# ACE Strategy with Virtual Channels

*Martin VONDRÁŠEK, Pavel SOVKA, Tomáš TICHÝ*

Dept. of Circuit Theory, Czech Technical University in Prague, Technická 2, 166 00 Praha 6, Czech Republic

vondram3@fel.cvut.cz, sovka@fel.cvut.cz, tichy@fel.cvut.cz

**Abstract.** *Cochlear implant is an electronic device, which can mediate hearing sensations to profoundly deaf people. Contemporary cochlear implants are sophisticated electronic devices; however, their performance could still be improved.*

*This paper describes an experiment we made in that direction: additional 21 virtual channels were implemented by sequential stimulation of adjacent intracochlear electrodes, and the ACE strategy with virtual channels (ACEv, Advanced Combination Encoder strategy with virtual channels) for the Nucleus® 24 Cochlear Implant System was created and verified in a clinical test with four patients.*

## Keywords

Cochlear Implant, Virtual Channels, Speech Processing.

## 1. Introduction

The cochlear implants are results of the research on electrical stimulation of the auditory nerve during the past forty years [1]. However, there is a long history of the attempts to provide hearing by electrical stimulation. A non-functioning Organ of Corti is substituted by direct stimulation of fibers of the Cochlear nerve, which are tonotopically arranged along the cochlear duct. Stimulation of apical fibers results in perception of low-pitched sounds; the closer to the base stimulation occurs, the higher the pitch of the percept. As the number of electrodes is limited, the number of tones cochlear implant users are able to differentiate is also limited.

The cochlear implant system is composed of two parts, implantable [1] (receiver/stimulator), and external (speech processor). The receiver/stimulator is usually implanted under the skin on the patients' head. The electronics in a metal box is connected with a stimulating electrode or array of electrodes inserted in the cochlea. In multi-channel cochlear implants, an electrode array is inserted in the cochlea so that different auditory nerve fibers can be stimulated at different places in the cochlea, thereby exploiting the place-pitch coding [1] theory. The information about which electrode should be stimulated, the amplitude of stimulated current and other parameters come from the second part of the cochlear implant system, the speech processor. The algorithm of conversion of speech into current pulses is called speech strategy.

### 1.1 Speech Processing Strategies

Three different coding strategies have been implemented in the Nucleus® 24 cochlear implant system [2]: Spectral Peak (SPEAK), Continuous Interleaved Sampling (CIS) and Advanced Combination Encoder (ACE). A patient uses the strategy, which is optimal for his comprehension in various listening situations. Each strategy has several parameters, which can be set to individualize the fit.

**Speak Strategy**

The block diagram of the SPEAK strategy [2] is depicted in Fig. 1. The input speech is segmented (128 samples length and 75% overlap), and the spectrum is calculated. Further, a filter bank with 20 band-pass filters with increasing bandwidth is used. Each filter corresponds to one intracochlear electrode. Electrodes 1 and 2 are not used (Nucleus® 24 includes 22 intracochlear electrodes, the SPEAK strategy works with 20 bands only). The apical electrode corresponds to band 1 (the narrowest bandwidth). The *energy calculation* block computes energy in each processed band. The *band selection* block selects $M$ bands with maximal energy. The $M$ may vary between 6 and 10. The energy of all non-selected bands is not used for stimulation. The *LGF* (Logarithmic Gain Function) block implements the logarithmic relationship between current amplitude and loudness of auditory perception [1].

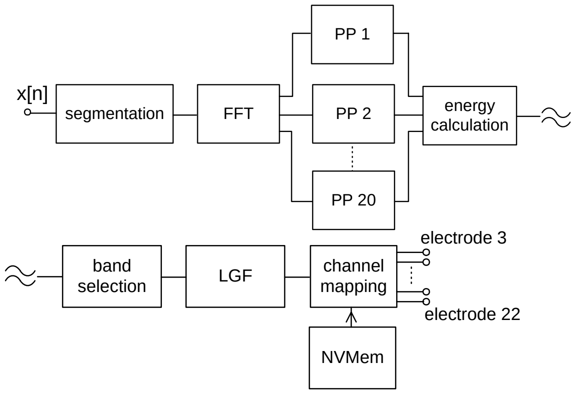


**Fig. 1.** The block diagram of ACE strategy.

The channel mapping block translates information from the LGF block to current pulses and defines the stimulating rate. The *NVMem* (random access memory with battery backup) block stores basic psychophysical parameters as Threshold Level, Comfort Level, Stimulation Rate [2], etc. The SPEAK strategy could be characterized as a strategy with a high number of processing bands but with a low stimulating rate of 250 Hz.

