CONVEYING LOW FREQUENCY INFORMATION THROUGH ANALOG ELECTRICAL STIMULATION IN COCHLEAR IMPLANTS

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ABSTRACT

Speech intelligibility in noisy environments and music perception are very limited using cochlear implants (CIs). One possible reason that explains these limitations is the poor pitch perception obtained through electrical stimulation. Research in the field of combined electric and acoustic hearing (EAS) has shown that low frequency information even below 300 Hz perceived through the residual acoustic hearing can improve speech perception in adverse listening situations. This paper investigates whether cochlear CI users can also make use of very low frequencies through electrical stimulation alone. A new strategy called extended low frequency HiRes (ELFHiRes) has been implemented in a research environment provided by Advanced Bionics. The new strategy uses analog stimulation to transmit the low frequencies. In a pilot study it was found that the pitch perceived as well as its quality were similar using both pulsatile and anlog stimulation. First tests in speech perception do not show any advantage for the ELFHiRes strategy, however there is potential for future developments to improve speech intelligibility by better transmission of low frequencies through a CI.

Index Terms— Cochlear Implant, Low Frequency, Research Platform, Analog Stimulation

1. INTRODUCTION

Even though the technological advances in the field of cochlear implants (CI) led to significant improvement in performance, speech perception abilities of many CI users in noisy conditions is still poor. Research in the field of combined electric and acoustic hearing (EAS) has shown that low frequency information even below 300 Hz perceived through the residual hearing can greatly improve hearing in adverse listening situations [3] [6].

The reference strategy used in CIs is the Continuous Interleaved Sampling (CIS) strategy. This strategy calculates envelopes from band pass signals that are used to amplitude modulated pulse trains. The key feature of the CIS strategy is that none of the pulses overlap in time. This strategy reduced some of the temporal information being delivered to the cochlea, but effectively avoided the problem of current interaction and the resulting waveform distortion [2]. In CIS the electrodes are stimulated in monopolar mode which produces broad electric fields in the cochlea, however, speech recognition with the broader configuration has been often reported to be equal or better than that achieved with the narrower bipolar configurations [2].

In order to regain some of the temporal information sacrificed by the CIS strategy, Advanced Bionics Corporation developed the Simultaneous Analog Stimulation (SAS) strategy. In SAS, the signal was first compressed with a fast acting automatic gain control, passed through 8 band pass filters, and then fed to corresponding electrodes. A potential problem with simultaneous stimulation strategies is current interactions, which can lead to distortions in the electrical waveforms. To reduce current interaction, the manufacturer recommended a narrow bipolar configuration instead of the classical monopolar stimulation used in CIS. Suprisingly, the SAS strategy seemed to be the strategy preferred by a remarkable proportion of CI users. In a clinical study only 15% of 56 CII implant recipients preferred the CIS strategy, whereas 52% preferred the SAS strategy in bipolar mode. One hypothesis why CI users preferred the SAS strategy is that analog stimulation might produce better pitch perception than sequential non-simultaneous stimulation [1].

It is well accepted that there are two independent mechanisms for pitch perception in CI subjects [8]. With electrical stimulation, the delivery of frequency information can be separated independently into place of stimulation and the rate of stimulation. The place of stimulation with a CI is determined by encoding which electrode is stimulated. Temporal pitch perception with a CI can be represented by changing the rate of stimulation of an electrode or by temporally modulating pulse trains of fixed rate delivered to that electrode.

Place pitch perception is limited by the number of electrodes inserted inside the cochlea and by the lack of isolation between the electrodes (channel interaction). This leads to a poor frequency resolution, as the bands associated to each electrode are relatively wide to accurately encode tonal components. Temporal pitch perception with CIs is severely limited and most patients cannot discriminate changes at all for rates above 300 Hz [7].

The goal of this research is to investigate whether CI users can benefit from low frequencies as observed in EAS CI users [3] [6], but transmitting the low frequency information through electrical stimulation. We hypothesize that adding an additional channel that transmits low frequency components (below 300 Hz) can be used by the hearing nerve to perceive temporal pitch information. Motivated by the fact that analog stimulation provides with accurate temporal information, in this research it will be investigated wether analog stimulation is suitable for transmitting the low frequency information. The applicability of an analog stimulation strategy for CIs, in terms of hardware limitations and strategy fitting will be presented. Additionally, the potential benefits of analog stimulation in terms of pitch and speech understanding will be investigated. The paper is organized as follows, In Section 2 the methods are presented: the new strategy, the hardware platform and the experiments performed in CI users are given. Section 3 presents the Discussion and finally Section 4 shows the Conclusions.

