Levels of measurement in pre- and postoperative testing of cochlear implant subjects

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journal: STL-QPSR
volume: 27
number: 2-3
year: 1986
pages: 045-059

http://www.speech.kth.se/qpsr
IV. SPEECH AND HEARING DEFECTS AND AIDS

A. LEVELS OF MEASUREMENT IN PRE- AND POSTOPERATIVE TESTING OF COCHLEAR IMPLANT SUBJECTS*
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Abstract
A test program used in the Swedish implant project is described where speech perception is seen as a process on five different levels: transformation, signal analysis, phonetic interpretation, information processing, and linguistic interpretation. By comparing the test results on the different levels, it is possible to understand more about the patients' difficulties. Results are given from pre- and postoperative testing of cochlear implant patients. The Vienna/3M extra-cochlear implant is used.

THE SWEDISH COCHLEAR IMPLANT PROJECT
The aim of the Swedish implant project is to operate on ten patients and then evaluate the results before further decisions are made regarding a permanent implant program. The Vienna/3M extra-cochlear implant was chosen for the pilot program. The program is run at the South Hospital in Stockholm in cooperation with the Royal Institute of Technology (KTH). The total number of patients implanted in Stockholm is at present seven. Two Swedish patients had earlier been implanted in Vienna (W1 and W2). In this paper, some results from the preoperative tests with the first nine patients and some postoperative results for patients W1, W2, S1, and S2 are presented.

PATIENT SELECTION
The cochlear implant is intended for patients that are "totally deaf". This classification is usually based on the results from the standard audiological tests, e.g., pure-tone audiometry and results from speech tests with lists of phonetically balanced words or lists of spondee words. Speech-perception ability reported from the cochlear implant subjects shows very large variations. A small number of "star" patients get some understanding of unknown words and sentences without simultaneous lipreading, but the majority of them receive some help only during lipreading and in identifying environmental sounds. The same effects reported from cochlear implant users are often obtained by a profoundly deaf persons using an ordinary hearing aid or a simple tactile aid, if they are given adequate training. This situation makes a

*Based on a paper presented at the Nordic Workshop on Cochlear Implants, Dec. 9-10, 1985, Södersjukhuset (The South Hospital), Stockholm.
careful preoperative testing necessary. In these, the same kind of tests must be used as in the evaluation of patients with cochlear implants, that is, tests with forced choice between a limited number of words, tests with simultaneous lipreading, etc. In the postoperative testing it is important to get detailed information on the type and amount of auditory information that the patient gets from the implant. This information can be used in fitting the processor and the training program to the patient's individual needs and also to explain the difference in results obtained by different patients.

**DESCRIPTION OF THE TEST BATTERY**

In both the pre- and postoperative audiological testing in the pilot program, an earlier developed test battery is used (Risberg & Agelfors, 1983). Speech perception is seen as a process on several different levels (Massaro, 1975). The lowest level is transformation from an acoustic signal to signals in the auditory system. Measurements are made of the detection threshold, the most comfortable level, and the uncomfortable threshold. In the preoperative tests, measurements are made with earphones. An audiometer is used that gives signals with a sound pressure level of 135 dB SPL over the whole frequency range. In the postoperative tests, measurements are made with electric stimulation via the implanted electrode.

The next test level is called signal analysis. On this level, measurements are made of the patient's ability to detect changes in the amplitude, time and frequency domain. The measurements are made at the subject's most comfortable loudness level. In the preoperative tests, the signals are presented over headphones and in the postoperative tests with direct coupling from the test equipment to the microphone input of the stimulator. Many different tests are possible on this level. At present, the following tests have been used:

1. **Time discrimination**
   The measurements are made by electric stimulation with the Vienna method (Hochmair-Desoyer, & al., 1983).