**CIS Strategy**

The block diagram of the CIS strategy [2] is similar to the SPEAK strategy (Fig. 1) with several changes. The segmentation and absolute spectrum calculation is the same as in case of the SPEAK strategy. The filter bank differs. The number of processing bands is not fixed (depends on individual patient setting) and is lower in comparison with the SPEAK. 4, 6, 8 or 12 bands could be used there. The band-pass width is also logarithmically increasing. The *energy calculation* block is also the same as the SPEAK strategy (Fig. 1) but there is no maximum selection block. The information from all the filters is used for stimulation not depending on the energy level. The *LGF* block, *channel mapping,* and *NVMem* have same the function as in the SPEAK strategy. Nonetheless there are two changes. The *NVMem* block stores also the number of processed bands (*N*). The number of processing bands is much lower than the number of electrodes in the Nucleus® 24 implant, and the electrodes used for stimulation must be specified individually. The CIS strategy can be characterized as a strategy with a very high stimulating rate (up to 1800 Hz) but a small number of processed bands.

**ACE Strategy**

The ACE strategy (Advanced Combination Encoder) is the newest strategy used with the Nucleus® 24 and Freedom implant systems [2]. The ACE combines a high number of processed bands with a higher stimulating rate. The ACE speech processing algorithm is very similar to the SPEAK strategy, but the filter bank with 22 band-pass filters is used (2 more filters than in the SPEAK). 22 bands give better frequency resolution. The basal electrode corresponds to band 22, the apical electrode corresponds to band 1. The stimulating rate can be much higher in comparison with the SPEAK strategy.

**Proposed Strategy Modifications**

This paragraph summarizes modifications proposed over past years which are currently used in cochlear implants or the results of preliminary studies show good improvement.

The fundamental frequency is important for good speech understanding, especially for differentiation of similar words. For example, in Chinese there is a one-syllable word “ma” which could be pronounced in four tonal patterns [3]. Each pattern has a different meaning depending on the flat, rising, falling-rising, or falling tone. The F0 could be added in the CIS strategy using stimulation rate changes. In case of a flat F0 tone, the stimulating rate is holding on its normal frequency. In case of a rising F0 tone, the stimulating rate increases, and in case of a falling F0 the stimulating rate is decreasing [3].

While the currently used numeric filters recognize small temporal changes of signal, the Discrete Wavelet Transform (DWT) [4] performs a multiresolution analysis providing a highly accurate decomposition of transient signals in the time-frequency domain. Studies of speech analysis [4] confirm that the Wavelet transformation is suitable for coding of short patterns that characterize some consonants.

## 1.2 Virtual Channel Stimulation

Efforts of many investigations in the world are focused on improvement of speech understanding with cochlear implant. One possibility how to reach a better performance is increasing the number of processing bands and electrodes so as to reach a better frequency resolution. As the number of physical electrodes of current implants is limited, the only possible way seems to be using virtual channels.

The idea of virtual channel creation (not only in case of cochlear implants) is that stimulation of two neighboring electrodes would result in a pitch that is between the two pitches perceived when the two electrodes are stimulated individually. The pitch corresponding to a virtual channel is different from the original ones and it is possible to change it by changing the ratio of amplitude of the current in the electrode pair or by the ratio of stimulation rates in a selected electrode pair. Thus, a ‘virtual channel’ or a ‘virtual electrode’ can be created. Wilson et al. for the first time coined this term [5] as means of increasing the effective number of electrodes. The way how to create a virtual channel depends mostly on hardware used.

