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A Review of Stimulating Strategies for Cochlear Implants

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1. Introduction

Many animals use sound to communicate with each other, and hearing is particularly important for survival and reproduction. In species that use sound as a primary means of communication, their hearing is typically most acute for the range of pitches produced in calls and speech. Human is one such species and Fig. 1 shows a human ear consisting of the outer, middle and inner ear. The eardrum of an ear converts incoming acoustic pressure waves through the middle ear to the inner ear. In the inner ear the distribution of vibrations along the length of the basilar membrane is detected by hair cells. The location and intensity of these vibrations are transmitted to the brain by the auditory nerves. If the hair cells are damaged (as shown in Fig. 2(b)), the auditory system is unable to convert acoustic pressure waves to neural impulses, which results in hearing impairment. Damaged hair cells can subsequently lead to the degeneration of adjacent auditory neurons. If a large number of hair cells or auditory neurons are damaged or missing, the condition is called *profound hearing impairment* (Yost, 2000).

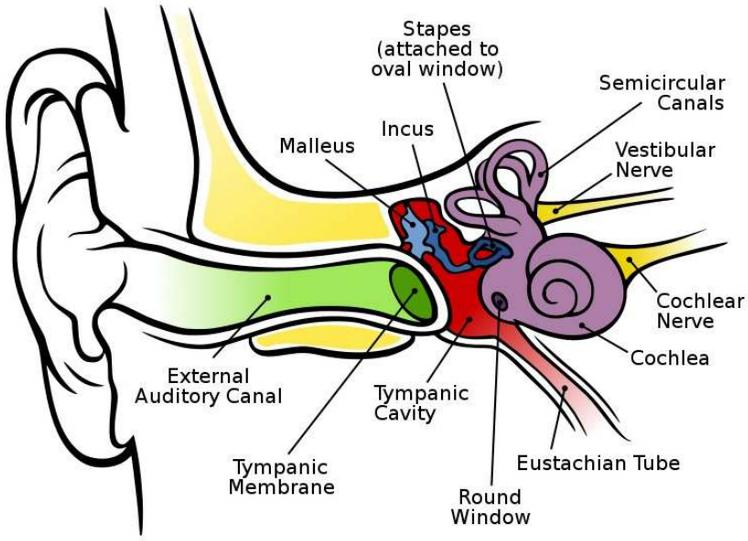
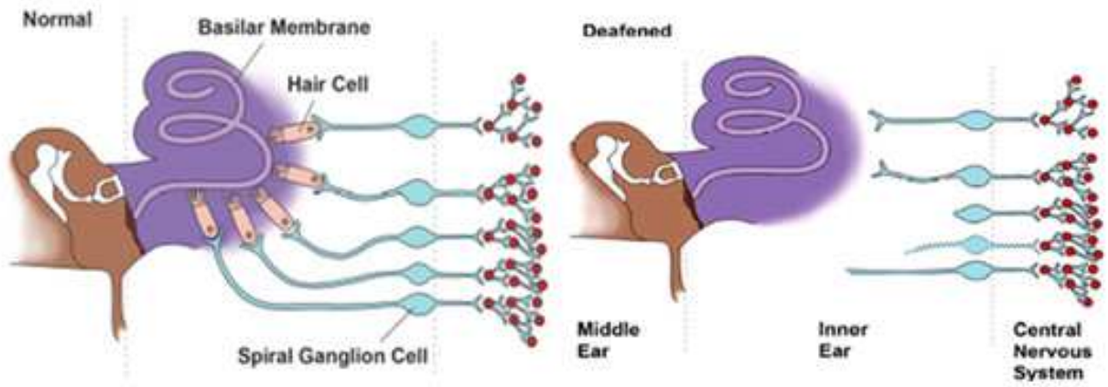


Fig. 1. A diagram of the anatomy of the human ear. (Chittka, L. & Brockmann, A. (2005))



(a) (b)

Fig. 2. (a) Normal human ear; (b) Profound hearing impairment. (Loizou, P.C. (1999))

Cochlear implants (*CI*) have been commercially available for nearly thirty years. Today cochlear implants still provide the only opportunity for people with profound hearing impairment to recover partial hearing through electrical stimulation of the auditory nerves (Loizou, 1998; Loizou, 1999; Spelman 1999; Wilson & Dorman, 2008). Fig. 3 is a diagram of a cochlear implant. The external part consists of microphones, a speech processor and a transmitter. Internally an array of up to 22 electrodes is inserted through the cochlea, and a receiver is secured to the bone beneath the skin. The microphones pick up sounds and the speech processor converts the sounds into electrical signals based on a stimulating strategy. The electrical signals, which determine the sequence in which the electrodes are activated, are then converted into electric impulses and sent to the implanted electrodes by the transmitter (Girzon, 1987; Suesserman & Spelman, 1993). The simulating strategy plays an extremely important role in maximizing a user's overall communicative potential.

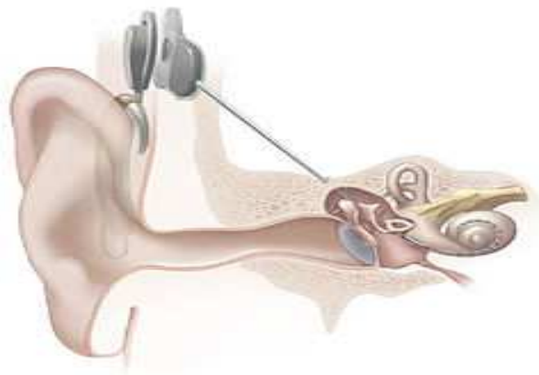


Fig. 3. A cochlear implant.