2. **Frequency discrimination with sinusoidal signal**
   Measurements are made in the frequency range 125 Hz to 3000 Hz. This test is seen as a general test of the signal-analyzing capacity (Risberg & Agelfors, 1984). A signal pair where the frequencies in pair are the same or different is presented. The response alternatives are "same" and "different". The frequency difference in the pair is reduced until the subject can detect the difference with 75% certainty. At present, no loudness balancing is used. The subjects report that they for large frequency differences, 15-20%, use loudness differences between the test tones.
3. Frequency discrimination with band-pass filtered pulse trains

The bandwidth of the filter is 500 Hz and the center frequencies are 500, 1000, and 2800 Hz. The pulse repetition frequency is 125 and 250 c/s. The test simulates intonation changes in voiced sounds for a male and a female voice. The test method is the same as above.

4. GAP-detection with band-pass filtered white noise

The test measures the time resolution by means of a short interruption in a two seconds' long band-pass filtered noise signal. The same band-pass filters as in the above-mentioned measurement are used. The duration of the gap is gradually reduced until the subjects cannot say whether there is a gap in the signal or not.

5. Identification time for periodic and nonperiodic signals

In this test, two signals are used, a pulse train with the repetition frequency 120 c/s and white noise. The signals are band-pass filtered with the same filters as used in tests 3 and 4. One signal at a time is presented, and the subject is asked to identify the signal as pulse or noise. The duration of the signal is gradually reduced and the shortest duration that gives 75% correct identification is established (Risberg, 1968). This test is intended to show if the subject can use short friction energy in the speech signal to detect fricatives and plosive sounds.

6. Pitch scaling

Preliminary tests have been made with a simple pitch-scaling task. Seven sinusoidal signals in the frequency range between 125 and 3000 Hz are selected and balanced for loudness. The 125 Hz signal is called "one" and the 3000 Hz signal is called "seven". The signals are then presented randomly, and the subject is asked to give a pitch to the presented signal between one and seven.

The next measuring level is phonetic interpretation. The tests on this level are designed to give an indication on the subject's learnt ability to extract basic linguistic information from an acoustic signal. Forced choice tests are used containing words or sentences with phonetic contrasts. The number of response alternatives are two or three. The following different tests are at present used:

1. Number of syllables

Words that mainly differ in the number of syllables, e.g. /bad-bada-badad/. If continuous consonants are used as syllable boundaries, the test will be more difficult. This is a test of the subject's ability to detect gross time-intensity patterns.
2. Vowel length
If the vowel is followed by a plosive sound, the test will be rather easy but more difficult if the vowel is followed by a con- tinuous consonant /m,n,l,j/. This is also a test of time resolution but requires that the subject can detect spectral boundaries.

3. Voiced-unvoiced plosives
This is a test of the ability to identify finer time-intensity patterns.

4. Male-female voices
Test of the ability to detect periodicity differences. It is not always true that this is a test of periodicity detection since the subject can perceive the male voice as "rough" and the female voice as "smooth".

5. Word stress
Three-word sentences with emphasis on the first, the second, and the third word are used. The words in the sentences contain voiced phonemes only and are read without exaggerated emphasis. The main effect of word stress is a change in the fundamental frequency.

6. Differences between s-st-t in initial position
Word triads with this difference are used. The test measures the subject's ability to use information in the frequency range above 3000 Hz.

7. Vowel test 1
Words pairs with the vowels /u:/-/ø:/ or /ø:/-/aː/. The difference between the vowels lies in the frequency range below 1000 Hz.

8. Vowel test 2
Word pairs with the vowels /iː/-/uː/ and /eː/-/øː/. The difference between the vowels lies in the frequency range above 1000 Hz.

The individual tests contain 15-20 test items. If the patient can identify 75% of the items correctly, it is assumed that he can use the acoustic differences between the test words. All results must, however, be interpreted with caution since the subjects, sometimes, can use secondary information in the pair for identification, e.g., the intensity difference between the vowels.

Many of these tests are similar to tests in the MAC-battery (Owens & al., 1981) but the tests used on the level phonetic interpretation are more systematically based on acoustic differences between the test items. This makes it easier to interpret the results in relation to those obtained on the test levels transformation and signal analysis.
On this test level, nonsense syllables and tests with synthetic speech might also be used (Fourcin, 1980). For the tests, and also for part of the training, a computer-assisted equipment is used (Mizuno & Risberg, 1984). In some of the tests, the subjects can repeat the stimulus any number of times before answering. This gives some information on the degree of the subject's confidence.