In case of simultaneous stimulation, the cochlear implant is able to send two current pulses in two neighboring electrodes at the same time. For example, the biphasic monopolar simultaneous stimulation occurs in electrodes 10 and 11 (see Fig. 2). The pitch can be changed by varying the current amplitudes in electrodes 10 and 11. But the total amount of charge delivered in cochlea has to be the same to ensure constant speech power. The simultaneous stimulation was experimentally confirmed by experiments with patients implanted with a six-electrode array [6]. The research was focused on reliability of virtual channel discrimination in case of three virtual channels created between a selected electrode pair. One of the latest experiments was performed on the Nucleus® 24RE implant [7]. The virtual channel was created using a new functionality called “Dual Electrode stimulation”. The implant is able to electrically connect two neighboring electrodes and to stimulate them with the same current pulse. The advantage is simple stimulation without undesirable effects (see section 2.3), the disadvantage is that there is no way how to change the pitch of the created virtual channel.

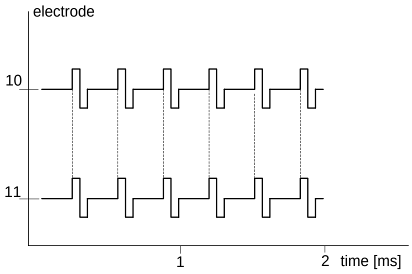


**Fig. 2.** Simultaneous stimulation.

The second case of stimulation occurs if the current pulses sent in two neighboring electrodes are time-shifted (non-simultaneous stimulation). This can happen if the stimulation rate in the first electrode is different from the stimulation rate in the second electrode or if the cochlear implant is not able to stimulate two electrodes at the same time. Fig. 3 represents stimulation in case of Nucleus® 24 implant. Stimulation occurs sequentially, as there is only one output current source in the implant.

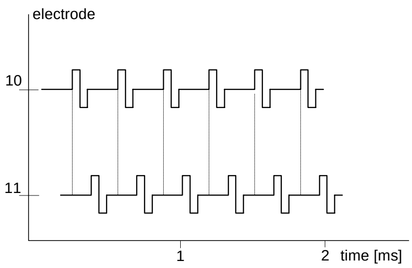


**Fig. 3.** Non-simultaneous stimulation.

The research [8] focused on comparison of the Fixed Stimulating Rate method (fixed stimulation rate in both electrodes, pitch was changed using changing of current amplitudes) and the Fixed Amplitude method (fixed current amplitudes in both electrodes, pitch was changed using changing of stimulation rates in selected electrode pair) on the Nucleus® 24 implant. The Fixed Stimulating Rate method has no limitations as for setting amplitudes in electrode pairs. The implementation of this method is very easy. The pitch of the virtual channel was always between pitches corresponding to one electrode of the selected electrode pair only. In case of the Fixed Amplitude method, if the stimulating rate in one electrode decreased below approximately 200 Hz, the patients heard a low-pitched tone corresponding to that low repetition rate. This fact limits practical usage of this method.

The second research on eleven cochlear implant users [9] focused on pitch determination. The main question was how many discriminable pitches can be created using one electrode pair. The average aggregate number of discriminable pitches across the entire array (21 physical electrodes) was 161, which is substantially higher than the numbers previously reported in competitive data [10]. When the intensity was adjusted to eliminate loudness cues, that number moved to 127 discriminable pitches across the entire array.

# 2. ACE Strategy with Virtual Channels

In the Czech Republic, the most used type is Nucleus® 24 and there are enough patients with appropriate experience. For this reason, the research is focused on the Nucleus® 24 implants. The ACE strategy was selected for modification based on our previous experiments [11] with all strategies currently used with Cochlear implant systems. The goal of this research is to increase speech and music understanding using virtual channels.

The idea of implementing virtual channels in the ACE strategy is depicted in Fig. 4. The whole processed frequency band is now split into 43 instead of 22 filters [11]. Correspondingly, the filter bank contains now 43 filters instead of 22. The filters corresponding to virtual channels are marked by ”v”. In case of the ACEv strategy, the frequency range of each filter in the original ACE strategy is divided into two narrower ranges, as presented in Fig. 4.