2. METHOD

2.1. Cochlear Implant Strategies

HiRes Strategy

The new strategies designed were based on the High Resolution Strategy (HiRes) of Advanced Bionics. The HiRes strategy is implemented in the Clarion, Auria and Harmony devices of Advanced Bionics. These devices can be used with the CII and the HiRes90k implants. In HiRes [4], an audio signal sampled at 17400 Hz is pre-emphasized by the microphone and then digitized. Adaptive gain control (AGC) is performed digitally. Afterwards the signal is broken up into frequency bands using infinite impulse response (IIR) Butterworth filters of order 6. The center frequencies of the filters are logarithmically spaced between 350 Hz and 5500 Hz. The last filter is a high-pass filter that extends its bandwidth up to the Nyquist frequency. In HiRes filter outputs are half-wave rectified and averaged. Half-wave rectification is accomplished by setting to 0 the negative amplitudes at the output of each filter band. The outputs of the half-wave rectifier are averaged for the duration T_s of a stimulation cycle. Finally, the acoustic values obtained for each frequency band are compressed into current values that are used to amplitude modulate biphasic pulses. A logarithmic compression function is used to ensure that the envelope outputs fit the patient's dynamic range. This function is defined for each electrode and is of the form presented in the following equation:

$$Y = \frac{(M-T)}{IDR}(X - m_{sat_{dB}} + 12 + IDR) + T \quad z = 1, ..., N, \tag{1}$$

where Y is the (compressed) electrical value, X is the acoustic amplitude (output of the averager) in dB and IDR is the input dynamic range set by the clinician. A typical value for the IDR is 60 dB. The mapping function used in HiRes maps the M at 12 dB below the saturation level $m_{sat_{dB}}$. The saturation level in HiRes is set to $20log_{10}(2^{15}-1)$. In each stimulation cycle, HiRes stimulates all N implant electrodes sequentially to partially avoid channel interactions. The number of electrodes for the HiRes90k implant is N=16 and all electrodes are stimulated a the same fixed rate. Because the audio signal is bandpass filtered above 300 Hz and CI users mostly can only benefit of temporal pitch for frequencies below 300 Hz, using this strategy no benefit of temporal pitch can be obtained.

Extended Low Frequency Strategy (ELF-HiRes)

In order to transmit information that can be perceived using the temporal pitch mechanism a new strategy has been designed. The new ELF-HiRes strategy incorporates a low pass filter that transmits sounds from 0 Hz until 300 Hz in a dedicated low frequency channel. It has to be noted that after this filter a 6 dB/octave high pass filter is used to remove the DC component and to accomodate for loudness effects as explained in section 3.1. For conveying the low frequency information we decided to stimulate the two most apical electrodes in bipolar mode using analog stimulation. In a preliminar test we used monopolar stimulation, but this configuration presented two problems. First, at low frequencies the M level using monopolar analog stimulation obtained was too small, thus restricting the amount of levels that could be transmitted to the electrode. Second, even at very low M levels, the sounds perceived were too much dominated by low frequencies, we assumed that current spread using monoplar stimulation was a main factor causing these effects. For this reason, we decided to use bipolar configuration for the analog channel, which restricts the spread of current in the cochlea. In total, the ELF-HiRes strategy transmits 15 band pass signals through 16 electrodes. For this reason, it was necessary to rearrange the band pass filters to cover the same spectrum as the HiRes strategy. In order to deliver charge balanced stimulation the filter band outputs were averaged preserving the sign of the signal, in other words no rectification was used. Moreover, if any signal produced residual unballanced stimulatio, additional stimulation with oposite phase was presented to avoid any charging of the tissues in the cochlea. The block diagram of the ELF-HiRes strategy together with the stimulation pattern for one period of stimulation (T_s) is presented in Figure 1.

2.2. Hardware Interface

The implementation of ELF-HiRes was performed on HRStream, a research environment developed by Advanced Bionics for designing speech processing strategies. In HRStream the computer (PC) is connected over USB to a streaming inter-

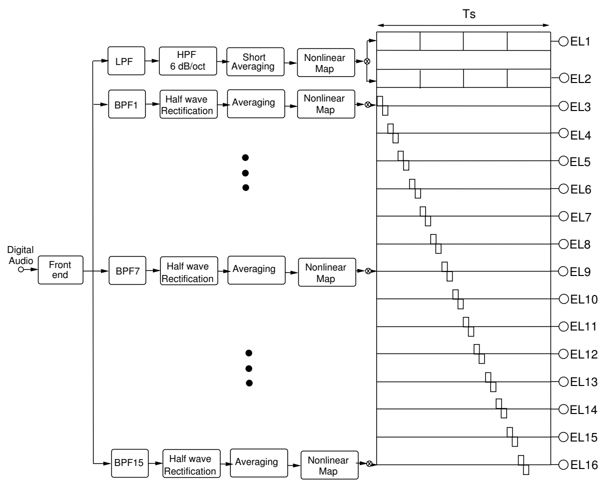

Fig. 1. Block Diagram of the ELF-HiRes strategy.