Until recently the main thrust in cochlear implant research has been to improve the hearing ability of CI users in a quiet environment (Dorman & Loizou, 1997; Loizou et al., 1999). There have been numerous improvements in the current generation of cochlear prosthesis, including the development of completely implantable cochlear implants. However, today CI users still have difficulty in listening to music and tonal languages, and in hearing in a noisy environment (Fu et al., 1998; Friesen et al., 2001; Xu et al., 2002; Kong et al., 2004; Lan et al.,

2004). One cause of these problems is that the spectral resolution perceived by CI user is not good enough. If a novel stimulating strategy is developed to increase spectral resolution, these problems can to some extent be relieved. In this literature review we first introduce basic stimulating strategies used in commercial cochlear implant systems. We then discuss a new *hybrid stimulating strategy*, and some experimental results of normal hearing tests are presented to compare the performance achieved by different stimulating strategies.

2. Stimulating strategy review

In the cochlear implant system, the stimulating strategy plays an extremely important role in generating the sounds heard by users (Wilson et al., 1991; Kiefer et al., 2001; Koch et al., 2004; Wilson & Dorman, 2008). It functions to convert sounds into a series of electric impulses which determines which electrodes should be activated in each cycle. A complete stimulating strategy should address the following:

1. The number of channels selected to reproduce the original spectrum;
2. The number of electrodes activated to generate each channel;
3. The number of consecutive clock cycles required to deliver selected channels,; and
4. The scheduling of the activating sequence of electrodes.

Many stimulating strategies have been developed over the past two decades. An ideal stimulating strategy is one that closely reproduces the original sound spectrum and allows a CI user to hear clear sounds. In the following we briefly describe and compare the *advanced combinational encoder* (*ACE*), *continuous interleaved sampling* (*CIS*), and *HiRes*120 strategies, which are frequently used in today's commercial cochlear implants.

2.1 Stimulating strategy using fixed channel

2.1.1 Advanced Combinational Encoder (ACE) (Kiefer et al., 2001)

The ACE strategy (Fig. 4), used in the Nucleus implant, is based on a so-called N of M principle. This system uses 22 implanted electrodes which can be activated to generate 22 fixed channels. The signal is processed into 22 frequency bands for each frame of recorded sound. After the envelope information for every frequency band is extracted, 8–10 (set by the audiologist) frequency bands with the largest amplitudes will be stimulated. Electrodes corresponding to the selected channels are then activated. Thus in the ACE strategy, a channel is generated by one implanted electrode, and the original spectrum is reproduced by 8–10 fixed channels.

2.1.2 Continuous Interleaved Sampling (CIS) (Wilson et al., 1991)

CIS is a strategy used in the speech processors of all major cochlear implant manufacturers. For Advanced Bionics implants, which have 16 implanted electrodes, a diagram of the strategy is shown in Fig. 5. For each frame of sound, the signal is applied through 16 band-pass filters, and the envelopes of these frequency bands are extracted by full-wave rectifying and low-pass filtering (with 200–400Hz cutoff frequency). Unlike ACE, all 16 frequency bands are then stimulated in sequence. Trains of balanced biphasic pulses modulated with extracted signal envelopes are delivered to each electrode at a constant rate in a non-overlapping sequence. The stimulation rate of each channel is relatively high, and the overlap across channels can also be

eliminated. So, in the CIS strategy a channel is still generated by one implanted electrode. The original spectrum is reproduced by 16 fixed channels, and all electrodes are turned on in a predefined sequence within 16 consecutive clock cycles.

