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Review Article

What Frequency Range of the Cochlear Implant is the Best For Speech Perception?

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Abstract

Frequency range (FR) of the cochlear implantation (CI) system is one of the main parameters of the CI speech processor. FR is set at the first connection and may change (according to indications) during the use of the CI. In implants of different companies, it is possible to set FR in different boundaries - from 70 Hz to 10 kHz, but since the main goal of CI is successful speech communication, the issue of setting the boundaries of FR is considered in this paper specifically in relation to the perception of a speech signal. What frequency range is the best range for speech perception by a subject with CI? In this article, we rely on the parameters of the Med-El implants, but all the above considerations are applicable to the CI systems of any companies. The issue of disconnection of failed and short-circuited electrodes are discussed.

Keywords: Cochlear implantation; speech intelligibility; frequency range; channel selectivity of stimulation

Introduction

The frequency range (FR) of the cochlear implantation (CI) system, i.e., the frequency range processed by the implant is one of the main parameters of the CI speech processor. To solve the issue of setting optimal FR boundaries, it is necessary to consider how the speech (acoustic) signal is processed by CI, what and how the CI patient hears as a result of processing and to correlate the perceived signal with the spectral characteristics of speech. Let's briefly consider how the CI processes an acoustic signal. At each moment of time, the speech signal has a certain instantaneous (momentary) spectrum. This instantaneous spectrum within the boundaries of the FR of the implant is divided in the speech processor into a limited number of frequency bands of different (defined) widths in accordance with the number of electrodes (in different CI models from 12 to 24). After processing, they are converted into electrical pulses. Each of these impulses stimulates a certain part of the auditory nerve corresponding to the position of the electrode in the cochlea and each of them causes some colored auditory sensation, in different channels – from different electrodes - differing in spectral sensation. The width of the bands into which the speech spectrum is divided determines the channel selectivity of stimulation (CSS) (the wider the FR, the smaller the CSS), and regardless of the bandwidth processed in this channel, the patient hears in this channel a signal of the same specific spectrum (tonotopy of cochlea). The spectrum of the audible sound band in each channel depends on the flow of current in the volumetric conductor between the electrode in the cochlea and the ground one under the skin behind the ear.

The instantaneous spectrum of speech is transmitted by a series of stimuli supplied from the first to the last electrode (not all electrodes can work in one series, but selectively - the n-of-m strategy). Thus, the implanted patient perceives the instantaneous spectrum of speech as sensations from a certain number of frequency bands. The patient perceives the picture of speech in time as a change in sensations from the change of pictures of the instantaneous spectrum. It is obvious that the normal speech spectrum changes significantly in implanted patients, but what is important: There are speech signs in the new - transformed - spectrum. The spectral redundancy of the speech signal (redundancy means that it can be removed from it without prejudice to its understanding) is so great [1] that the speech signs that are present in the speech signal after processing by the processor are quite enough for the implanted patient to fully master speech. The main task solved by an audiologist when setting up a speech processor is to maximally convey the information that is available in the transformed speech signal and is transmitted using electrical stimuli directly to the auditory nerve. For an implanted patient, every bit is expensive. That is why it is of great importance to install the correct FR. The width of single-channel bands depends on the FR value. As the FR increases, the width of all single-channel bands increases. There may be such a situation that some frequency band processed in two channels with a wide FR of the implant will be processed in three channels with a narrow FR, i.e., with a narrow FR, the CSS will increase. Naturally, the higher the CSS, the more accurately the spectrum of processed speech is transmitted by the implant.

