Contributions
Minoo Lenarz, data analysis, concept and design, drafting the article; Hasibe Sönmez, data acquisition and analysis; Gert Joseph, data acquisition and analysis; Andreas Büchner, article revision; Thomas Lenarz, article revision.

Disclosures
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