Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

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NEURAL INTERFACES AND PROSTHESES

(Neurális interfészek és protézisek)

LECTURE 8

COCHLEAR IMPLANTS

(Cochleáris implantátumok)

RICHÁRD FIÁTH and GYÖRGY KARMOS

CONTENTS

- Aims
- Implantable hearing devices (IHD)
  - Cochlear implants (CI)
    - History of CIs
    - Parts of CIs
    - Electrical stimulation strategies
    - Speech performance
    - Commercially available CIs
  - Electric Acoustic Stimulation (EAS)
  - Auditory brainstem implants (ABI)
  - Auditory midbrain implants (AMI)

AIMS:

In the previous lecture we presented the structure of the human ear and cochlea, the auditory pathway and different hearing disorders. This was followed by a short review of traditional hearing aids. Finally, the detailed description of the bone anchored hearing apparatus (BAHA) and middle ear implantable hearing devices (MEIHD) could be read.

This lecture is about the cochlear implant (CI) and contains the basic build-up parts of such a prosthesis, the main speech processing or electrical stimulation strategies of the electrodes placed in the cochlea, the avaible solutions of the four companies producing CIs and the detailed view of these systems. After these, the efficiency of implantable hearing devices will be discussed, concentrating on the relationship between the understanding of speech and the number of electrodes or the insertion depth and the advantages of the implantation in childhood. Finally two experimental devices, the auditory brainstem implant (ABI) and the auditory midbrain implant (AMI) will be demonstrated.

IMPLANTABLE HEARING DEVICES (IHC)

- Bone anchored hearing apparatus (BAHA)
- Middle ear implantable hearing devices (MEIHD)
- **Cochlear implants (CI)**
- **Electric Acoustic Stimulation (EAS)**
- **Auditory brainstem implants (ABI)**
- **Auditory midbrain implants (AMI)**

INTRODUCTION TO IHDs

Auditory prostheses are one of the most successful neural prostheses that restore human sensory function. They have been used to partially restore hearing in more than 60000 hearing-impaired people worldwide. There are several solutions of IHDs according to the place of the damage in the auditory system or type of hearing loss (Figure 1.). The most successful one is the cochlear implant (CI), demonstrated in this lecture in detail. CIs use electrical stimulation with electrodes placed in the cochlea to produce hearing sensations. The device is totally implanted in the patients. When conductive hearing loss is present, a bone conducting hearing device like the BAHA restores hearing by vibratory conduction through the skull to the inner ear. Sensory hearing impairment is also treated by MEIHDs which amplifies the sound signals through implanted transducers which can be either piezoelectric crystals or electromagnetic transducers. Devices in experimental phase like the auditory brainstem implant (ABI) and auditory midbrain implant (AMI) will be discussed also in this lecture.

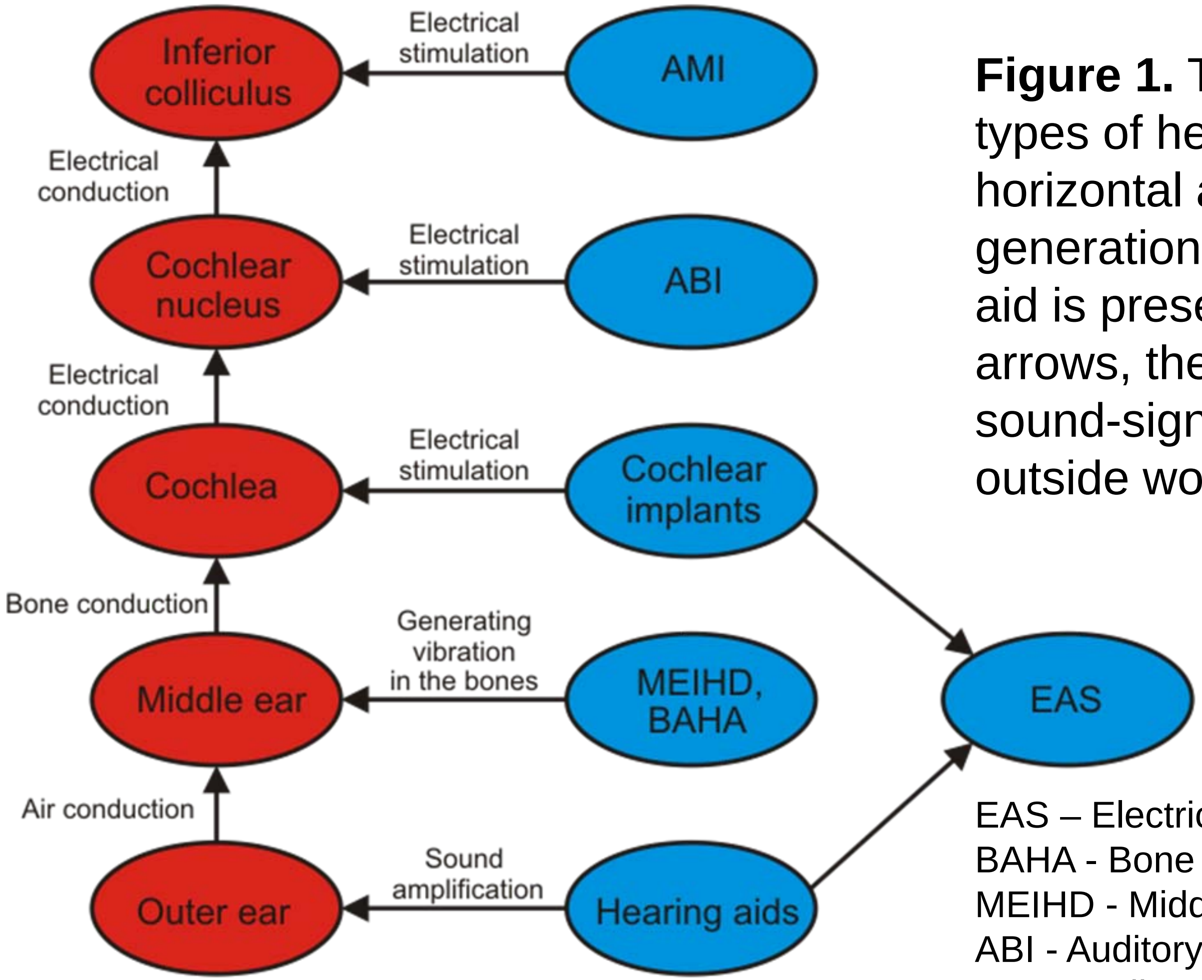

Figure 1. Targets (red) of different types of hearing aids (blue). On the horizontal arrows the method of signal generation of the respective hearing aid is presented. Next to the vertical arrows, the ways of transmitting the sound-signals originating from the outside world are shown.

EAS – Electric Acoustic Stimulation
BAHA - Bone anchored hearing apparatus
MEIHD - Middle ear implantable hearing devices
ABI - Auditory brainstem implants
AMI - Auditory midbrain implants

COCHLEAR IMPLANTS (CI) - INTRODUCTION

Patients with a profound, bilateral, sensorineural hearing loss or with auditory neuropathy are candidates of cochlear implants. The patient selection criteria is a less than 50% open-set sentence recognition with properly fitted hearing aids (suprathreshold speech-based criteria). Over 120000 people were implanted with CIs, providing restored or partial hearing (2008). In children, early implantation promotes the maturation process in the auditory cortices and normal language development. Postlingually deafened CI users go through a learning or adaptation process from a few months to as long as a few years, during which their speech performance continues to get better.

The goal of these devices is to safely use electric stimulation to provide or restore functional hearing in totally deafened persons. An electrode array is inserted into the scala tympany to directly stimulate discrete sectors of auditory nerve, taking advantage of the tonotopic organization of the cochlea (The frequency-to-structure map is called tonotopic organization.). The cost of CIs ranges from $40000 to $75000 (device, surgery and hospital costs).

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HISTORY OF COCHLEAR IMPLANTS

- XVIIIth century - First documented attempt to provide electrical stimulation directly to the auditory system: Alessandro Volta inserted metal rods attached to an active circuit into his ears.
- 1950s - First successful electrical stimulation of hearing nerves by inserting an electrode in a deaf subject's inner ear (Djourno and Eyries, 1957). Perceiving the rhythm of speech and assistance in lipreading.
- 1970s - First wide-spread clinical application: single-channel devices that sent coded information to only one electrode site. Provided speech and sound awareness, enhanced lipreading ability, but no auditory-only speech recognition.
- 1980s – Multichannel devices with multiple electrode sites, where all electrodes are stimulated at once, or sequentially (where electrodes are stimulated one at a time). With these devices the understanding of speech without lipreading was achieved.

MAIN PARTS OF COCHLEAR IMPLANTS

1. Microphone
2. Externally worn speech processor (body worn or behind the ear (BTE))
3. Inductive link (coil)
4. Implanted receiver-stimulator
5. Electrode array

Figure 2. shows a schematic representation of the components of a cochlear implant, while on Figure 3. you can see the parts of the device in relationship with the human ear structures.