In the speech-perception model behind the test battery, it is assumed that the information-processing ability varies from subject to subject. This means that for subjects with the same linguistic knowledge, the results on higher level speech tests will vary even if the same results are obtained on the lower test levels. At present, no formal tests are made on this level.

The last measuring level is linguistic interpretation. On this test level, tests with forced choice between a limited number of words, e.g., 12 spondee words or sentences, and with unknown words and sentences are used. Tests with unknown material are usually made with simultaneous lipreading, and the results are compared without or with the technical aid. One example of a test used is the so-called question-test (Ewertsen, 1973). This test consists of 20 simple questions, e.g., "How many legs has a cow?", that should be answered.

In Table I, a summary of the test battery is given.

Table I. Levels of measurement in pre- and postoperative testing of cochlear implant patients.

I. Transformation. Detection threshold and dynamic range

II. Signal analysis. Discrimination in frequency, time, and amplitude.

III. Phonetic interpretation. Closed speech tests with phonetic contrasts.

IV. Information-processing ability. Memory and speed of processing. Interaction between sensory modalities.

V. Linguistic interpretation. Speech tests with forced choice between words and sentences. Tests with unknown words and sentences with and without lipreading.

SOME RESULTS FROM PREOPERATIVE TESTS

In June 1985 nine patients have gone through the preoperative tests and four have been operated on. Fig. 1 shows the pure-tone audiogram and the results from the frequency-discrimination measurements on one subject (P3/S3). Based on the results from earlier measurements, a
frequency discrimination ability better than about 10% seems to indicate some useful residual hearing.

![Graph showing hearing loss and frequency discrimination ability](image)

Dif. 1. Pure-tone audiogram and frequency-discrimination ability of subject P3/S3.

Some subject data and results from the measurements on levels "I" and "II" from seven subjects are shown in Table II. The frequency-discrimination ability was measured with sinusoidal signals in the frequency range 125 to 4000 Hz. The lowest DL in per cent and the test frequency are given. The lowest GAP-time and test mid-frequency are given in the table. At present, four subjects have been implanted in Stockholm (S1, S2, S3, S4). Three of them had some small residual hearing and one used a hearing aid on the nonimplanted ear but the other two did not get any benefit from a hearing aid.

### Table II. Some subject data and results from measurements on levels I and II.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age</th>
<th>Years deaf</th>
<th>Present</th>
<th>Use of HA</th>
<th>PTA, dB</th>
<th>Best DL, freq, %</th>
<th>Best GAP, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1/S1</td>
<td>F</td>
<td>30</td>
<td>3</td>
<td>NO</td>
<td>NO</td>
<td>108</td>
<td>7(250)</td>
<td>10 (1000)</td>
</tr>
<tr>
<td>P2/S2</td>
<td>M</td>
<td>55</td>
<td>34</td>
<td>NO</td>
<td>NO</td>
<td>108</td>
<td>20(500)</td>
<td>28 (1000)</td>
</tr>
<tr>
<td>P3/S3</td>
<td>M</td>
<td>53</td>
<td>7</td>
<td>YES</td>
<td>YES</td>
<td>107</td>
<td>20(500)</td>
<td>30 (1000)</td>
</tr>
<tr>
<td>P6</td>
<td>F</td>
<td>50</td>
<td>37</td>
<td>YES</td>
<td>YES</td>
<td>95</td>
<td>7(250)</td>
<td>36 (500)</td>
</tr>
<tr>
<td>P7/S4</td>
<td>M</td>
<td>42</td>
<td>20</td>
<td>NO</td>
<td>NO</td>
<td>&gt;120</td>
<td>NR</td>
<td>300(500)</td>
</tr>
<tr>
<td>P8</td>
<td>M</td>
<td>34</td>
<td>26</td>
<td>NO</td>
<td>NO</td>
<td>117</td>
<td>NR</td>
<td>190(1000)</td>
</tr>
<tr>
<td>P9</td>
<td>M</td>
<td>53</td>
<td>12</td>
<td>YES</td>
<td>YES</td>
<td>107</td>
<td>30(500)</td>
<td>100(1000)</td>
</tr>
</tbody>
</table>