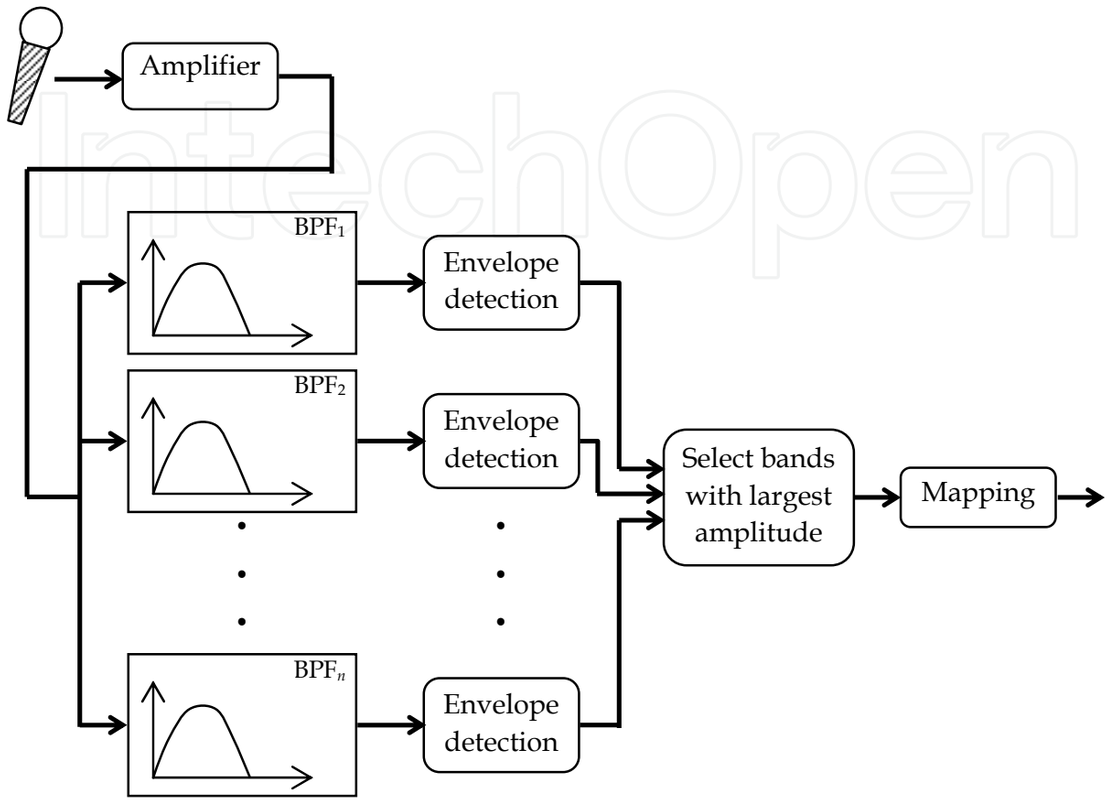


Fig. 4. A block diagram of the ACE stimulating strategy.

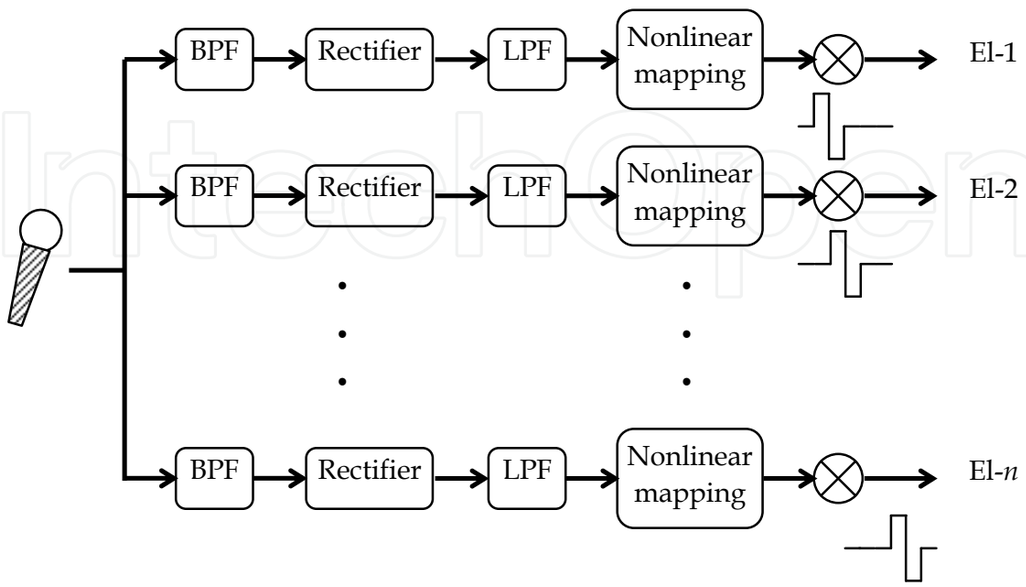


Fig. 5. A block diagram of the CIS stimulating strategy.

2.2 Stimulating strategy using virtual channel

As described above, both ACE and CIS strategies only use fixed channels to reproduce the original sound spectrum. There are, however, around 30,000 auditory nerve fibers in a human ear, but only 16–22 electrodes can currently be implanted into a CI user's ear to generate 16–22 fixed channels. Due to the limitation of the electrode design, the electrode has limited stimulation selectivity. Thus, these electrodes can only excite a small number of specific auditory nerve fibers, thus restricts the resolution and information received by a CI user is thus restricted.

2.2.1 Virtual channel technique

One possible way to achieve better spectral resolution is by increasing the number of electrodes. If, however, the number of implanted electrodes is limited and fixed, an alternative is to use the *virtual channel* technique (Donaldson et al., 2005; Koch et al., 2007). This technique uses *current steering* to control the electrical interaction. When two (or more) neighboring electrodes are stimulated in a suitable manner, intermediated channels, also known as virtual channels, are created between the electrodes. These virtual channels can enable CI users to perceive different frequencies between two fixed channels (Koch et al., 2004; Choi & Hsu, 2009). Using the virtual channel technique not only allows for more stimulating space, but also improves the reproduction of the original spectrum. This is Illustrated by the example in Fig. 6. Fig. 6(a) shows a sample original spectrum, and Figs. 6(b) and (c) show spectrums generated using fixed and virtual channel techniques, respectively. There appears to be much similarity between Fig. 6(a) and Fig. 6(c), but Fig. 6(b) is distorted from the original. Therefore, in order to better reproduce the original spectrum and increase the perceptual quality of CI users, it would be beneficial to apply the virtual channel technique to the stimulating strategies of cochlear implants.