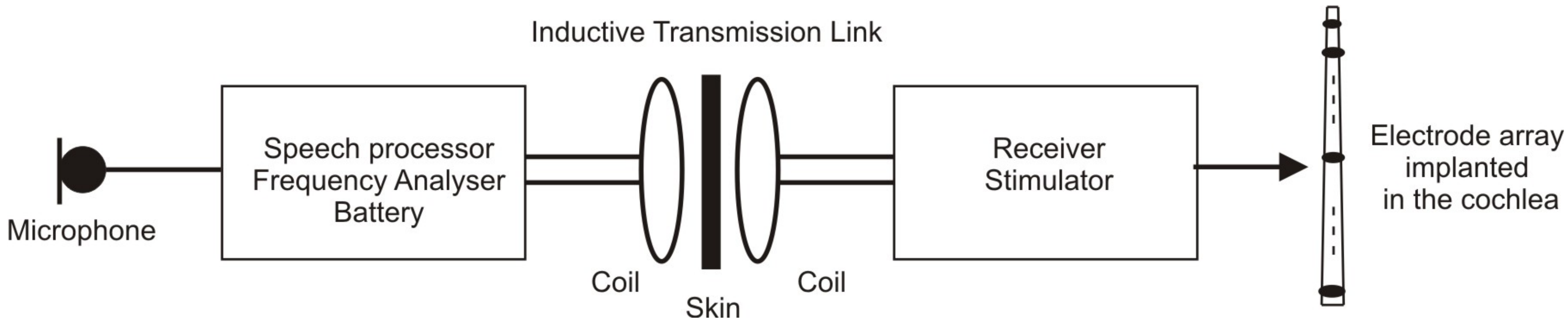
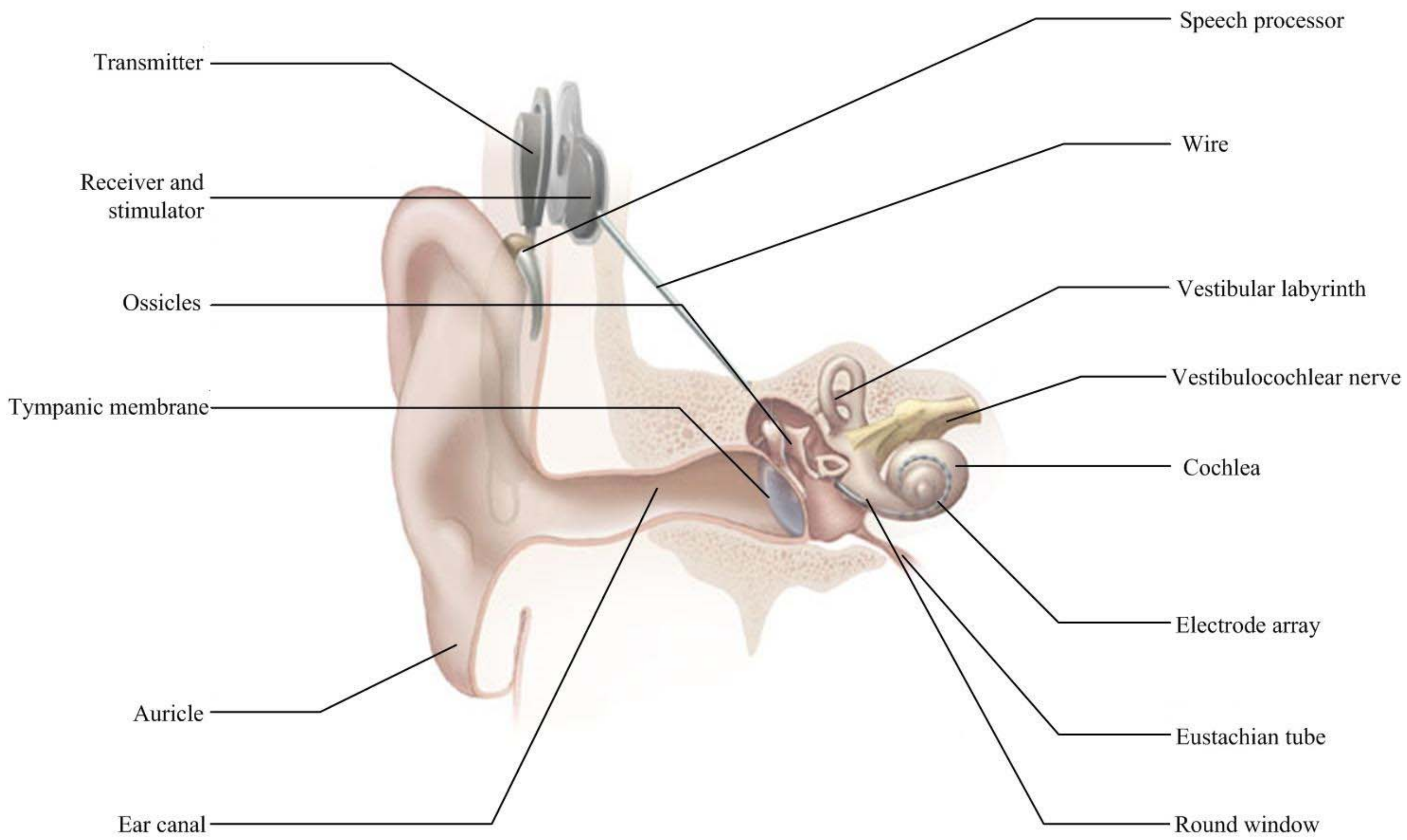


Figure 2. Schematic representation of a cochlear implant.

SIMPLIFIED WORKING MECHANISM OF THE COCHLEAR IMPLANTS

1. Sounds are picked up by the microphone in the audio (speech) processor.
2. The audio processor analyses and codes sounds into a special pattern of digital information.
3. This information is sent to the coil and is transmitted across the skin to the implant.
4. The implant (receiver-stimulator) interprets the code and sends electrical pulses to the electrodes in the cochlea.
5. The auditory nerve picks up the signals and sends them to the auditory centre in the brain. The brain recognizes these signals as sound.



(commons.wikimedia.org)

Figure 3. The sturcture of the human ear and the main parts of the cochlear implant

EXTERNAL UNIT (SPEECH PROCESSOR)

The external unit takes its input from a microphone. It has 3 main components:

- Digital signal processing (DSP) unit
- Power amplifier
- Radio frequency (RF) transmitter

EXTERNAL UNIT (SPEECH PROCESSOR)

The digital signal processor (DSP) unit extracts features from the sound picked up by the microphone and converts these into a stream of bits, which are than transmitted by the RF link to the implanted internal unit. The DSP contains a memory, which stores patient-specific information. It performs also a frequency mapping (allocating filter channels to electrodes) and an amplitude mapping (optimizing the loudness to improve speech perception). Depending on the design the DSP may also process back telemetry information from the internal unit.

The processed data is transmitted through an transcutaneous electromagnetic link. The RF transmitter is a pair of inductively coupled coils. It transmits both power and data and uses a frame or packet coding scheme for transmission. Radio frequencies between 2.5 and 50 MHz are used. The transmitted data is amplitude and frequency modulated. The efficiency of the link is a major determining factor of battery life and battery size. (70% of available power is consumed by the transmission link)

PARAMETERS OF A FEW TYPES OF COCHLEAR IMPLANTS:

Product Name	RF	Stim Rate	No. of Current Sources
Nucleus 24 (Cochlear)	5 MHz	14400 Hz	1
Sonata (Med-El)	12 MHz	50700 Hz	12 (12 electrodes)
Clarion HiRes 90K (Advanced Bionics)	50 MHz	83000 Hz	16 (16 electrodes)

IMPLANTED INTERNAL UNIT

The receiver-stimulator consists of a receiver coil (RF receiver), a decoder, and a charge delivery system (stimulator). The receiver coil, which is in magnetic coupling with the transmitter coil and is located under the skin, picks up both the power and the data transmitted from the external coil. The data is decoded to produce the current waveform used to stimulate the auditory nerve via the electrodes located in the scala tympani.

In modern devices there is also feedback loop that monitors critical electric and neural activities in the implant and transmits these information back to the external unit (back telemetry). Back telemetry allows the external unit to check status of the internal unit and to measure and monitor critical information regarding the electrode-tissue interface (electrode impedance, electrode field potential, neural responses).

The implant electronics is designed to last the patient's lifetime. The internal unit is packaged in ceramic or biocompatible metal (titanium), hermetically sealed to avoid ingress of moisture.

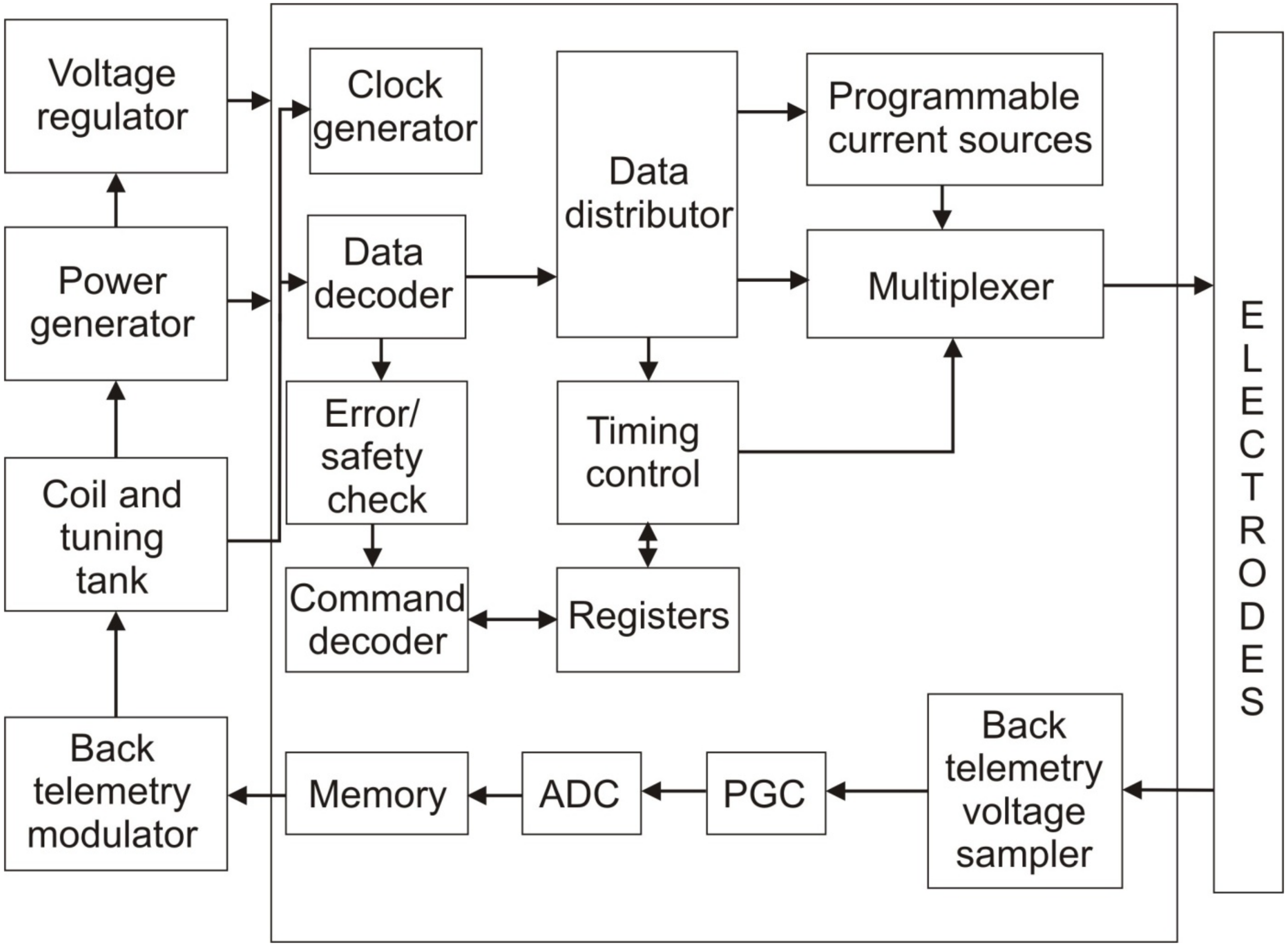


Figure 4. Block diagram of the internal unit of a cochlear implant

THE ELECTRODE ARRAY

The electrode array consists of a number of platinum contacts distributed along a flexible silicone carrier and is inserted into the scala tympani. The design goals of the electrode array are deeper insertion to better match the tonotopic place of stimulation to the frequency band assigned to each electrode channel, improving efficiency of stimulation, and reducing insertion related trauma.