The speech of many European languages has quite similar spectral characteristics and therefore, for the best perception (understanding) of speech, general recommendations, and rules for setting the boundary of the frequency range in all CI systems can be found. FR is directly related to the content of speech information in it and the distribution of information between the channels of the implant. All other things being equal, in order to obtain maximum speech intelligibility in CI systems, it is necessary to use the best frequency range. Based on many years of experience in CI, the author had the idea that in order to improve speech intelligibility, it is necessary to make some changes to the acoustic signal processing program in the processor. Let's consider a speech signal from the point of view of its processing in CI. Speech signals are limited to the frequency range of 100-10000 Hz [2]. It has been established, however, that the quality of speech is quite satisfactory when the spectrum is limited to frequencies of 300-3400 Hz. These frequencies are accepted by the International Telecommunication Union as the boundaries of the effective speech spectrum, i.e., this mid-frequency range contains a significant part of speech information. With this frequency band, the intelligibility of phrases is more than 99% and the satisfactory naturalness of the sound is preserved. Naturally, after processing this band of the speech spectrum in the CI, some of the information is lost and what the CI patient hears will not be enough for a 100 percent understanding of speech. It is obvious that for CI patients, these losses must be compensated by expanding the band of perceived frequencies of this effective speech spectrum. Question: to what limits in the direction of low and high frequencies? Is the range from 100 to 10000 Hz suitable? It should be understood that CI is not a hearing aid (HA). This is in the HA, the wider the frequency range the patient hears, the better.

To resolve the issue of setting the boundaries of the FR, we must consider the data on the contribution of low and high frequency regions of the speech spectrum in speech intelligibility. We consider the processing of the speech spectrum in a wide FR of the Med-El implant - 70-8500 Hz. In the study of M.A.Sapozhkov was shown that the frequency band up to 420 Hz contains 5% of speech information [3]. This band with a wide FR (70-8500 Hz) of CI is processed in the first-second and partially in the third channels of the implant. Obviously, the lower the frequency band of the first, second and third channels on the frequency scale, the less speech information it contains. It is obvious that the band of the first channel contains only a small part of speech information (less than 1%) and with a wide FR, the first electrode works almost in vain. The band of the second channel contains slightly more information than the band of the first channel. It follows that from the first and second channels only a small part of the audio information comes to the implant. Therefore, it is not necessary to expand the FR towards the low frequency to 70 Hz. When considering high frequencies (HF) in the FR it follows that the band from 6500 to 8500 Hz contains 5% of speech information [3], which partially contains information about only a few high-frequency phonemes. It must be remembered that the spectral features of these HF phonemes are also present in the low and midrange frequencies. It can be assumed that by narrowing the FR from the HF side, we will lose a small part of the HF information, but we will increase the CSS and thereby sharpen the perception of the remaining low-middle frequency phonemes.

Thus, by narrowing the FR of 70-8500 Hz, we lose a small part of the speech information from the low-frequency and high-frequency parts of the speech spectrum, but we increase the CSS in the informative mid-frequency part of the spectrum. So, in this way we can find the golden mean between the loss of information in the low and high-frequency zones (with a narrowing of the FR 70-8500 Hz) and increase the CSS by reducing the width of all processed single-channel bands. From the point of view of the above considerations, it is interesting to consider the results of our previous study. In that study, we modeled 4 CI with different FR and compared the intelligibility of the processed speech. It should be noted that in this work, we developed a methodology for measuring the intelligibility of words which was successfully applied. It can also be used when comparing CI programs with different strategies. For further discussion, we will present a table of the results obtained in the previous study [4]. The averaged results of measurements of the intelligibility of spectrally deprived words depending on the width of the frequency range of the CI are presented in Table 1.

Table 1: Intelligibility of spectrally deprived words (%) depending on the width of the frequency range (Hz) of the cochlear implant.

Frequency Range, Hz	350-6500	250-6500	250-8500	70-8500
Intelligibility, %	71	73	64	63

As can be seen from this table the highest intelligibility of words is obtained at a frequency range of 250-6500 Hz. When the lower boundary of the FR of 250-6500 Hz is shifted to 350 Hz, the intelligibility of words decreases somewhat. It can be assumed that when removing the band 250-350 Hz from processing (and perception) we lose some of the information, but somewhat increase the intelligibility of speech by increasing the CSS. The CSS is only slightly increased and the loss of information from the remote 250-350 Hz band is not compensated by increasing the CSS. When the upper boundary of the FR 250-6500 is shifted to 8500 Hz, the intelligibility of words decreases significantly. We assume that this is due to a noticeable decrease in the CSS, which is not compensated by the information contained in the 6500-8500 Hz band. Speech intelligibility in FR 70-8500 and 250-8500 does not differ. No differences in speech intelligibility in these FR can presumably be explained as follows. By adding a band of 70-250 Hz to a FR of 250-8500 Hz, we gain a little information, but we lose this acquisition due to some decrease in CSS. It is possible that the acquisition is small. One thing is absolutely certain: a wide FR is unsuitable for speech perception, since in this case the first two channels of the implant work almost in vain and, compared with a narrow FR (250-6500 Hz), the CSS is reduced due to the band of a channel 12, which is partially needed only for a few HF phonemes. The obtained results of the study give grounds for a more thorough investigation in the frequency range of 200-7000 Hz. The search for a golden mean between the loss of speech information due to the narrowing of the frequency range of CI and its acquisition due to an increase in the CSS should be continued.