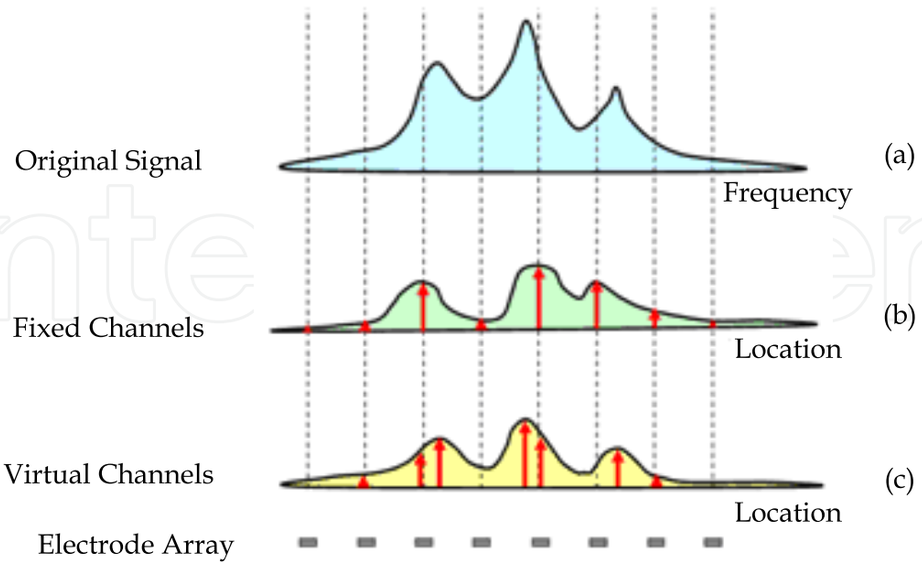


Fig. 6. A comparison of spectrums generated using different stimulating strategies. (a) A sample original spectrum; (b) A spectrum generated using fixed channels; (c) A spectrum generated using virtual channels.

2.2.2 HiRes120 (Koch et al., 2004)

To apply the virtual channel technique to a cochlear implant system, each electrode must have an independent power source to allow the current to be delivered simultaneously to more than one electrode. Theoretically, with a fine control over the current level ratio of neighboring electrodes, the locus of stimulation is steered between electrodes to create virtual channels. The HiRes120 strategy, used in the Advanced Bionics implant, is the first commercial stimulating strategy that uses the virtual channel technique. Virtual channels are created by adjusting the current level ratio of two neighboring electrodes. Since the Advanced Bionics implant has 16 implanted electrodes, there are 15 electrode pairs that can be used to steer the focus of the electrical stimulation. Fig. 7 is a diagrammatic representation of the HiRes120 strategy. For each frame of sound, the signal is divided by 15 band-pass filters and the envelope is extracted for every frequency band. In addition, 15 spectral peaks, which indicate the most important frequency within each frequency band, are also derived using the *Fast Fourier Transform* (*FFT*). These spectral peaks are then steered by corresponding electrode pairs based on the virtual channel technique. The HiRes120 strategy also delivers channels in sequence with a high stimulation rate similar to that of the CIS. Thus, in the HiRes120 strategy a channel is generated by two neighboring electrodes. The original spectrum is reproduced by 15 virtual channels, and all electrode pairs are turned on in a predefined sequence within 15 consecutive clock cycles.