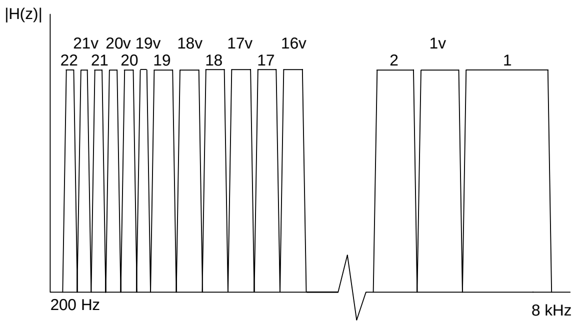


**Fig. 4.** The filter bank of ACEv strategy.

The band-pass filter ”1” has the same bandwidth in both strategies. In future tests, the boundaries between filters should be modified if necessary.

Usage of virtual channels leads to several changes in speech processing algorithm. The changes are described as follows.

## 2.1 FFT Parameters

The Fast Fourier Transform used in the standard ACE strategy calculates the spectrum in 128 bins. The frequency resolution is then:

$$\Delta f = \frac{fs}{128} = 125 \text{ Hz.} \tag{1}$$

The passband width of the narrowest band-pass filter of the standard ACE is also 125 Hz. This band should also be divided into two bands, so the FFT must be processed at least in 256 samples. The frequency resolution is then 62.5 Hz. The ACEv strategy calculates the spectrum in 256 bins.

## 2.2 Band Selection Block

In the standard ACE [2] strategy, the block *Band selection* selects *N* bands with maximal energy (Fig. 1). In the case of the ACEv strategy, this algorithm is not optimal. Two problems must be solved: how to stimulate neighboring electrodes, and how to describe less important maxima.

Standard maxima selection for the ACE strategy is depicted by an example in Fig. 5a. 8 bands with maximal energy have been selected (gray colored). If the same algorithm was used in the ACEv strategy, bands with maximal energy would describe only the most important maxima in spectrum of the processed signal (Fig. 5b).

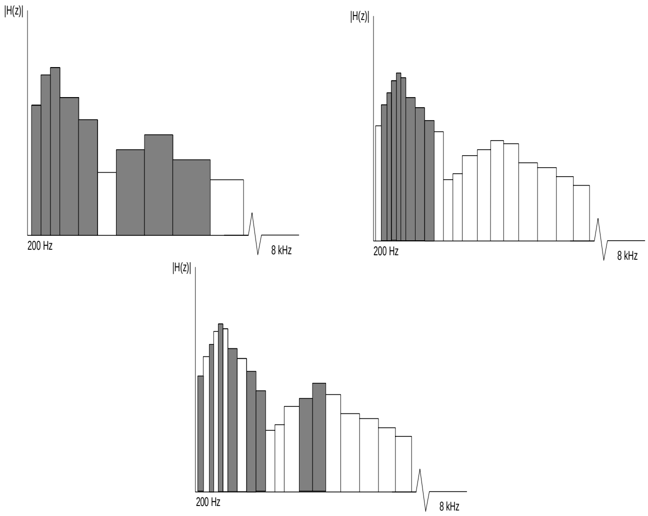


**Fig. 5.** Band selection: a) standard ACE, b) ACEv with standard maxima selection, c) ACEv with optimized band selection block.

The second problem appears if a physical electrode and a neighboring virtual channel are selected for stimulation in the same processing segment.

Fig. 6a shows stimulation in channels 18, 20v and 22. Each vertical line represents one stimulation pulse. Stimulation is divided into two cycles. In both, one current pulse is sent into each selected electrode. In case of stimulation of a standard channel, a physical electrode with the same/corresponding number is stimulated in both cycles. In case of stimulation in a virtual channel, the physical electrode with a lower number is stimulated in the first cycle and the physical electrode with a higher number is stimulated in the second cycle. Fig. 6b presents a potential problem, which occurs if one physical electrode is used for stimulating both standard and virtual channels in the same segment. In this case, electrodes 19, 19v and 22 are selected. Physical electrode 19 is used in 2 channels – 19 and 19v. As a result, two pulses with a small pause will be sent to that electrode. The distance between these pulses is defined by overall repetition rate of the implant. For example, if electrodes 18v, 19, and 19v are stimulated, repetition rate is increased in electrode 19. This phenomenon may result in problems with loudness and distortion of the processed speech. The potential risk is that amplitude of the percept could exceed maximum comfortable loudness.