face board (SIB). The SIB is connected to a standard speech processor with the clinical programming cable. The SIB connects to the portable speech processor which transmits the signals to the implant. HRStream enables the researcher to set any stimulus pattern on any of the 16 electrode contacts of the HiRes90K device of course within the limitations of the implant hardware. Stimuli were pre-processed on a standard PC and then streamed to the subjects implant. Due to the nature of HRStream, any tests with the subjects could only be conducted acutely. The HiRes and the ELFHiRes strategies were fitted based on the clinical program of the study participant. The clinical values for rate, input dynamic range, the most comfortable levels (M level) and the threshold level (T level) were imported into a fitting software developed for HRStream.

3. EXPERIMENTS AND RESULTS

3.1. Exp 1: Loudness using analog electrical stimulation

Three CI users having normal hearing in the unimplanted ear participated in the fitting sessions. First of all we investigated the effect that has the frequency of analog stimulation on loudness. Loudness is related to the amount of charge injected through each electrode. Using analog stimulation, the lower the frequency, the more charge will be injected to the electrode and therefore, the louder will be the sound perceived. We asked the CI users to detect the minimally perceived current level of stimulation (T level) as well as the most comfortable level of stimulation (M level) using bipolar analog stimulation from frequencies ranging from 80 Hz until 400 Hz. The results for the three study participants are presented in Figure 2.

At low frequencies the T level for the 3 study participants was very low due to the large amount of charge injected in each cycle of stimulation. As the frequency increases the T level also increases. Note that the levels are given in μA. From these results it was decided to incorporate a high pass filter operation (6 dB/octave slope) just after the Low Pass Filter used in the low frequency channel of the ELF-HiRes in order to compensate for loudness effects over frequency.

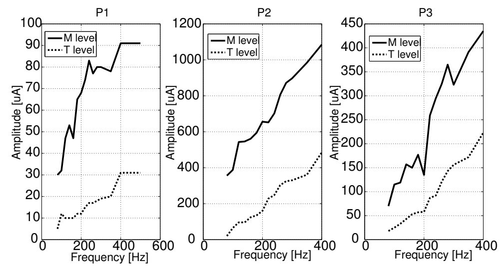

Fig. 2. Results for the loudness experiment using analog stimulation. M and T levels were estimated for frequencies from 80 Hz until 400 Hz in steps of 20 Hz.

3.2. Exp 2: Pitch perception using analog stimulation

With the same three CI users we performed a pitch matching task between the unimplanted ear and the CI. A 2 alternative-forced-choice adaptive procedure was used. In one interval, a 500 ms acoustic tone was presented through a loudspeaker at 65 dB SPL. In the other interval (500 ms later) an electrical tone was presented at a current level equivalent to 65 dB SPL. The study participants were asked if they could perceive a difference in pitch between both intervals. The matching procedure was performed at different reference frequencies (from 80 Hz until 400 Hz in steps of 50 Hz) and for each frequency it was repeated two times starting with an acoustic tone at different frequencies (10% below and above the reference frequency). The initial step size and the minimum step size were set to 32 Hz and 4 Hz respectively, the step size was reduced after two consecutive correct answers and increased every incorrect answer. Results were obtained after 4 reversals. The results of the pitch matching experiment using bipolar analog stimulation and amplitude modulate pulse trains of fixed rate are presented on Figure 3. The horizontal axis shows the original frequency of the acoustic tone, and the vertical axis shows the frequency at which the electrical tones were matched by the CI listeners. From Figure 3 it seems that both, the analog tone and the amplitude modulated tone delivered similar pitch perception.