Cochlear developed the Advanced Off Stylet (AOS) technique for an easier insertion of the electrode arrays. Some parameters of the electrode arrays can be read here:

Length	No. of contacts	Contact spacing	Shape
20-31.5 mm	6-22	0.75-2.4 mm	Spiral, Straight or Pre-curved

SAFETY ISSUES

- Sterilization to eliminate infection
- Mechanical design with its potential to cause structural tissue damage
- Energy exposure limits and the resulting tissue and neural damage
- Using biocompatible and non-toxic materials: titanium, platinum, iridium, gold, zirconium, ceramic, glass, silicone rubber, parylene, teflon
- Simulation safety is a top priority in the design of the stimulator:
- Parity check to detect bit errors from transmission or data decoding
- Stimulation parameter check
- Maximum charge check to prevent over stimulation
- Charge balance check to prevent unbalanced stimulation (shorting all stimulating electrodes between pulses) and DC stimulation (capacitors serially connected to the electrodes)
- Implant electronics is protected from electrostatic discharge

SYSTEM ISSUES

- Power consumption is between 13 and 250 mW (speech processor 10%, RF link 70%, implanted internal unit 20%)
- Power sources: disposable zinc air „button" cells develop for the hearing aid industry (lasting for 16-120 hours) or Nickel Metal Hybrid rechargeable cells or polymer-lithium ion cells. (short service life, recharging of batteries on a daily basis)
- A normal hearing has a 120 dB dynamic range, 200 discriminable steps and loudness grows as a power of function of intensity. A cochlear implant user has a 10-20 dB dynamic range, 20 discriminable steps and loudness grows as an exponential function of electric currents.
- The faster the stimulation rate, the more accurate the timing of sound.
- The higher the spectral resolution, the more detailed sound you hear.
- The wider the input dynamic range, the more sounds you hear

ELECTRICAL STIMULATION STRATEGIES

Stimulation possibilities:

- Analog
- Pulsatile (sequential or simultaneous stimulation) with biphasis pulses: 20-200 us (Figure 5., Figure 6.)

Electrode configurations (Figure 7.):

- Monopolar
- Bipolar

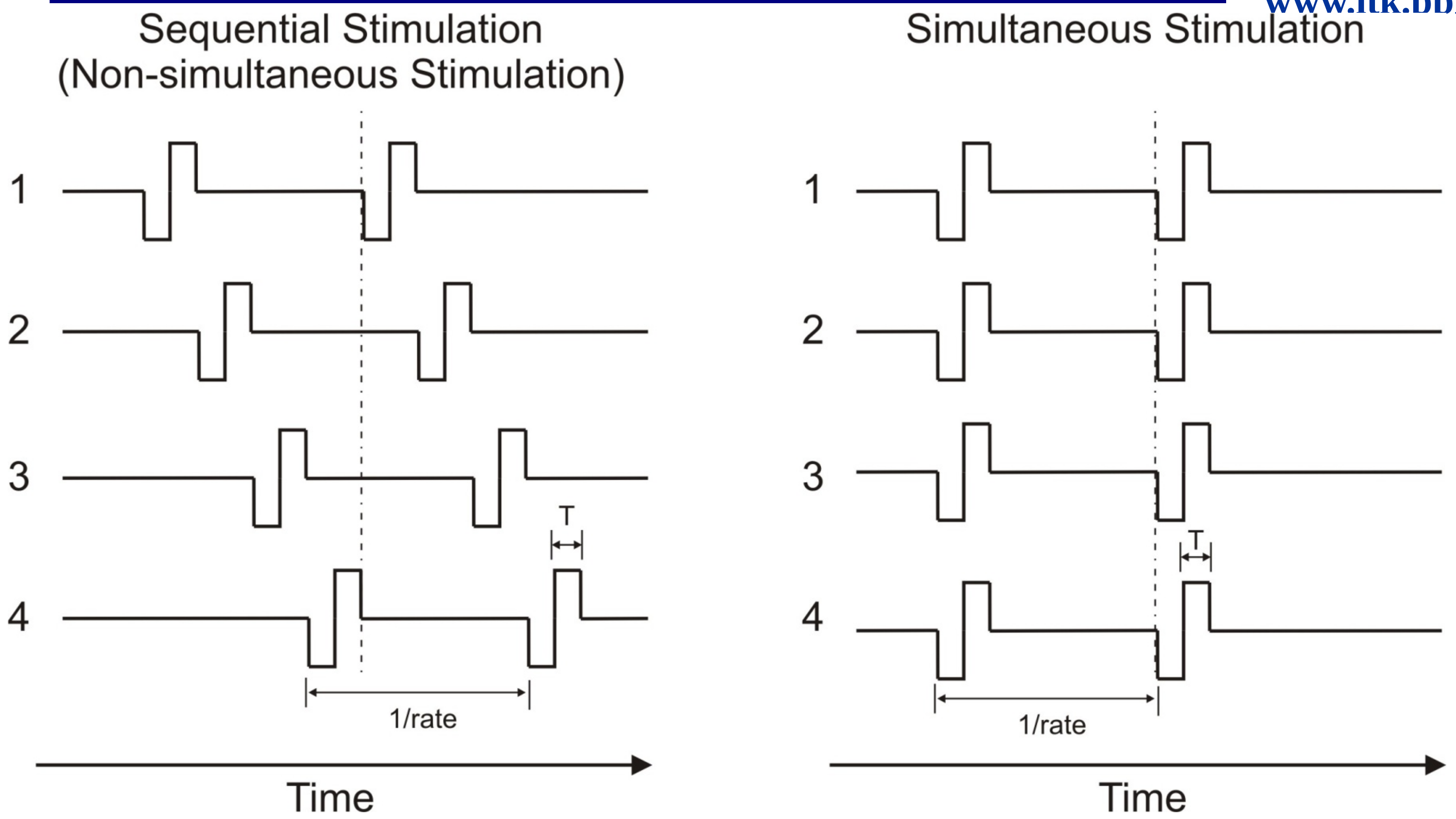


Figure 5. Sequential (interleaved pulses) stimulation and simultaneous stimulation used on four different channels. In case of sequential stimulation one electrode is stimulated at one time. (T - pulse duration, 1/rate duration between pulses)

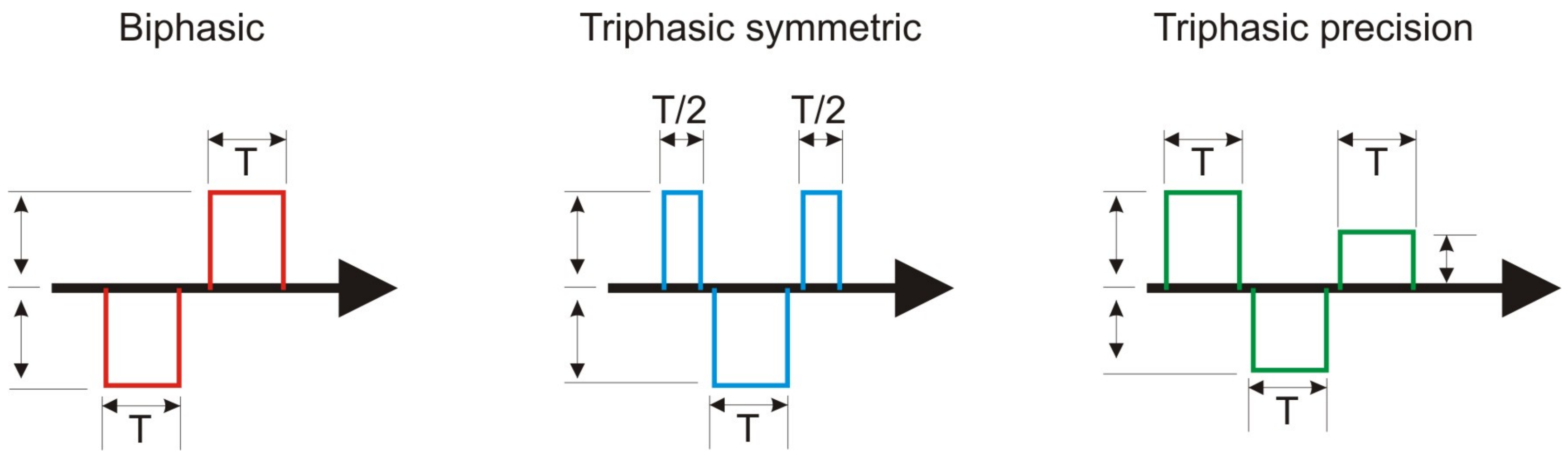


Figure 6. Various signal shapes can be used for electrical stimulation with difference in the amplitude or duration time. Biphasic pulses are the common signal shapes used for stimulation of cochlear implant electrodes.

ELECTRICAL STIMULATION STRATEGIES

Coding temporal information into electrical waveforms:

1. **Analog waveforms -** The acoustic signal is filtered, compressed and transmitted as an analog signal.
2. **Pulse trains** – The frequency of the pulses corresponds to some frequency in the acoustic signal.
3. **Amplitude-modulated pulse trains** – The rate of the pulse train is fixed and components of the acoustic signal are selected to modulate the amplitude of the pulse train.

Analog waveform carries the most information. Some temporal detail is lost in the two pulsatile strategies, but they have the advantage that different channels can be stimulated at different times. (no problems with current interaction on adjacent channels)

MONOPOLAR AND BIPOLAR STIMULATION STRATEGIES

- In a monopolar mode, the return electrode is located outside of the cochlea, usually in the temporalis muscle behind the ear but can be attached to the case housing the internal electronics. (active electrodes are located far from the reference (ground) electrode, Figure 7. left side)
- In a bipolar mode, the return electrode is an adjacent intro-cochlear electrode to the stimulation electrode. (active and reference electrodes are placed close to each other, Figure 7. right side)
- In a tripolar mode, the return electrodes are two adjacent electrodes with each receiving half of the current delivered to the stimulating electrode.