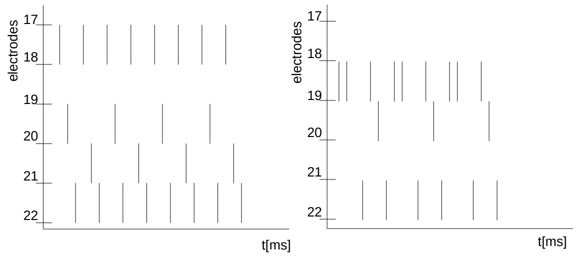


**Fig. 6.** Neighboring bands: not selected - a), selected - b).

Both problems mentioned above lead to changes in *band selection* block (Fig. 1). The solution of the first problem depicted in Fig. 5b is taking energy of the neighboring bands (masking effect between the neighboring channels) into account. Therefore, another routine was included, which checks for presence of neighboring channels among the selected maxima and if there are any, it calculates the ratio of energy of the two corresponding pulses. If the weaker pulse has less than 70 % of energy of the stronger one, it is rejected from stimulation and another band is selected for stimulation. The 70% value was set after comparing the original and the reconstructed signal [11] using cepstral distance. The result of optimized *band selection block* is depictured in Fig. 5c.

The second problem was analyzed on patients with cochlear implant. The patients were stimulated using the sequence depicted in Fig. 7. During the test, the *number of pulses in group* and parameters *a* and *b* were changed. If the inter-stimulus interval *b* was longer than 4 ms, the patients started to hear a low frequency sound not depending on the stimulated electrode. The repetition rate of pulses in the group was 250 Hz or lower and in that case, the patients could hear the corresponding frequency. If the value of parameter *a* was smaller than 0.3 ms and number of pulses in the group was 3 or higher, the amplitude of the percept corresponding to the pitch started to increase. Because of that phenomenon, there was a potential risk that amplitude of the percept could exceed maximum comfortable loudness. Therefore the limit was set such that no more than 2 frequency bands using the same physical electrode may be selected in one processing cycle.

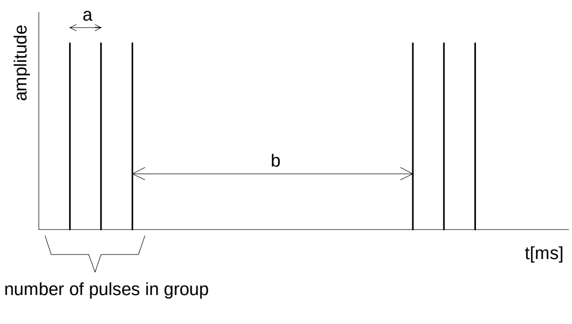


**Fig. 7.** Stimulus sequence.

## 2.3 Segmentation

The standard ACE strategy uses the length of the processed segment 128 samples and overlap 32 samples [2]. For the ACEv strategy, the same length of the segment is not optimal. Imagine an easy experiment. If a sine wave with increasing frequency from 0 to 8 kHz (chirp signal) is used as an input signal for the standard ACE strategy, the output (electrode activity) will be what can be seen in Fig. 8. Up to four channels may have a non-zero output at the same time. As the input signal consists of one frequency only, there should be only one active electrode at a time. What can be seen in Fig. 8 results from leakage in the spectrum. One vertical line represents one current sample sent to cochlea. In case of the ACE strategy, no problem with electrode stimulating occurs.