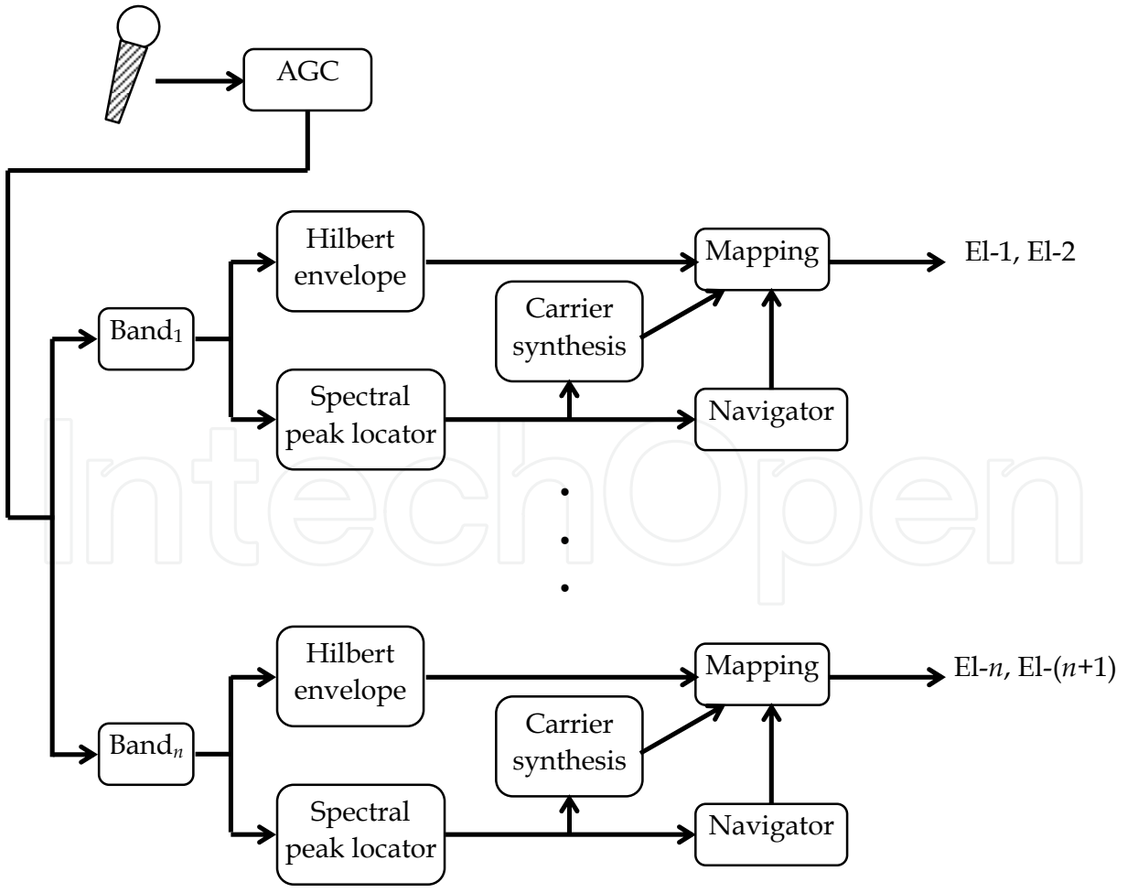


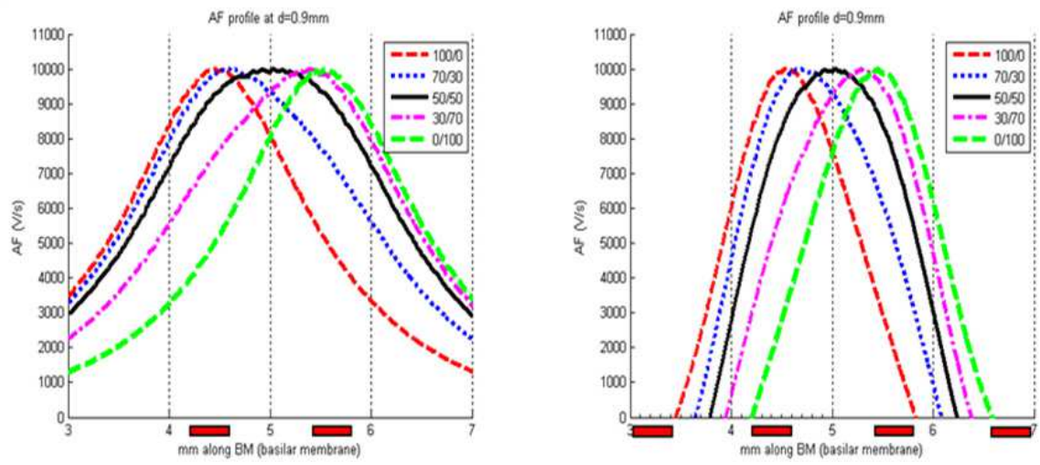
Fig. 7. A block diagram of the HiRes120 stimulating strategy.

3. Hybrid stimulating strategy

3.1 Four-Electrode Current Steering Schemes (FECSS) (Choi & Hsu, reviewing)

CI users with the HiRes120 strategy devices usually have better hearing performance compared to those with the CIS strategy devices (Koch et al., 2004; Wilson & Dorman, 2008), indicating that applying virtual channel technique does improve the perceptual quality of CI users. However, since the HiRes120 strategy only adjusts the current level ratio of two neighboring electrodes, its spectral resolution is actually not high enough due to the relatively wider stimulation region of the immediate channels. For a channel with a wider stimulation region, more auditory nerve fibers are excited. This increases the difficulty of CI users to discriminate between different channels, and limits the total number of immediate channels that can be generated. In the HiRes120 strategy only seven virtual channels are generated between two electrodes.

If more adjacent electrodes are used to steer the current, it will narrow the stimulation region to focus on firing specific auditory nerve fibers. *Four-electrode current steering schemes* (*FECSS*) is a current steering technique developed to control four adjacent electrodes simultaneously (Choi & Hsu, reviewing; Choi & Hsu, 2009). As shown in Fig. 8, the locus of stimulation is focused between the middle electrode pair, and the stimulation region is apparently narrower. This indicates that applying FECSS to stimulating strategies can help the CI user hear sounds with more specific frequencies, thus improving the perceptual quality and number of discriminable virtual channels.



(a) (b)

Fig. 8. Current steering technique. (a) Virtual channels generated using two adjacent electrodes; (b) Virtual channels generated using four adjacent electrodes (FECSS).

3.2 Hybrid stimulating strategy (Choi et al., reviewing)

Although FECSS has the potential to achieve better hearing performance for CI users, it is primarily an algorithm to control the electrical current spread spatially and does not consider the activating sequence of the electrodes. Furthermore all current commercial stimulating strategies are highly inflexible, because the number of electrodes used to

generate a channel and the number of channels delivered in every clock cycle are both fixed, which makes it difficult to closely reproduce the original sound spectrum.

In (Choi et al., reviewing) a flexible *hybrid stimulating strategy* is proposed to overcome the limitations mentioned above. This strategy utilizes a combination of the two-electrode current steering scheme (TECSS) and FECSS to reproduce the original sound spectrum. In FECSS it has been shown that it is possible to generate a sharper spectral peak by using 4-electrode stimulation (Choi & Hsu, reviewing). Hence, in the hybrid stimulating strategy algorithm, TECSS and FECSS are used to generate wider and narrower spectral peaks, respectively. The entire spectrum is delivered within eight to fifteen clock cycles, and a number of spectral peaks are delivered in each clock cycle.