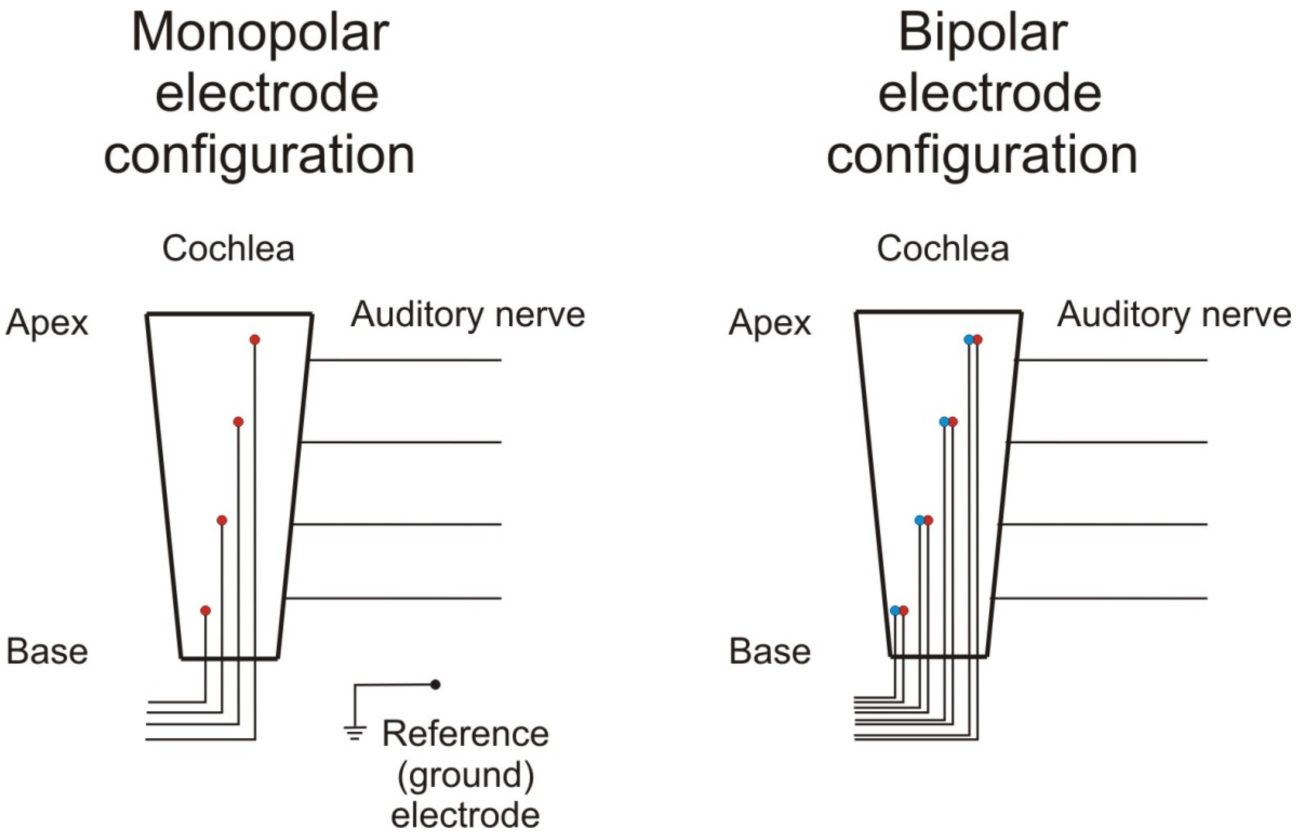


Figure 7. Two different electrical stimulation strategies: monopolar and bipolar electrode configuration

ELECTRICAL STIMULATION STRATEGIES

Features of electrical stimulation important for electrical hearing:

- Temporal features:
  - Analog stimuli: Frequency and phase
  - Pulsatile stimuli: Phase duration, Pulse rate, Pulse polarity
  - Analog or pulsatile stimuli: Stimulus duration, Duty cycle
- Spatial features:
  - Electrode location
  - Electrode orientation
  - Electrode site separation
  - Electrode configuration: Multipolar, Tripolar, Bipolar, Monopolar
- Stimulus level:
  - Operating range, Compression algorithm

ELECTRICAL STIMULATION STRATEGIES

Electrical stimulation strategies or speech processing strategies determine the way in which various features of the acoustic signal are selected and how those features are represented across the various channels of prosthesis. The main strategies can are listed on the next slide and are also shown on Figure 8. Some of these will be detailed in the next few slides. The recently developed high rate stimulation strategies like the HiResolution from Advanced Bionics or Tempo from Med-El are not presented here.

SPEECH PROCESSING STRATEGIES

Strategy Name	Abbreviation
Compressed Analog	CA
Simultaneous Analog Stimulation	SAS
Continuous Interleaved Sampling	CIS
F0/F1/F2	F0/F1/F2
Multipeak	MPEAK
Spectral Maxima Sound Processor	SMSP
Spectral Peak	SPEAK
Advanced Combination Encoders	ACE
Paired Pulsatile Sampler	PPS
Multiple Pulsatile Stimulation	MPS

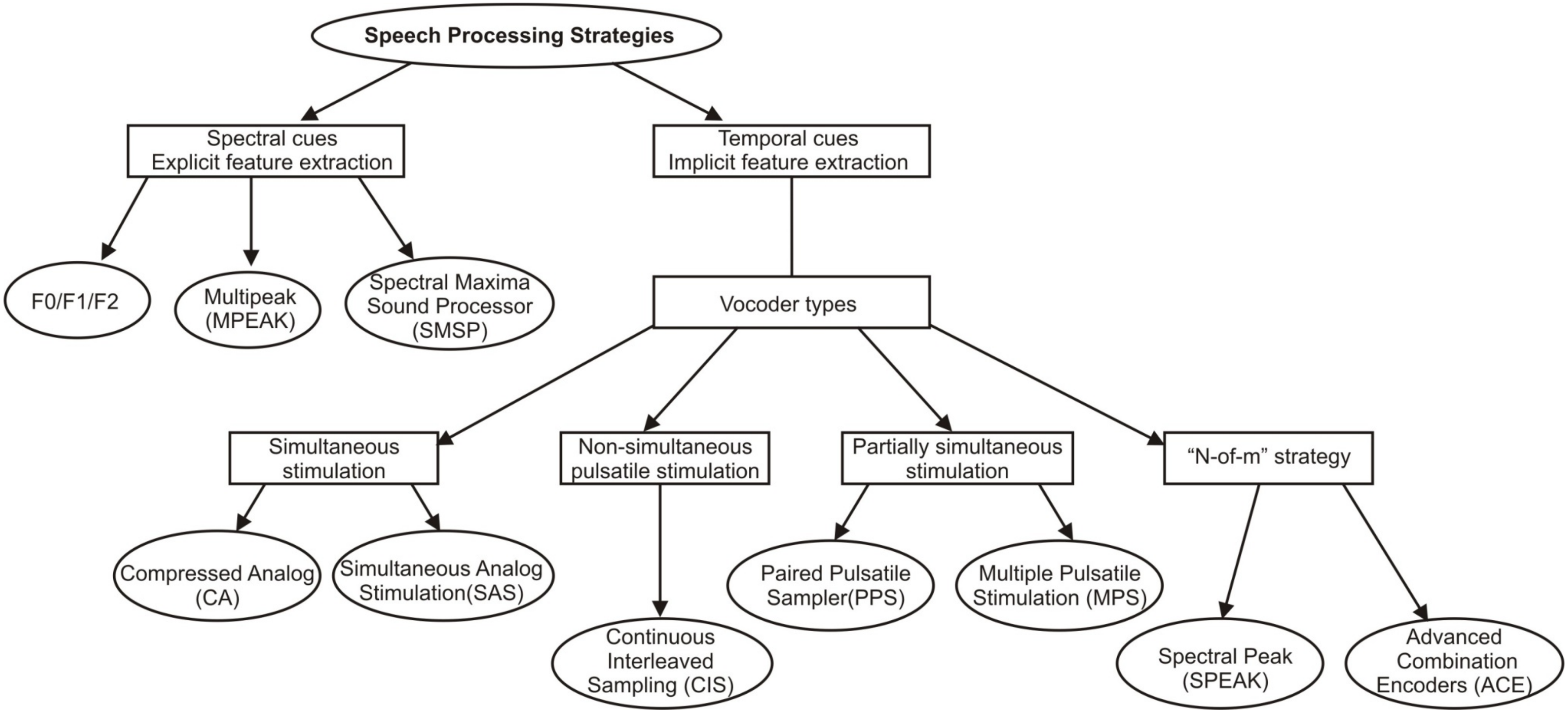


Figure 8. Different speech processing strategies used in cochlear implants. Some strategies developed recently are not indicated (like the Tempo from Med-El or the HiResolution from Advanced Bionics).

CONTINUOUS INTERLEAVED SAMPLING (CIS)

CIS strategy is implemented by all major manufacturers. The sound recorded by a microphone enters band-pass filters (5-20, number of BPFs identical to the number of electrodes) with different cutoff frequencies. The temporal envelope from each band is extracted by rectification followed by a low-pass filter. The cutoff frequency of the low-pass envelope filter is around 160-320 Hz. After that, the envelope is logarithmically compressed to match the widely varying acoustic amplitudes to the narrow electric dynamic range. This compressed envelope amplitude modulates a fixed-rate biphasic carrier. (100-1000 Hz/s). Carriers are time interleaved between the bands to avoid simultaneous electrical field interference (no simultaneous stimulation occurs between the bands at any time). This non-simultaneous stimulation (Figure 9.) needs only one current source with a multiplexer. The slowly varying temporal envelopes from 3 to 4 spectral bands can deliver high levels of speech intelligibility in quiet. The schematic representation can be found on Figure 10.