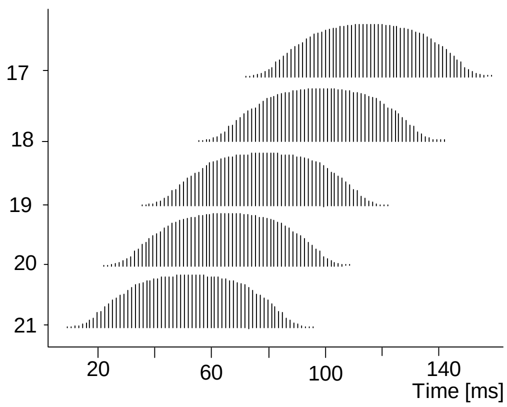


**Fig. 8.** ACE response, sinusoidal signal.

If the same segmentation were used in the ACEv, we would have a problem on low frequencies (see Fig. 9). Due to the leakage in the spectrum, four spectral peaks are non-zero (should be only one). One bin corresponds to one band band-pass of filters on the lowest frequencies. Due to limitations of maxima selection algorithm of the ACEv strategy (see Section 2.2), the stimulation in these electrodes is switched off and on (Fig. 9). For example, stimulation in band 19v is described. Physical electrode 20 is used for stimulating in band 19v, 20v and also for 20. The stimulation in band 19v could not start before time 75 ms because physical electrode 20 is used for stimulating in band 20 and 20v at that time. At time 75 ms, the amplitude in band 20v is lower than amplitude in band 19v, stimulation in band 20v is stopped and stimulation in band 19v is started. Switching off in the band 20 at time 90 is described bellow. The amplitude in band 19 at time 90 ms is higher than in 20. Stimulation in band 20 is stopped at that time.

The switching on and off was perceived as an unpleasant noisy background during the tests with patients and also during simulations with hearing volunteers.

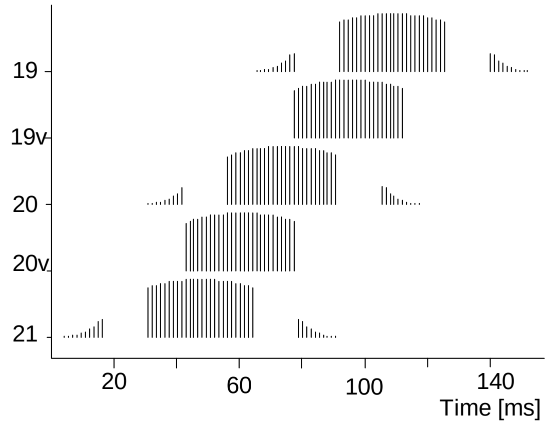


**Fig. 9.** ACEv, sinusoidal signal: segment 128 samples.

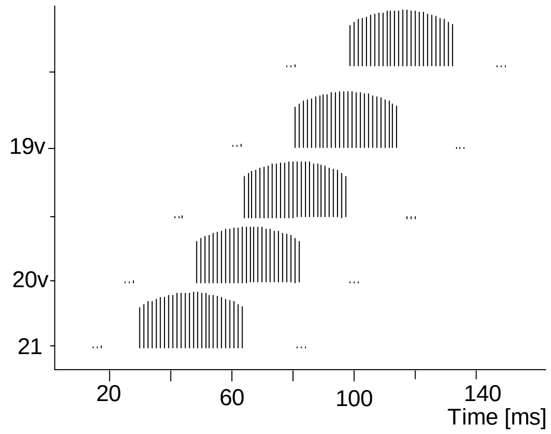


**Fig. 10.** ACEv, sinusoidal signal: segment 256 samples.

The described problem can be solved by using a longer segment of speech. The length of segment is 256 samples with 32 samples overlap. Fig. 10 shows the activity of electrodes if a new segmentation is used. The switching on and off is still obvious, but it is not as unpleasant as previously. However, with the new segment length, the speech is reported as more metallic in comparison with the ACE strategy. It is caused by a lower number of stimulated bands.