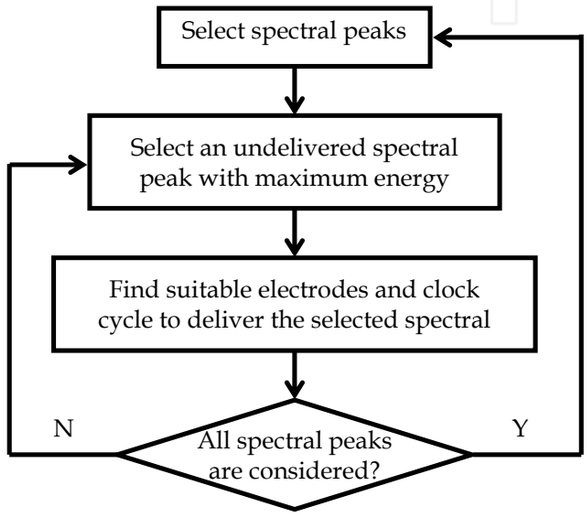


Fig. 9. A flowchart of the hybrid stimulating strategy.

		Hybrid	HiRes120	CIS	ACE
Manufacture		***	Advanced Bionics	Advanced Bionics	Cochlear
No. of implanted electrodes		*m*	16	16	22
Virtual channel technique		Yes (>300 channels)	Yes (120 channels)	No	No
To reproduce a signal frame	No. of spectral peaks	~*n* (adaptive)	15	16	8~10 (fixed) (adjustable)
	No. of electrodes to generate a channel	at most *u* (adaptive)	2	1	1
	No. of clock cycle	*k* (fixed) (adjustable)	15	16	8~10 (fixed) (adjustable)
	No. of spectral peaks per clock cycle	adaptive	1	1	1

Table 1. The characteristics of the stimulating strategy of cochlear implant system including ACE, CIS, HiRes120, and hybrid.

Fig. 9 shows a flowchart of the hybrid stimulating strategy. For each frame of sound, the signal is divided by m band-pass filters. After the envelope information for every frequency band is extracted, n ($n \geq m$) spectral peaks are derived using the FFT. A combination of TECSS and FECSS is used to duplicate these n spectral peaks within k clock cycles. Each selected spectral peak is generated by at most u adjacent electrodes (two or four electrodes) and is scheduled to be generated within 8 to 15 clock cycles, without causing temporal and spatial interactions. Notice that not all n spectral peaks will be selected at a time. Table 1 lists the characteristics of stimulating strategies including hybrid, HiRes120, CIS, and ACE.

3.3 Hybrid stimulating strategy with psychoacoustic model (Choi et al., reviewing)

Hearing is not a purely mechanical wave propagation phenomenon, but also a sensory and perceptual event. In the phenomenon called *masking*, as shown on Fig. 10, a weaker sound is masked if it is made inaudible in the presence of a louder sound (Hellman, 1972; Zwicher & Fastl, 2008).

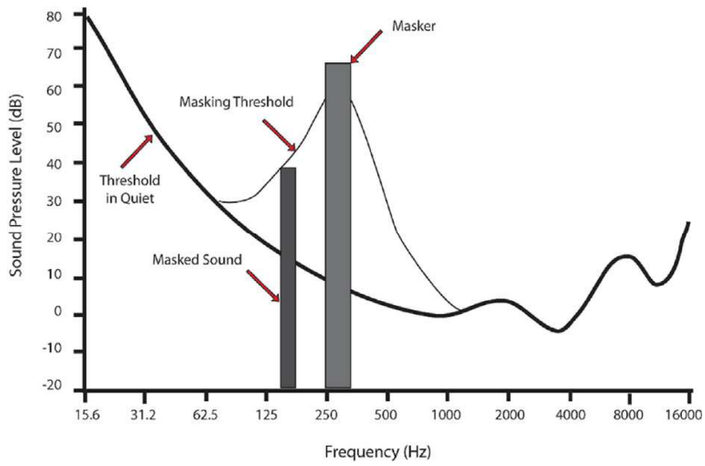


Fig. 10. An audio masking graph.

The psychoacoustic model is a computation model developed to detect the less perceptually important components of audio signals. It has been successfully used in the field of audio coding in order to reduce bandwidth requirements. Authors of the hybrid stimulating strategy also incorporate their strategy with a psycho-acoustic model (Zwicher & Fastl, 2008), and the implementation steps are shown in Fig. 11. After incorporating

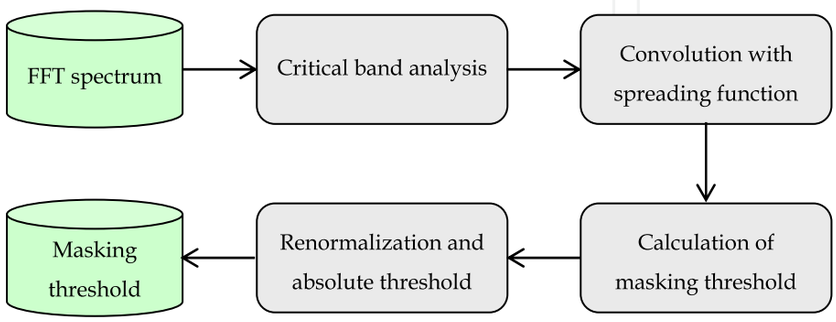


Fig. 11. A block diagram of the psychoacoustic model.

the psychoacoustic model, the number of activated electrodes is reduced compared to basic hybrid strategy, but more power is saved and the hearing performance of CI users is retained.