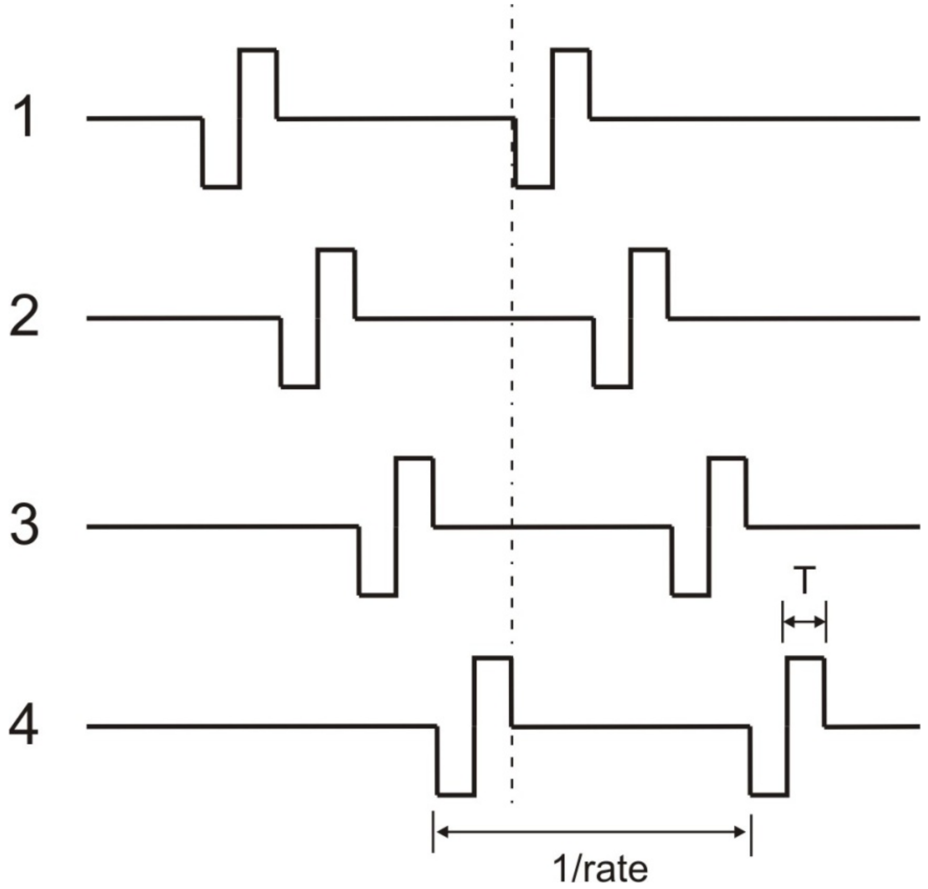


Figure 9. Interleaved pulses used on four electrodes in case of the Continuous Interleaved Sampling strategy (CIS). T is the pulse duration and 1/rate is the duration between pulses on each channel.

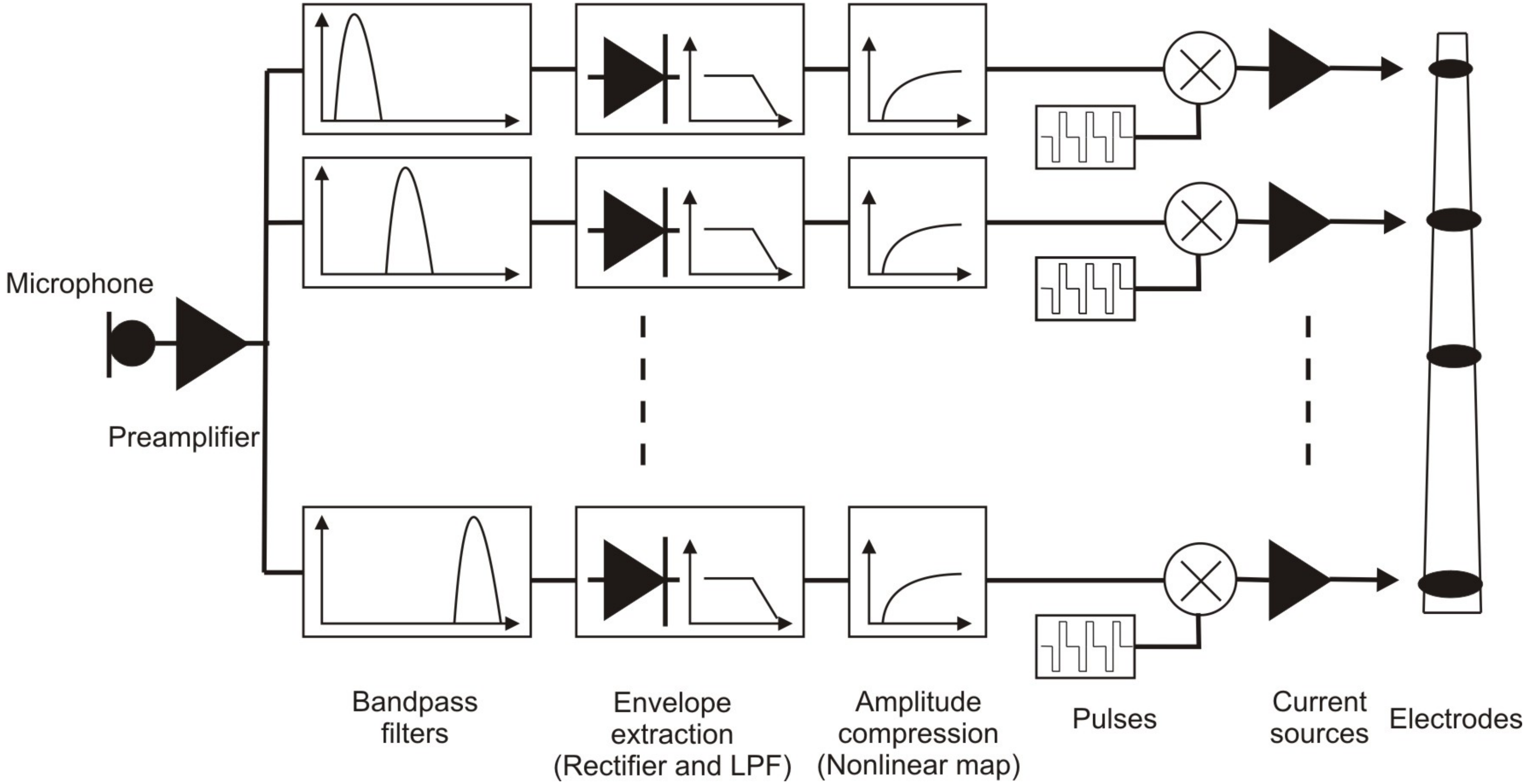


Figure 10. Continuous Interleaved Sampling (CIS) strategy.

COMPRESSED ANALOG (CA) AND SAS

The CA strategy delivers band-specific, amplitude-compressed analog waveforms to different electrode locations in the cochlea. The sound picked up by a microphone is attenuated or amplified by the automatic gain control (AGC) depending on environmental circumstances (e.g. the distance of the talker from the microphone). The signal is then divided into frequency bands by passing a number of band-pass filters. (On Figure 11. there are 4 BPFs) After that the narrow-band signal is compressed in amplitude to match the widely varying acoustic amplitudes to the narrow electric dynamic range. The compressed analog signals are converted to currents and delivered to different electrodes in the cochlear electrode array. All electrodes are stimulated simultaneously. Simultaneous Analog Stimulation (SAS) uses a bipolar stimulation configuration, this way there is less current spread compared to a monopolar configuration.

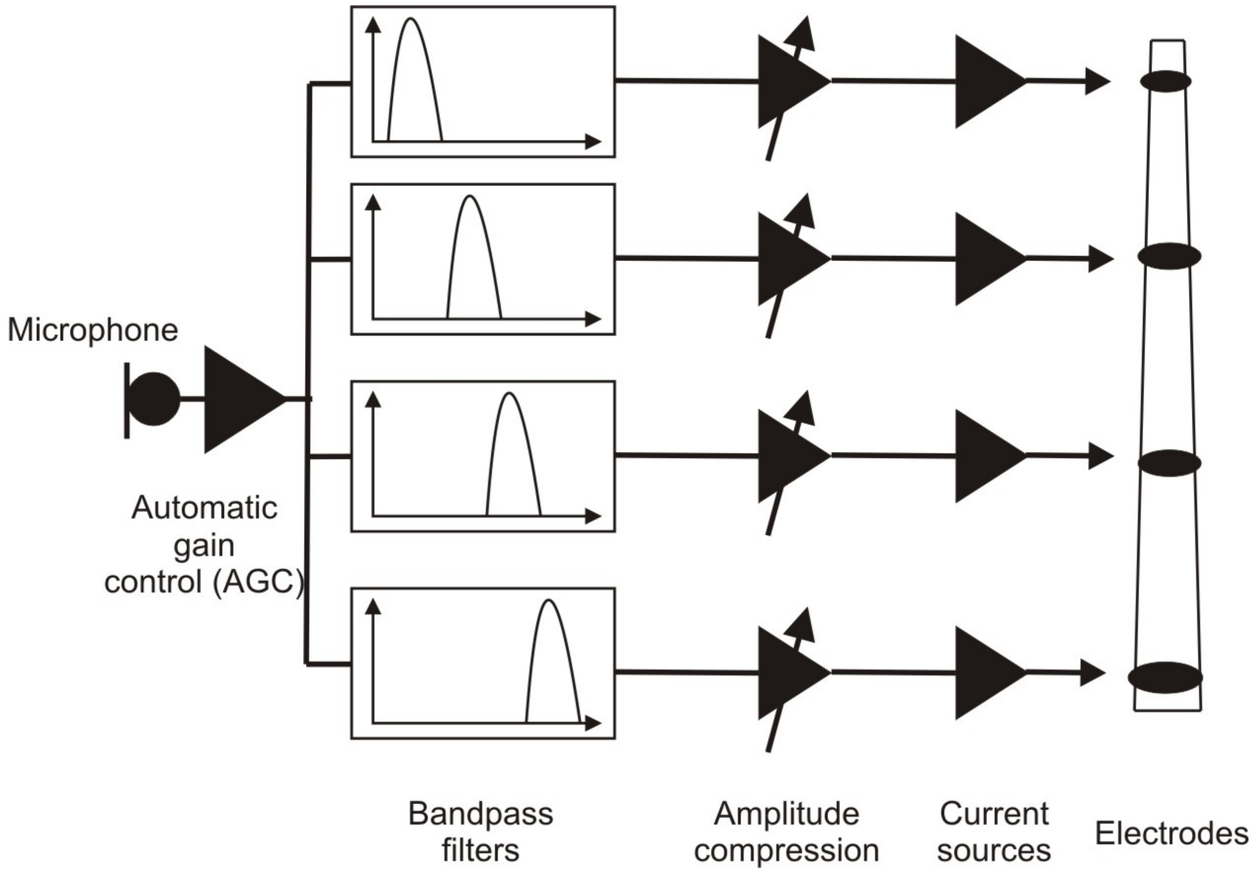


Figure 11. Compressed Analog (CA) and SAS strategy.

F0/F1/F2

In the F0/F1/F2 strategy (Figure 12.) spectral peaks or formants, which reflect the resonance properties of the vocal tract, are extracted and delivered to different electrodes according to the presumed tonotopic relationship between the place of the electrode and its evoked pitch.