# 3. Experiments on Patients

The hearing test was used to consider capability of speech understanding. The semi-closed test on "Set of tests for evaluation of speech perception" database [12] is used. The database consists of 25 tests, each of them is focused on a different phenomenon of the Czech language. 13 more difficult tests were selected for testing with patients. The focused phenomenon and number of questions are summarized in Tab. 1.

| Test number | Phenomenon | Number of questions |
|---|---|---|
| 3 | differentiation of melody | 20 |
| 8 | differentiation of vowel duration | 20 |
| 9 | identification of vowel duration | 20 |
| 10 | world pattern – two phonemic characters identification | 40 |
| 11 | vowel quality differentiation | 20 |
| 12 | word identification according to vowel | 24 |
| 13 | consonant identification | 30 |
| 14 | hard consonant differentiation | 30 |
| 15 | soft consonant differentiation | 20 |
| 16 | hard consonant identification | 20 |
| 17 | soft consonant identification | 20 |
| 20 | one-syllable word identification | 20 |
| 21 | three-syllable word identification | 20 |

**Tab. 1.** Set of tests for evaluation of speech perception.

For each question in each test, two up to five possible answers are presented. Example of test no. 15, questions 4 and 5 are depicted in Tab. 2.

| | | |
|---|---|---|
| 4 | a | pak |
| | b | puk |
| | c | pik |
| 5 | a | maž |
| | b | muž |
| | c | myš |

**Tab. 2.** Example of the test.

Both ACE and ACEv strategies were used to evaluate the impact of virtual channels. Each test was randomly separated in two subsets and processed using one strategy. The word used for stimulation of the patient was also randomly selected. The patients marked their answers on paper with the printed version of the test. Finally, each correct patients' answer was evaluated by one point, wrong answer means zero points. The percentage of successful tests for each tested strategy was:

$$\text{Percentage successful test} = \frac{\text{acquired score}}{\text{maximal score}} 100\,[\%] \qquad (2)$$

where maximal score is 152. During the test, the word or sentence selected for stimulation was processed using the given strategy implemented in Matlab programming language with Nucleus Implant Communicator toolbox [13] and sent through special hardware used for individual patient setting to patient's cochlear implant.

The patient had to be an adult and also good or rather excellent cochlear implant user. The patient had also to live in Prague or nearby to be able to take part in tests. The last but not least criteria are goodwill to cooperate and ability to precisely describe their auditory perceptions. Due to the reasons described above, only four cochlear implant users were tested. These patients were also tested on virtual channel determination [8].

## 4. Results

Tab. 3 summarizes all results for patients with cochlear implants. The table presents average percentage of correct answers for each tested patient for both ACE and ACEv strategy. For patients A and C, better scores in speech tests results in case of the ACEv can be seen. For the B and D, both strategies are almost the same.

Here it must also be noticed that the ACE strategy was used by tested patients for a longer time. Also, their individual settings were optimal. The ACEv strategy was presented to patients only in the laboratory, and there was no optimalization of the individual settings. If the ACEv strategy were implemented in the speech processor and the patients would use it "in real time" results for the ACEv strategy could be better.

| Patient | Strategy | |
|---|---|---|
| | ACE | ACEv |
| A | 70 | 81 |
| B | 89 | 86 |
| C | 68 | 78 |
| D | 89 | 87 |

**Tab. 3.** Percentage successful test.

## 5. Conclusions

Virtual electrodes were used newly for the ACE strategy requiring a modification of this strategy. The ACEv strategy described in this paper uses one virtual electrode for each neighboring physical electrodes of the Nucleus® 24 implant. The number of stimulating channels was changed from 22 to 43. The increase of number of channels was enabled by incorporating 21 virtual channels. The virtual channels were implemented using the Fixed Stimulating Rate method.

To implement the virtual electrodes in the ACE strategy, it was necessary to make changes in the speech processing algorithm of the original strategy. The length of the processing segments and the frequency resolution of the FFT were increased. The maxima selection algorithm in *Band selection* block was changed. The new algorithm took into account adverse effects resulting from the stimulation of neighboring electrodes and also from masking effect between the neighboring channels. The virtual channels and the ACEv strategy were implemented in Matlab with Nucleus Matlab Toolbox. For the tests with cochlear implant users, a special hardware was used. The ACEv strategy was tested with 4 experienced users of the Nucleus® 24 cochlear implant. The results confirm that the ACEv strategy brings a better frequency discrimination, which is reflected in better scores in speech tests.