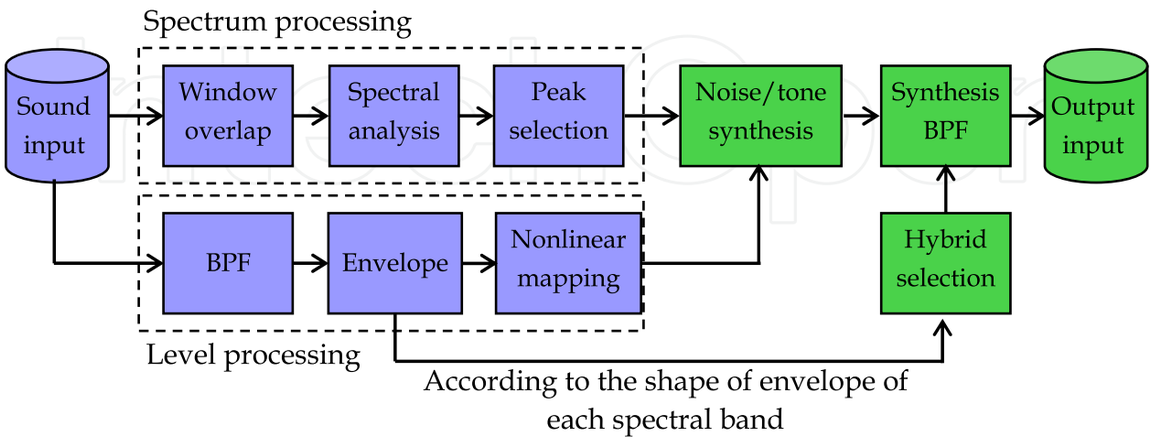


Fig. 12. A block diagram of the acoustic cochlear implant model.

4. Experimental results

4.1 Acoustic cochlear implant model

When a new stimulating strategy for cochlear implants is developed, it is impractical to apply it directly to a speech processor for testing by CI users. Researchers normally implement the strategy in an acoustic cochlear implant model (also called a vocoder), to simulate the sounds heard by CI users for conducting normal hearing tests with normal hearing subjects first.

As shown in Fig. 12, an acoustic cochlear implant model was implemented using LabVIEW (Choi et al., 2008), which contained two main paths. The *spectrum processing* path was used to derive spectral peaks using FFT, and the temporal envelope information for every frequency band was extracted in the *level processing* path. Both white noise and pure tones were used as carriers to synthesize the sounds as heard by CI users. The stimulating strategies implemented included the CIS, HiRes120, and hybrid, with and without a psychoacoustic model.

4.2 Subjects and materials

Normal hearing tests were conducted to evaluate the performance of a hybrid stimulating strategy (Choi et al., reviewing). Chinese sentences were used as test material (Tsai & Chen, 2002), and subjects were asked to listen to each sentence and recognize the final word. All sentences were mixed by multi-talker babble and white noise in 0, 5, or -5 dB SNR (signal-to-noise ratio). All normal hearing tests were conducted in a quiet room. The test subjects were 25 adults between 25 and 30 years old. SENNHEISER HD-380 PRO headphones were used.

4.3 Performance comparison of different stimulating strategies (Choi et al., reviewing)

Fig. 13 shows the results of the normal hearing tests for different stimulating strategies. The mean recognition % and standard deviation are both presented in Fig. 13, and the higher recognition % indicates more Chinese sentences can be correctly recognized. In general, the hybrid strategy showed a better performance.

The recognition % achieved in different SNRs is as follows. An SNR of -5 dB is considered a relatively noisy environment. The hybrid strategy achieved a recognition % of 50–70% at -5 dB SNR, a performance approaching that of people with normal hearing. The HiRes120 and CIS only achieved recognition % of 40–50% and < 20%, respectively. These results indicate that in a noisy environment the hybrid strategy has noticeable advantages compared to the HiRes120 and CIS. With an SNR of 0 dB, the recognition % of the hybrid strategy was 80%–85%, compared to 70%–85% for HiRes120 and <50% for CIS. With an SNR of 5 dB, a relative quiet environment, both hybrid and HiRes120 strategies had a recognition % of >85%. The CIS strategy also improved the recognition % to >50% when SNR was 5 dB.

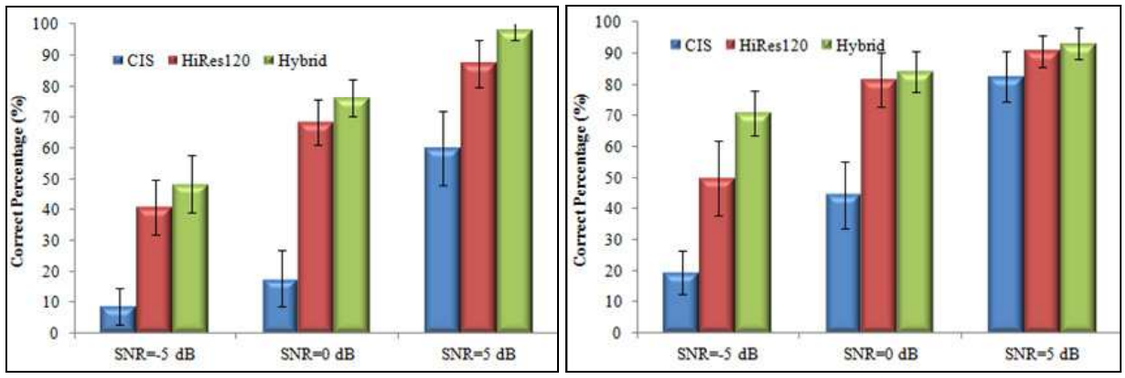


Fig. 13. Results of the normal hearing tests: a comparison among stimulating strategies CIS, HiRes120, and hybrid. (a) Multi-talker babble; (b) White noise.