The F0 fundamental frequency (below 270 Hz), the first formant (F1, 300-1000 Hz) and the second formant (F2, 1000-3000 Hz) are extracted from the sound signal with the help of zero crossing detectors. Two electrodes are selected for pulsatile stimulation, one corresponding to the frequency of the first formant (5 most apical electrodes) and one corresponding to F2 frequency (remaining 15 electrodes). The pulse rate is controlled by the F0 for voiced segments (F0 pulses/sec) and for unvoiced segments the electrodes are stimulated at a quasi-random rate (with an average rate of 100 pulses/sec). The F0/F1/F2 strategy uses 200 µs long biphasic pulses with 800 µs spacing between the pulses to avoid interaction between different channels.

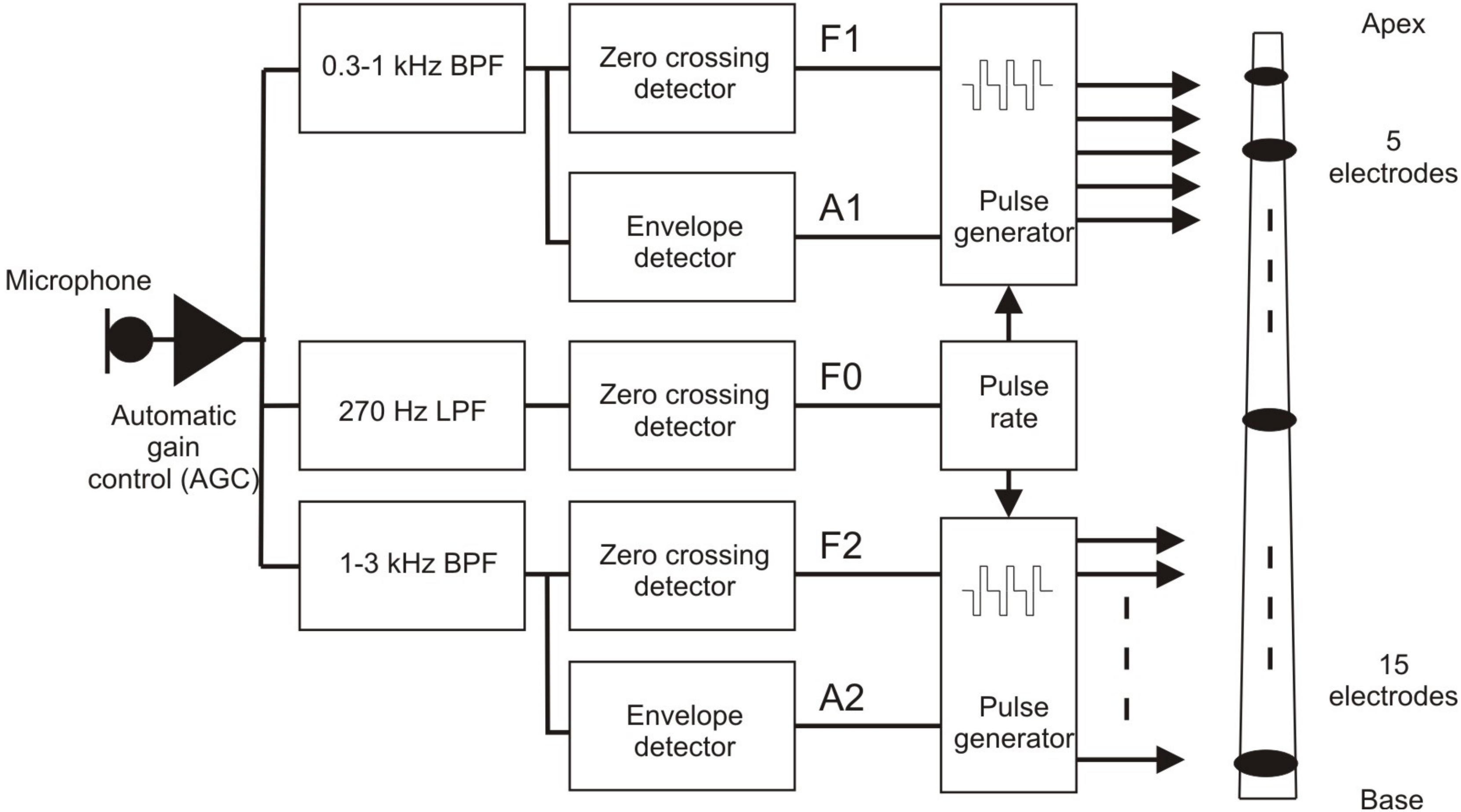


Figure 12. F0/F1/F2 strategy in the Nucleus Wearable Speech Processor (WSP)

MULTIPEAK (MPEAK)

The MPEAK strategy is an improved version of the F0/F1/F2 strategy. Similar to the F0/F1/F2 strategy, F1 and F2 formant frequencies were extracted using zero-crossing detectors and their amplitudes were calculated using envelope detectors. The frequency range of the second formant was changed to 800-4000 Hz. Additional high frequency data is computed in three different frequency bands (2000-2800 Hz, 2800-4000 Hz, 4000-6000 Hz) to enhance the representation of F2 and include high-frequency information (important for perception of consonants). Electrodes 1, 4 and 7 are allocated to the output of these band-pass filters. Four electrodes are stimulated at a rate of F0 in case of voiced segments (F1, F2, electrodes 4 and 7) and at quasi-random intervals for unvoiced sounds (F2, electrodes 1, 4, 7). On Figure 13. you can see a schematic implementation of the MPEAK strategy.

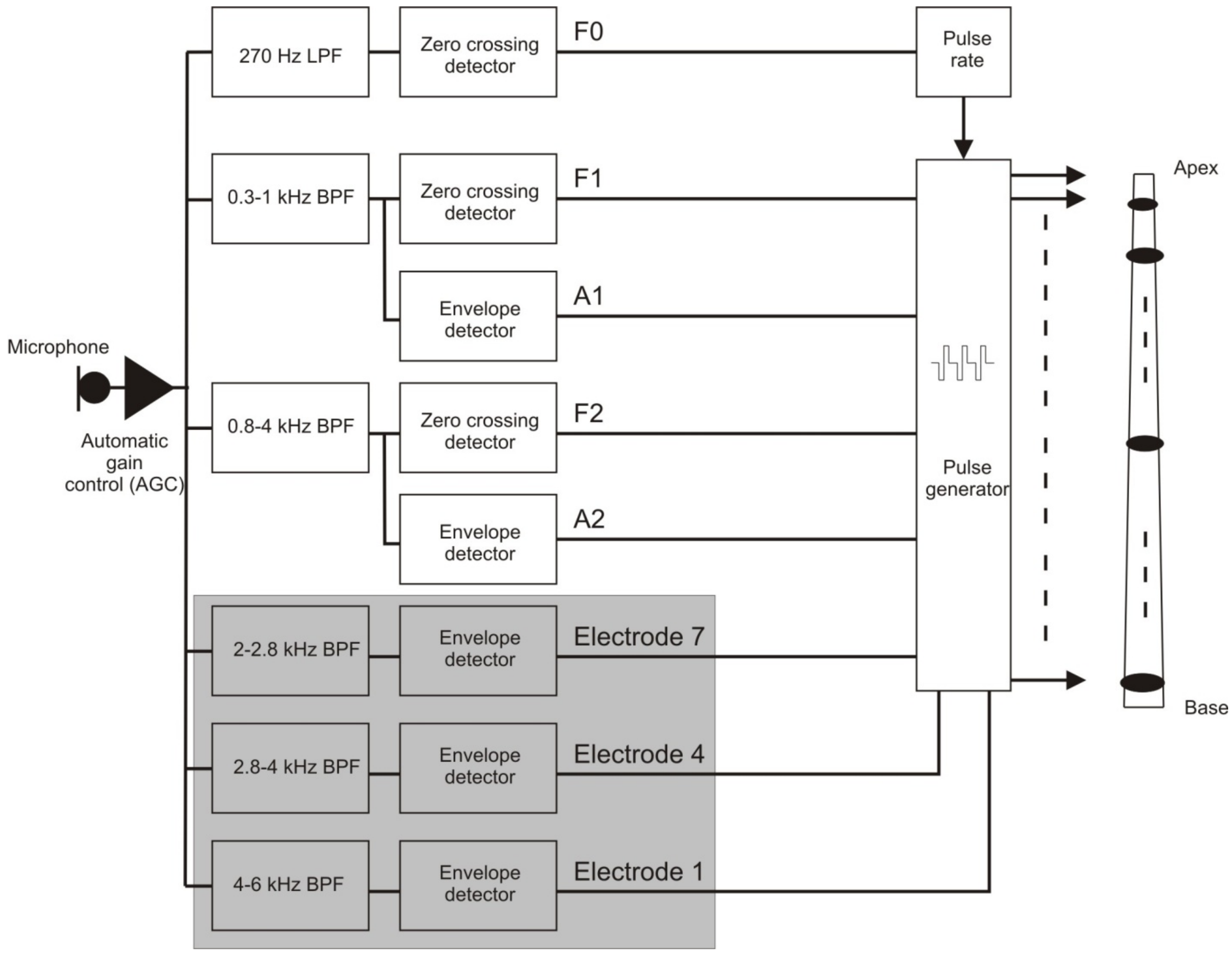


Figure 13. MPEAK strategy in the Cochlear Miniature Speech Processor (MSP)

SPECTRAL MAXIMA SOUND PROCESSOR (SMSP)

The SMSP strategy analysis the speech waveform instead of extracting features from the signal. It uses 16 band-pass filters and a spectral maxima detector. The pre-emphasized signal (preamplified sound signal picked up by the microphone) is processed through the bank of 16 band-pass filters (frequency range from 250 to 5400 Hz). After envelope detection (rectification and 200 Hz low-pass filtering) the six largest envelope outputs are selected for stimulation in 4 ms intervals. The selected amplitudes are logarithmically compressed and transmitted to the six selected electrodes through the RF link. The largest envelopes are not necessarily the spectral peaks, several „maxima” may come from a single spectral peak. Six interleaved (non-simultaneous) biphasic pulses are delivered to the selected electrodes at a rate of 250 pulses/s. On Figure 14. you can see a schematic implementation of the SMSP strategy.