3.3. Exp 3: Tonal quality with analog stimulation

We investigated whether the tonal quality elicited by analog stimulation is different than the tonal quality elicited by pulsatile stimulation. The CI user was provided with an electric tone on the implanted ear and an acoustic tone of the same fre-

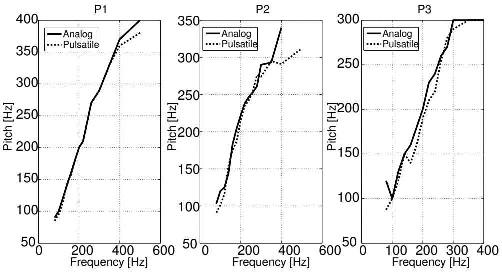

Fig. 3. Results for the Pitch matching experiment for the analog tone and the pulse train amplitude modulated by a tone.

quency presented through a loudspeakers at 65 dB SPL on the normal hearing ear. We asked the study participant to select from 11 different acoustic sounds the one that matched best the electric tone. The electric tone was fixed and the acoustic tone was varied. The first acoustic tone (tonal index 1) was a pure acoustic tone with the same frequency as the electric tone. The rest of acoustic tones (tonal index 2 to 11) were generated processing white gaussian noise through a FIR filter with a relation between center frequency and bandwidth of: 10, 7, 5, 3.5, 2.5, 2.0, 1.5, 1, 0.5 and 0.25. The experiment was performed at three frequencies (80, 160 and 300 Hz) using bipolar analog stimulation and using pulsatile stimulation at the clinical stimulation rate of each CI user. Using both types of stimulation the signals were presented at an electric level that matched the level of a 65 dB acoustic pure tone. The results obtained are presented in Table 1 for each participant.

Table 1. Tonal quality for analog and pulsatile stimulation at different frequencies.

Tonal Quality P1	80 Hz	160 Hz	300Hz
Pulsatile	1	1	1
Analog	1	1	1
Tonal Quality P2	80 Hz	160 Hz	300Hz
Pulsatile	2	3	3
Analog	2	3	3
Tonal Quality P3	80 Hz	160 Hz	300Hz
Pulsatile	2	4	5
Analog	1	2	3

The results presented in Table 1 show that both pulsatile and analog stimulation produce a similar tonal quality, and therefore analog stimulation does not seem to provide any benefit with respect to pulsatile stimulation.

3.4. Experiment 4: Speech tests

Three additional CI users participated in the evaluation of the ELFHiRes strategy on the HRStream research platform. The study participants were one bilateral CI user and 2 monolateral CI users without any contralateral residual hearing. First of all, the ELFHiRes analog channel was fitted by presenting a 150 Hz electric tone to find the M and T levels. Speech was processed on a PC and delivered directly to the CI using the SIB interface. The presentation level was equivalent to 65 dB SPL. Three conditions were evaluated, HiRes strategy, ELF-HiRes strategy without analog channel (M level set to 0) and ELF-HiRes with the analog channel activated. Speech was evaluated using the HSM sentence test [5]. Two lists of 20 sentences were presented to the study participants using the ELFHiRes and the HiRes strategy. The study participants were also asked to describe the sound with the new strategy. Figure 4 presents the results of the HSM sentence test in CCITT noise at a signal to noise ratio of 15 dB. Except

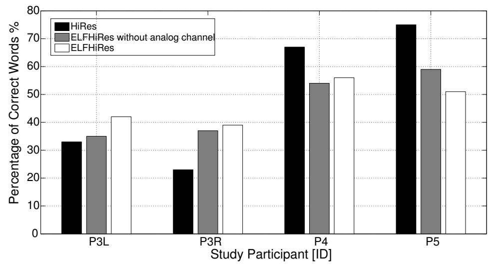

Fig. 4. Results of the HSM sentence test in noise.

subject P3 no clear benefit could be observed from using the ELFHiRes strategy with respect to HiRes. However, study participants P3 and P4 obtained benefit of using the analog channel with respect to not using it (ELFHiRes vs ELFHiRes without analog channel). Subjectively, all CI users reported that the sound was too much dominated by low frequencies.

3.5. Experiment 5: Frequency Difference Limen

A frequency difference limen (FDL) experiment was performed to assess if the ELF-HiRes strategy provides with better frequency discrimination in the low frequencies than the HiRes strategy. The pitch discrimination test was administered using PACTS (PsychoACoustic Test Suite) coupled to HRStream. The reference frequency was 150 Hz (+ 4 harmonics), and a one-down/two-up 3AFC staircase procedure with six reversals was used for this task. Initial probe was 15% above 150 Hz and loudness levels were roved by 20%. Figure 5 presents the results for the FDL experiment. Again the task was performed using the HiRes and the ELF-HiRes with and without the low frequency channel.