However, the ACEv strategy sounds more metallic and for some patients, it sounded as if the speaker had higher fundamental frequency F0. On the other hand, the patients could hear sounds processed by the ACEv strategy only in our laboratory and they had no time to get accustomed to that speech processing algorithm.

## Acknowledgements

We would like to thank the Cochlear CTCE in Mechelen for technical support. This work has been supported by the research program Transdisciplinary Research in Biomedical Engineering II No. MSM6840770012 of the Czech Technical University in Prague and the grant GACR 102/05/0278 New Trends in Research and Application of Voice Technology.

## References

[1] CLARK, G. *Cochlear Implants, Fundamentals and Applications.* New York: Springer NY, 2003. 830 p. ISBN 0-387-95583-6.

[2] ACE and CIS DSP Strategies. *Software Requirements Specification*, Cochlear Ltd. Australia, 2002.

[3] LAN, H., NIE, K. A Novel speech-processing strategy incorporating tonal information for cochlear implants. *IEEE Transactions on Biomedical Engineering*, 2004, vol. 51, no. 5, p. 752-760. ISSN 0018-9294.

[4] TONGOLA, G., BASSELI, M. Wavelet speech processing for cochlear implants. In *EMBEC 2005*, Prague (Czech Republic), 20-25 Nov. 2005.

[5] WILSON, B., ZERBI, M., LAWSON, D. Identification of virtual channel conditions on the basis of pitch. *Third Quarterly Progress Report*, NIH project NOI-DC-2-2401.

[6] POROY, O., LOIZOU, P. C. Pitch perception using virtual channels. In *Conference on Implantable Auditory Prostheses*, Asilomar, Monterey, CA, 2001.

[7] BUSBY, P. A., PLANT, K. Dual electrode stimulation using the Nucleus CI24RE cochlear implant: Electrode impedance and pitch ranking studies. *Ear & Hearing,* October 2005, vol. 26, no. 5, p. 504-511.

[8] VONDRÁŠEK, M., TICHÝ, T., SOVKA, P. Virtual channels in Nucleus® 24 Implant. [Invited unpublished lecture.] *Cochlear Mechelen*. 2006-10-13.

[9] HONET, C. Pitch Steering with Sequential Stimulation of Intracochlear Electrodes. *Cochlear research report*. Cochlear USA, 2006.

[10] DONALDSON, GS., KREFT, HA., LITVAK, L. Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users. *Acoustic Soc Am* 101:440-455, 2005.

[11] VONDRÁŠEK, M., TICHÝ, T., SOVKA, P. Speech Reconstruction for Cochlear Implants. In *EMBEC 2005*, Prague(Czech Republic), 20-25 Nov. 2005.

[12] SVOBODOVÁ, K., TICHÝ, T., VAČKÁŘ, M., SEDLÁK, S., TOPOL, M. *Soubor percepce řeči sluchem*. Klinika otorhino-laryngologie a chirurgie hlavy a krku 1. LF UK, Fakulta elektrotechnická ČVUT, 1995. (in Czech)

[13] SWANSON, B. *Nucleus® Reference manual*. Cochlear Ltd. Australia, 2001.

## About Authors...

**Martin VONDRÁŠEK** was born in Borovany, Czechoslovakia in 1977. He received his M.Sc. degree from the Faculty of Electrical Engineering, Czech Technical University in Prague in 2004. His current research interests include speech enhancement, speech pre-processing for cochlear implants, and others.

**Pavel SOVKA** was born in Jihlava, Czechoslovakia in 1957. He received his M.Sc. and CSc. degrees fromt the Faculty of Electrical Engineering, Czech Technical University in Prague in 1981 and 1986, respectively. His current research interests include application of adaptive systems to noise and echo cancellation, speech analysis, changepoint detection and signal separation.

**Tomáš TICHÝ** was born in Prague, Czechoslovakia in 1952. He received his M.Sc. and CSc. degrees from the Faculty of Electrical Engineering, Czech Technical University in Prague in 1975 and 1980, respectively. His current research interests include electric stimulation of the acoustic nerve, speech coding strategies in cochlear implants, cochlear implant diagnostics, neural response telemetry.