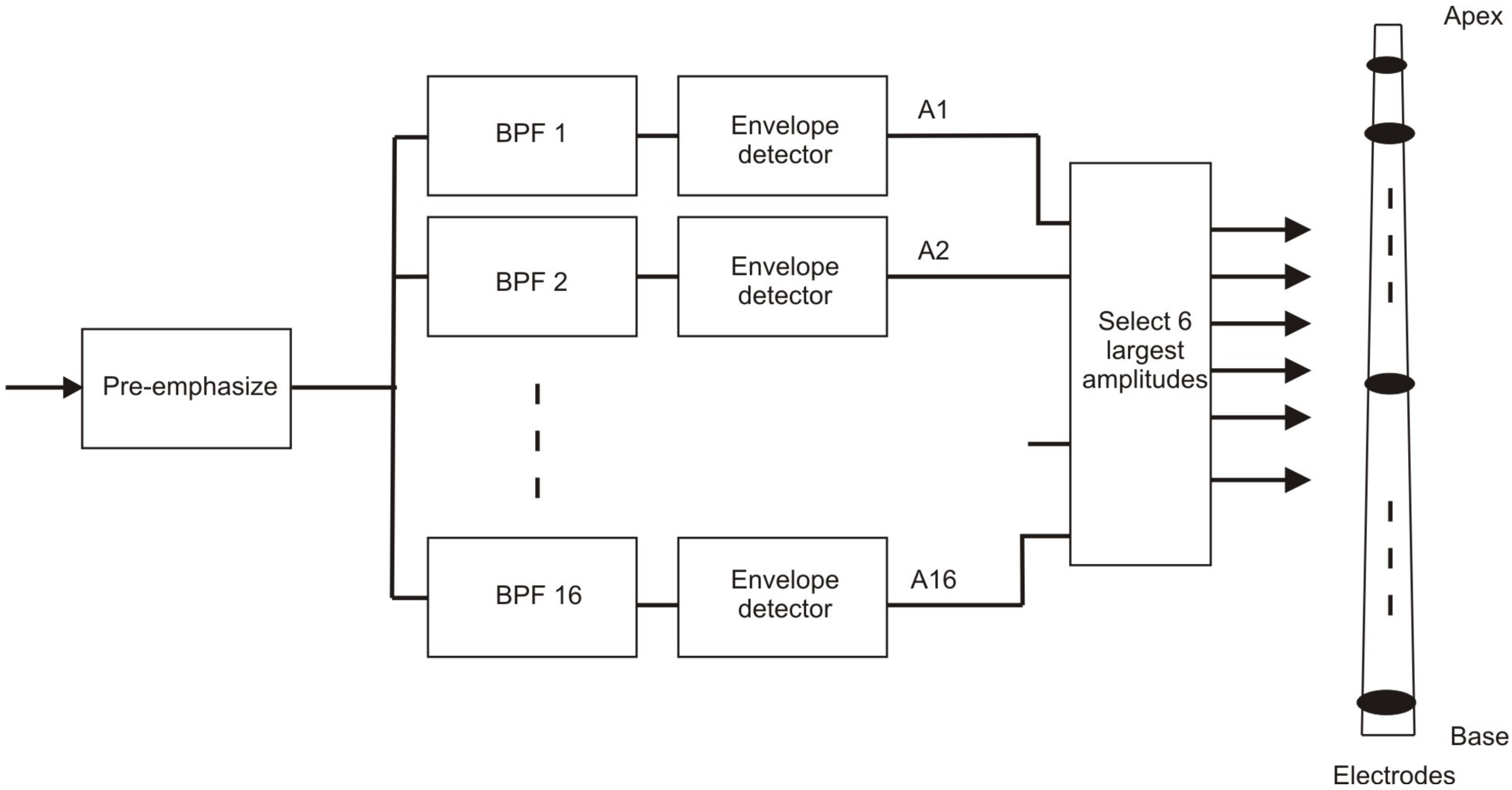


Figure 14. SMSP strategy in the Nucleus Spectral Maxima Sound Processor

„N-OF-M" STRATEGY

The „n-of-m" strategy is the basis of the SPEAK and ACE strategies. It is similar to CIS, there are band-pass filters and the envelope extraction block, but there is greater number of band-pass filters. (e.g., m=22, usually the number of electrode sites). It is based on temporal frames lasting 2.5-4 ms. After band-pass filtering and envelope extraction „n" number of bands with the largest envelope amplitude are selected. After that, the process is the same as by the CIS strategy and only the chosen „n" electrodes are stimulated. The SPEAK strategy selects 6-10 largest peaks and has a fixed 250 Hz per channel rate. The ACE strategy has a larger range of peak selection and higher rate than the SPEAK strategy. If „n" equals „m" then the SPEAK and ACE strategies are essentially same as the CIS strategy. On Figure 15. you can see a schematic implementation of the „n-of-m" strategy.

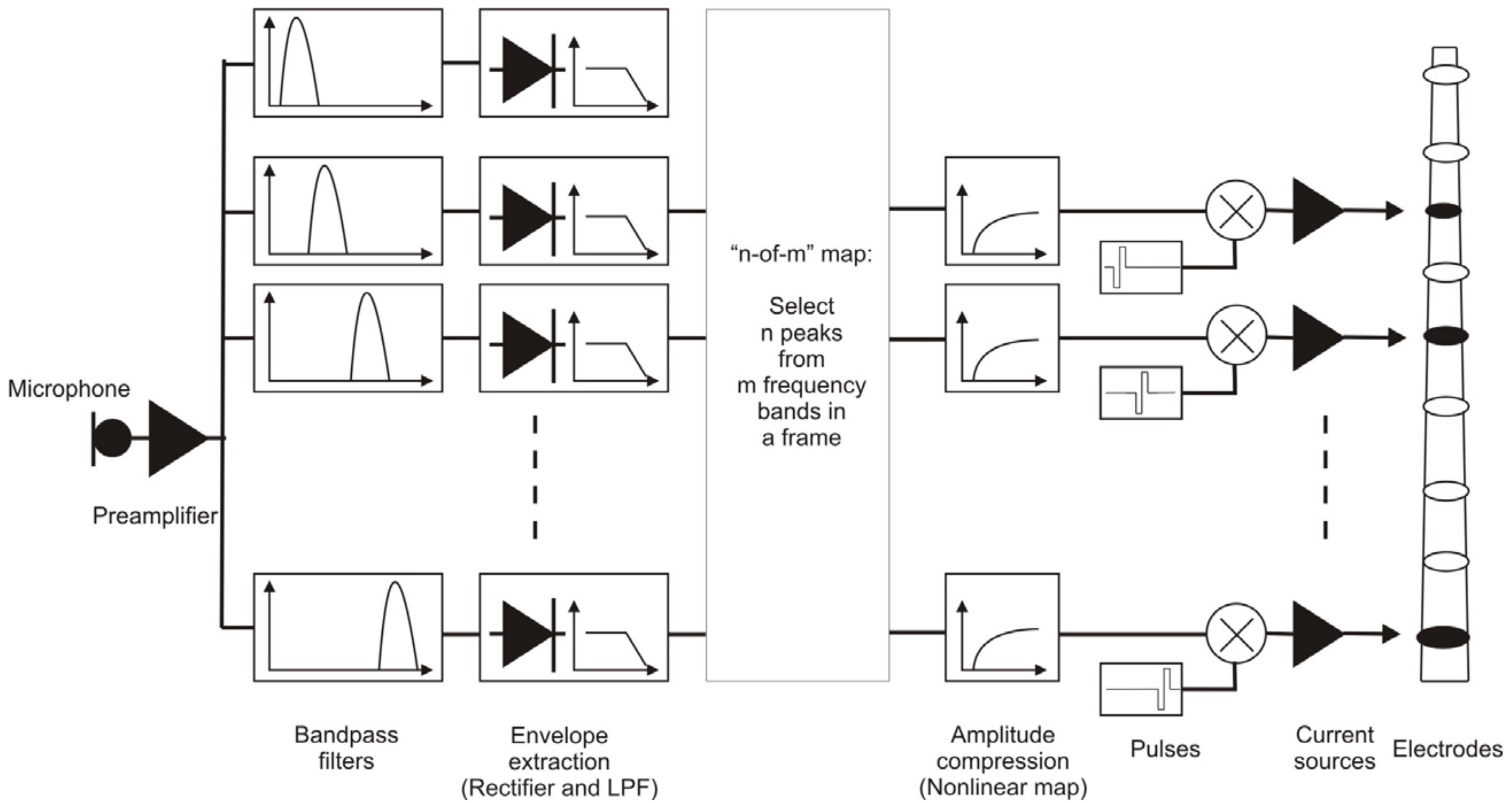


Figure 15. The „n-of-m" strategy

AUDITORY PERFORMANCE OF CI USERS

Auditory performance (AP): the ability to discriminate, detect, identify or recognize speech. We can measure it with the percent correct score on open-set speech-recognition tests.

The auditory performance is affected by several factors for example the number of electrodes used for stimulation(Figure 17.), electrode placement and insertion depth (Figure 18.).

The three-stage model of auditory performance shows the changes of the AP in different time periods of postlingually deafened people (details on Figure 16.).

FACTORS AFFECTING THE PERFORMANCE OF CI USERS

Duration of deafness: has a strong negative effect on auditory performance. Shorter duration of auditory deprivation provides better auditory performance.

Age of onset of deafness: has a major impact on the success of CIs. People with postlingual deafness perform better than people with prelingual or congenital deafness.

Age of implantation: People implanted at an early age seem to perform better than people implanted in adulthood.

Duration of cochlear implant use: Duration of experience with the CI has been found to have a strong positive effect on auditory performance.