Normal hearing: <2 <10
In Figs 2 and 3, results on test level III, *phonetic interpretation*, and from one test on the level of *linguistic interpretation* (the spondee test) are shown. The levels of guessing and of significance are shown in the figures. In the figures some results on the same tests are also given when a normal hearing subject, made "deaf" with noise masking, was tested with a bone conductor on the index finger. The range of results on postoperative tests obtained by the two best subjects 12 months after implantation is also shown (hatched area). These results can be used in criteria on implantation. It is apparent that subject P6 has too good residual hearing.

Fig. 2. Results from the preoperative tests on the level *phonetic interpretation* for nine patients. "T" shows the results from tactile tests with a bone conductor. The hatched area shows the range of results on the postoperative test 12 months after implantation for the two best patients.

In Figs. 2 and 3, the results from the test with 12 known spondee words are shown on the last test level, *linguistic interpretation*. This test might be used as a simple screening test for potential implant pa-
Patients. If the patients get a good result on this test, they are probably not suitable candidates. In Fig. 4 results on the question test for three subjects are shown. This test was run with lipreading and with and without technical aids. The subjects that did not use a hearing aid were tested with a tactile aid (Spens & Plant, 1983) that they had been trained with for 1-2 months before the test. Subject P1/S1 is a very good speech-reader and this test is too easy for her. Even the results on this test show that P6 has too good residual hearing.

Fig. 3. The same as Fig. 2 on other tests.
In the preoperative tests, a detailed otological examination, tests with electric stimulation at the promontory, and a detailed psychological and social evaluation are included. In the final decisions on implantation, the results from the last tests are given a very high importance. In the tests with electric stimulation, the test equipment and programs developed in Vienna are used.

**SOME RESULTS ON THE POSTOPERATIVE TESTS**

After operation, the patients go through a longer, structured training program at the pedagogical unit of the audiological department. Detailed measurements are made one, three, six, twelve and twenty-four months after the operation. Observations and evaluations of signal analysis and speech perception ability are made on the same five levels used in the preoperative testing program. Here some results are given mainly on levels II and III.

**Level I. Transformation.** Detection threshold, most comfortable level, and uncomfortable threshold. Measurements are made with the technique and equipment developed in Vienna. Postoperative results show an increase in the useful dynamic range relative to the values from the preoperative tests by 5-20 dB below 250 Hz and 0-10 dB in the frequency range above 1000 Hz.

**Level II. Signal analysis.** Results are given from four different tests.

**Frequency discrimination with sinusoidal signal**

Fig. 5 shows the results for subjects S1-S2 one, three, six, and 12 months after operation. Only subjects S1 and S2 have gone through the total test program. A big improvement is seen during the test period.
Fig. 5. Results from frequency discrimination measurements with sinusoidal signals 1, 3, 6, and 12 months after implantation for patients S1 and S2.

Fig. 6. Results from frequency discrimination measurements with band-pass filtered pulse trains with six subjects. The center frequency of the band-pass filter is 500 Hz and the bandwidth 500 Hz. Pulse repetition frequency 125 and 250 c/s.
For S1, the discrimination ability stabilizes after six months but for S2, an improvement is seen during the period six to 12 months after the operation. This slower effect of training is typical for many of this subject's test results.

**Frequency discrimination with band-pass filtered pulse trains**

Fig. 6 shows the result on this test for six subjects. Even in this test, the results for subjects S1 and S2 show some improvement over time. The four other subjects did not obtain not as good results on this test.

**GAP-detection with band-pass filtered white noise**

Fig. 7 shows the results for the center frequency 500 Hz for the six subjects. A slight improvement over time can be seen for subjects S1 and S2. The result for subject S4 deteriorates at the measurement three months after the operation. The fact that no significant improvement seen in the results over time is seen on this test, compared to the results on the frequency discrimination tests, might indicate that time resolution is more dependent on neurophysiological factors and cannot be improved with training.