Two-way ANOVA and Post Hoc tests were used to further analyze the results obtained as shown in Fig. 13. ANOVA indicated a significant main effect for SNR and the strategies. The Post Hoc test indicated that there was always a statistically significant difference between the hybrid and the CIS. Between the hybrid and the HiRes120, statistically significant differences only existed at an SNR of -5 dB. When SNR was equal to 5 dB, the hybrid performed similarly to the HiRes120 and no statistically significant difference existed between them.

4.4 Performance comparison of hybrid strategy with and without psychoacoustic model (Choi et al., reviewing)

Fig. 14 shows the results of the normal hearing tests for the hybrid strategy with and without the psychoacoustic model, showing that the recognition % before and after incorporating the psychoacoustic model are almost the same. ANOVA also indicated a significant main effect for SNR, but no statistically significant difference existed between the hybrid strategy with and without the psychoacoustic model. These results indicate that

incorporating the hybrid stimulating strategy with the psychoacoustic model is a feasible concept. The number of activated electrodes is reduced for power saving, and the hearing performance can be successfully retained.

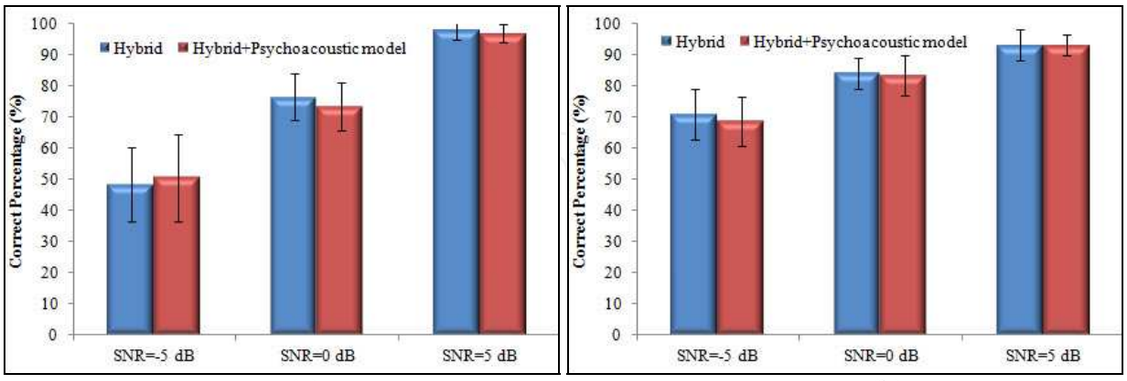


Fig. 14. Results of normal the hearing tests: the comparison between hybrid strategy with and without a psychoacoustic model. (a) Multi-talker babble; (b) White noise.

5. Conclusions

In this chapter we considered the most challenging problems currently facing CI research and demonstrated the importance of the stimulating strategy in cochlear implant systems. Some basic stimulating strategies used in commercial systems were reviewed, and a new hybrid stimulating strategy based on the virtual channel technique was introduced. The hybrid strategy can activate implanted electrodes in a more flexible way to reproduce the original sound spectrum. The results from the normal hearing experiments show the hybrid stimulating strategy achieves a better hearing performance when compared with the results from commercial stimulating strategies. The hybrid strategy can also be incorporated with a psychoacoustic model for power saving and load reduction on the stimulating cycles, without compromising the hearing performance. We therefore believe that developing a new stimulating strategy is a possible alternative to improving the hearing ability of CI users.

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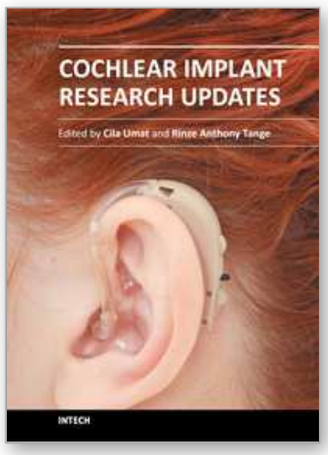
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For many years or decades, cochlear implants have been an exciting research area covering multiple disciplines which include surgery, engineering, audiology, speech language pathology, education and psychology, among others. Through these research studies, we have started to learn or have better understanding on various aspects of cochlear implant surgery and what follows after the surgery, the implant technology and other related aspects of cochlear implantation. Some are much better than the others but nevertheless, many are yet to be learnt. This book is intended to fill up some gaps in cochlear implant research studies. The compilation of the studies cover a fairly wide range of topics including surgical issues, some basic auditory research, and work to improve the speech or sound processing strategies, some ethical issues in language development and cochlear implantation in cases with auditory neuropathy spectrum disorder. The book is meant for postgraduate students, researchers and clinicians in the field to get some updates in their respective areas.

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