4. DISCUSSION

A new strategy called extended low frequency HiRes (ELF-HiRes) was implemented in a research environment provided

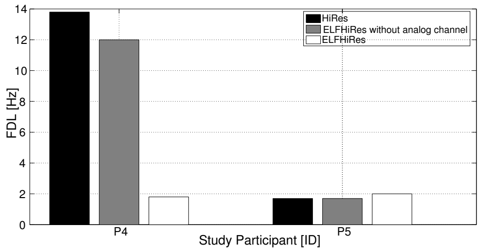

Fig. 5. Results of the FDL experiment.

by Advanced Bionics. While the lower cut off frequency of the clinical Advanced Bionics system is at around 300Hz, the new strategy adds an additional filter that is used to transmit sounds from 0 Hz until 300Hz in a dedicated low frequency channel. To transmit the low frequency signal, we decided to use analog stimulation in narrow bipolar configuration. To avoid that very low frequencies dominate the stimulation a high pass filter was introduced with a slope of 6dB/octave.

The new strategy was implemented on the HRStream platform. Several iterations were required to find suitable stimulation parameters for the lowest channel (e. g. stimulation mode, loudness growth, etc). In a first experiment, the loudness produced by analog stimulation at different frequencies was investigated. 3 subjects with normal hearing in one ear and a CI in the other ear participated in the experiment. The characterization of loudness over frequency was used to design an equalizer filter to compensate the loudness variations over frequency. In a second experiment with the same CI users, pitch perception on the acoustic side was compared to pitch perception using analog and pulsatile stimulation. No difference between both modes of stimulation could be observed. In a third experiment the tonal quality of pure tones generated through the CI was investigated. Electric tones were compared to acoustic tones that ranged from very tonal (pure tone) to noisy tones (band pass filtered noise). No clear difference in tonal quality could be observed between analog and pulsatile stimulation.

Finally, a pilot evaluation of speech intelligibility was performed in 3 CI users (4 ears). Preliminary results of this ongoing work indicate that it is indeed possible to give CI users access to signal in the lower frequency domain via electrical stimulation. However, the determination of the stimulation parameters seems to be critical. So far, no clear benefit could be demonstrated by our current approach of conveying low frequency information through electrical stimulation. One possible reason to explain this is that the sound balance between low and high frequencies was too much dominated by low frequencies. The introduction of a high pass filter to compensate for loudness over frequency seems to be a step into the right direction. However, future work has to focus on measuring loudness perception or loudness growth in the very low frequency region below 300 Hz.

5. CONCLUSION

In this paper we have investigated if analog stimulation on the low frequencies can be beneficial to improve pitch perception for cochlear implant users. A new strategy that uses analog stimulation in the most apical channel has been designed and implemented on a research platform called HRStream. Using both modes of stimulation (analog and pulsatile) the pitch and the tonal quality perceived were similar. First experiments assessing speech intelligibility could not show a benefit in speech understanding with respect to the clinical strategy. One possible reason is the fact that the sound balance between low and high frequencies becomes too much dominated by low frequencies using the new low frequency strategy.

6. REFERENCES

[1] L. Xu, T. A. Zwolan, C. S. Thomson, B. Pfingst, Efficacy of a Cochlear Implant Simultaneous Analog Stimulation Strategy Coupled with Monopolar Electrode Configuration, Annals of Otology, Rhinology and Laryngology 114(11):886-893, 2005.

[2] Blake S. Wilson, Charles C. Finley, Dewey T. Lawson, Robert D. Wolford, Donald K. Eddington and William M. Rabinowitz, Better speech recognition with cochlear implants, Letters to Nature 352, 236 - 238, 1991.

[3] M.F. Dorman, A.J. Spahr, P.C: Loizou., et al, **Acoustic simulations of combined electric and acoustic hearing (EAS)**. Ear Hear, 26, 371-380,1997.

[4] W. Nogueira, L. M. Litvak, B. Edler, J. Ostermann, A. Buechner, **Signal Processing Strategies for Cochlear Implants Using Current Steering**, EURASIP Journal on Advances in Signal Processing ID 531213, 2009.

[5] I. Hochmair-Desoyer, E. Schulz, L. Moser and M. Schmidt, **The HSM sentence test as a tool for evaluating the speech understanding in noise of cochlear implant users**, American Journal of Otology, vol. 18, no. 6, supplement, p83, 1997.

[6] C. A. Brown, S. P. Bacon, **Low-frequency speech cues and simulated electric-acoustic hearing**, J. Acoust. Soc. Am. 125 (3), March 2009.

[7] R. P. Carlyon and J. M. Deeks, **Limitations on rate discrimination**, Journal of the acoustical society of america, pp. 1009–1025, vol. 112, 2002

[8] C. M. McKay and H. J. McDermott and R. P. Carlyon, **Place and temporal cues in pitch perception: are they truly independent**, Acoustic Research Letters Online, vol. 1(1), pp. 25–30, 2000.