![Graph showing frequency discrimination results](image)

**Fig. 7.** Results from the measurement of time resolution with a GAP-test for six subjects. The signal is filtered with the same filter as used in Fig. 6.

**Pitch scaling**

In a pitch-scaling experiment, S1 could scale pitch in the frequency range 125 to 3000 Hz, see Fig. 8. She reports that 125 Hz sounds as a pure tone but at all other frequencies the signal is more or less
noisy. Subject S2 could scale pitch only up to 750 Hz. He reports that signals above the frequency 750 Hz all have the same pitch.

Level III. Phonetic interpretation

All tests are made with a direct coupling between the tape recorder and the stimulator. In Fig. 9, the test results for subject W1 and W2 are shown 24 months after implantation, and in Fig. 10 the results for subjects S1 and S2 are shown 12 months after implantation.

Level IV. Information processing. At present, no formal tests are made on this level. Subject S1 seems to have a very high information-processing ability which is also seen in her good lipreading ability.

Level V. Linguistic interpretation. On this level, a test with 12 known spondee words, a question test, everyday sentences, speech tracking is used, and for subject S1 some open speech tests. Results on the spondee and question tests are seen in Figs. 9 and 10. In a list of unknown words within the categories "food and vegetables", subject S1 scored 57% correct; most of the wrong answers are phonetically very close to the correct answer. When she was tested in June 1986 with unknown sentences presented without lipreading, she got about 50% of the words correct.

Subject S2 is not yet able to identify unknown words but his results show improvements over the last months. When S1 is asked about how speech sounds through the implant, she says that most words sound as she remembers them. From the beginning, music sounded like "crushing of china" but now she now can enjoy piano and guitar music.
Fig. 9. Results on speech tests 24 months after operation for subjects W1 and W2.

Fig. 10. Results on speech tests 12 months after operation for subjects S1 and S2.
CONCLUSION

From Fig. 5, it is evident that the signal the subjects get from the implant is very unspecific and they can only perceive frequency differences for the lowest frequency test. The results improve rapidly. When subject S1 was asked 12 months after implantation how the different test frequencies sound, she said that 125 Hz sounds like a pure tone but all other frequencies as noisy tones.

The results given in Figs. 6 and 7 show large variations in the results for the different subjects. Subjects S1 and S2 obtain the best results on almost all tests. This might partly be the result of training as only these two subjects, at the time of the measurements, have gone through the systematic training program. The differences might also be an effect of differences in etiology, age of onset of deafness, etc.

The test results for W1 on the level of phonetic interpretation, Fig. 9, are poor which might be explained by the etiology. The cause of deafness is meningitis at the age of eight years. He was placed in a school for the deaf and has mostly used sign language. The best result is obtained by S1. She is probably a typical "star" patient, she is young and her deafness is a result of a progressive hearing impairment.

The subjects have difficulties to perceive the presence of fricative energy and to identify vowels. Unvoiced plosives and fricatives are often confused. This difficulty is explained by the very limited dynamic range above 1000 Hz. The results might be improved with an adjustment of the stimulator. The difficulties in identification of vowels are probably due to the lack of frequency selectivity. The results from the tests on this level for the two good subjects can be summarized as follows: fundamental frequency range and intonation patterns can be identified relatively well. The difference between voiced and unvoiced consonants can be identified. The limited dynamic range in the frequencies above 1000 Hz results in difficulties with fricatives and unvoiced plosives. Some vowel identification is possible by their first formant frequency.

The described test battery gives a detailed description of the subject’s ability to detect differences between signals, recognize phonemes and perceive speech both in limited sets and in open speech. It is apparent that speech perception requires a certain signal-analysis ability. Based on the results on the different speech tests, it seems that the results obtained by S1 and S2 on the signal-analysis tests are required for a reasonable good speech perception ability. These two subjects show about the same results on this level, except for the pitch-scaling task. Subject S1’s superior performance can probably, to a large extent, be explained by her ability to maximally use limited information in the acoustic signal.
References