The above reasoning is also applicable when stimulating a channels in one run from the first to the last electrode with the n-of-m strategy for a wide range - up to 10 kHz, since due to the expansion of the frequency range to 10 kHz, single-channel bands become wider and thereby the CSS decreases. In addition, there is an assumption that the wider the channel band, the less the SPL changes in successive measurements of the instantaneous spectrum. To test this hypothesis, it is necessary to calculate the changes of the SPLs in bands of different widths (for example, 300-450 and 300-550 Hz) in time. After the above reasoning, the issue of disconnecting the implant electrodes should be considered, which may need to be done for various reasons, for example, incomplete insertion (how to deal with problems with the insertion of a chain of electrodes we described earlier [5]) or mechanical failure of the electrode. If the electrode fails or it is not inserted, then the frequency band processed in the corresponding channel falls out of the implant processing and, consequently, out of the patient's perception. Such an electrode must be switched off. After it is turned off, the entire FR is redistributed between the other electrodes. In this case, the channel selectivity of stimulation decreases (all bands become wider) and therefore it is necessary to reduce the previously installed FR, depending on which electrode has failed. N.B. Disconnecting of electrodes no. 1, 2 or 3 slightly changes the CSS.

As for the recommendations on disconnecting short-circuited electrodes, I think that this issue should be considered more closely. Why? Imagine that 3 and 9 electrodes are short circuited. After processing the instantaneous spectrum, pulses of the corresponding amplitude will be created in these channels. When a series of stimuli is applied from the first to the last electrode to transmit this instantaneous spectrum, the pulse from the third electrode will be applied to the 9-th electrode, and the pulse applied to the 9-th electrode will be applied to the 3-rd electrode. Naturally, the sensations in channels 3 and 9 will differ (tonotopy). With a series of stimuli to transmit the next instantaneous spectrum, channels 3 and 9 and channels 9 and 3 will also be stimulated simultaneously and the sensations from each of them will also differ. But what is important, the sensations from the second series of stimuli of the instantaneous spectrum will differ from the sensations during the first series of transmission of the spectrum to these electrodes. I.e., the information will change both through channels and series, and it will display changes in the instantaneous speech spectrum. It should be remembered that the effect of disconnecting a short-circuited electrode is the same as when disconnecting a failed one – the FR is redistributed between the other electrodes and a decrease in CSS occurs. But in case of a short circuit, the electrode that transmits the information is switched off. Question: Is it necessary to disconnect the short-circuited electrode that transmits information? The above reasoning concerns two short-circuited electrodes and is not an absolute indication not to disconnect one of them. To answer the question about disabling one of the two short-circuited ones, it is necessary to compare the two programs. Our new method of comparing programs, successfully applied by us on a model of implants with different FR, can be used to compare programs in CI patients with one of the two short-circuited electrodes disconnected and not disconnected. The question of three short-circuited and other combinations of electrodes requires further consideration.

Conclusions

a) To achieve the maximum possible intelligibility of speech, it is necessary to set the optimal frequency range in the speech processor. The best frequency range of CI for speech perception is the golden mean between the loss of low and high frequency information and value of the channel selectivity of stimulation.

b) The issue of disconnecting short-circuited electrodes requires closer investigation.

c) A new method of comparing programs, successfully applied on the CI model, can be used in implanted patients.

The speech signal spectra of many European languages differ slightly and therefore the optimal FR may be the same in different countries.

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