Other factors: number of surviving spiral ganglion cells, number of electrodes used (Figure 17.), electrode placement and insertion depth (Figure 18.), electrical dynamic range, signal processing strategy, social support

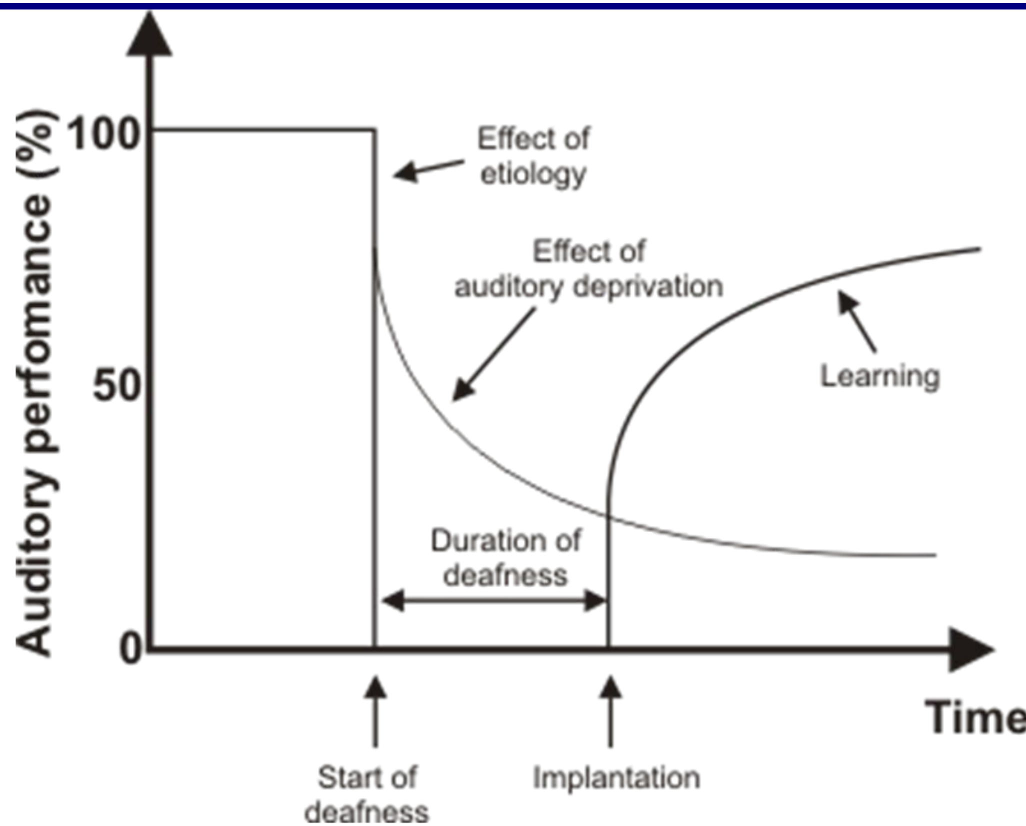


Figure 16. The three-stage model of auditory performance (AP) for postlingually deafened adults. Stage 1 begins after normal language development. (AP around 100%) Stage 2 begins at the onset of deafness. (immediate drop in the AP and a further decrease until implantation) Stage 3 begins with the implantation (increase in the AP, and rises further as a result of learning and experience)

SPEECH PERFORMANCE

With one channel the recognition of sentences is poor, but with four channels, performance is near 100% for simple sentences in a quiet background. (Figure 17.) In noisy backgrounds more channels are required for a high auditory performance. Speech recognition scores increases as a function of the channel number up to 4-8 channels and then asymptotes (no further increase for more than 8 channels, Figure 17.)

The age is extremely crucial for the child’s language and cognitive development, therefore implantations in childhood have very good results. It helps the children to be able to speak clearly and to able to understand speech. Some children might get more benefit form a CI than from a traditional hearing aid. Both prelingually and postlingually deafened children benefit from CI. Prelingually deafened children acquire the speech production and speech perception skills at a slower rate.

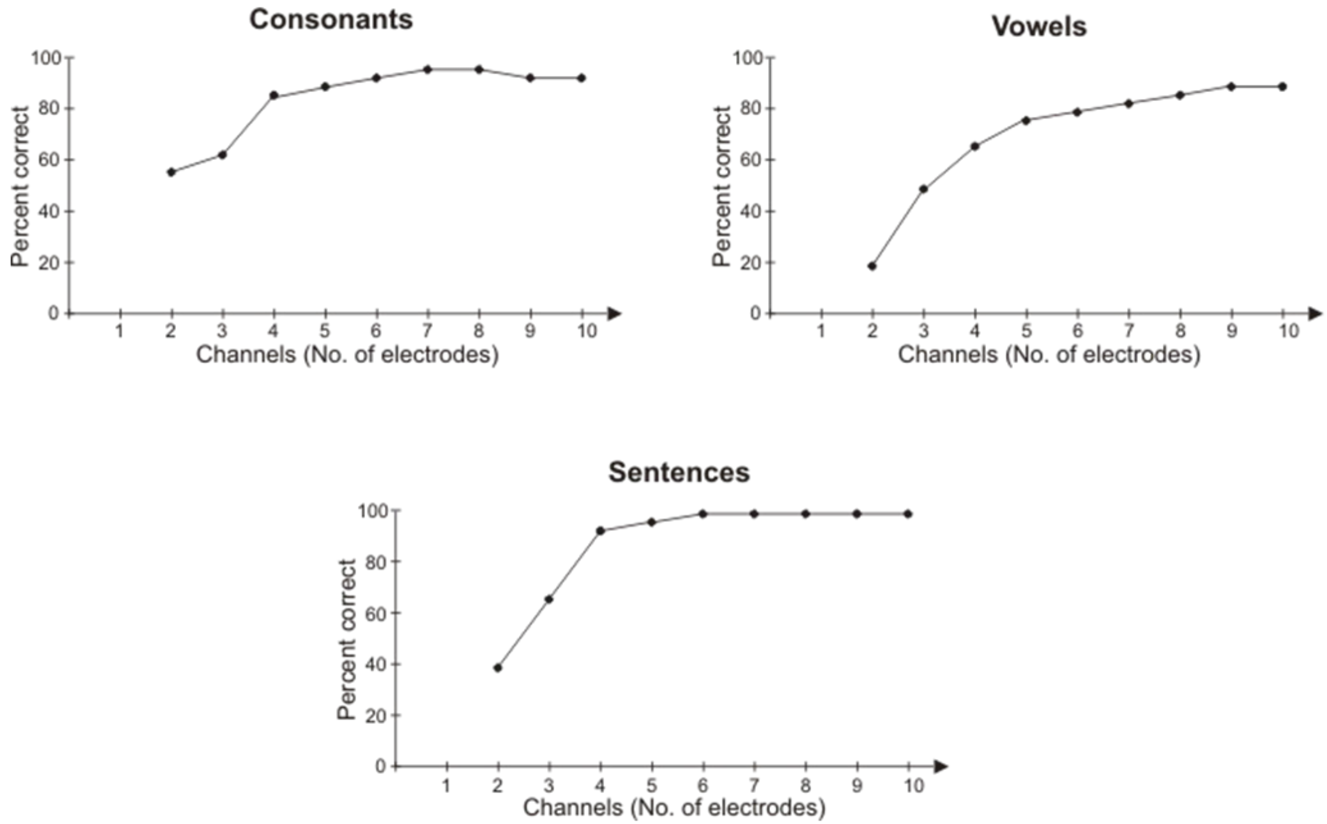


Figure 17. The understanding of speech depending on the number of electrodes. Mean percent correct scores on recognition of consonants, vowels and sentences as a function of number of channels. Very good auditory performance can be obtained with 5-8 independent channels of stimulation.

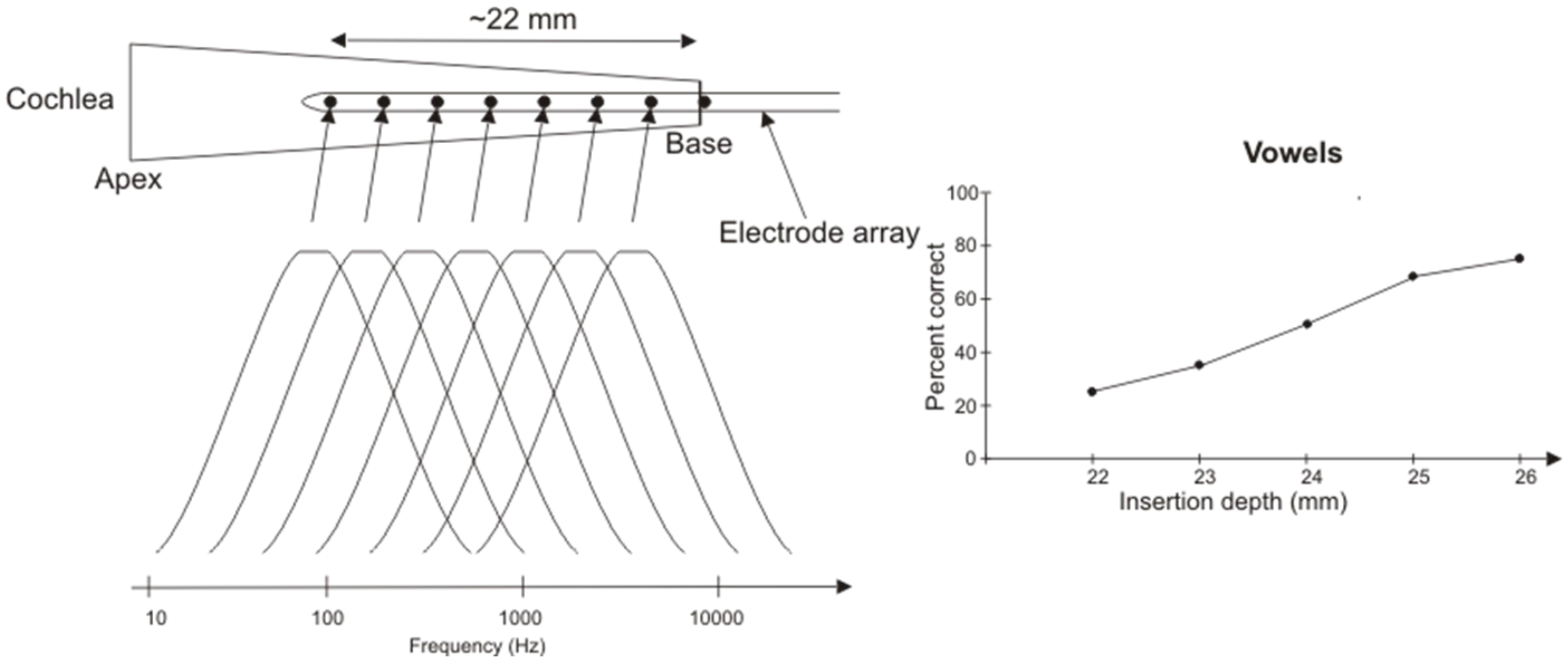


Figure 18. The effect of the insertion depth of the implant on vowel recognition.

THE BIGGEST COMPANIES RELATED TO COCHLEAR IMPLANTS AND THEIR PRODUCTS

Company Name	Company Headquarters	Offered Cochlear Implant (2010)
Cochlear	Australia	Nucleus 5 System
Med-El	Austria	MAESTRO Cochlear Implant System
Advanced Bionics	USA	Harmony HiResolution Bionic Ear System
Neurelec	France	Digisonic SP Cochlear Implant System

MED-EL MAESTRO COCHLEAR IMPLANT SYSTEM

Med-El MAESTRO (Figure 19.) is medical option for individuals with severe to profound sensorineural hearing loss. The system contains features optimized for the appreciation of music and for listening in challenging situations. The MAESTRO CI consists of an internal (CONCERTO, SONATAti100 or PULSARci100) and an external component (OPUS 1 or OPUS 2 with the FineTuner remote control). The internal implant is surgically placed under the skin just behind the ear. It consists of a durable housing, which contains electronics, the a receiving antenna and a magnet, and the electrode array, which is implanted into the cochlea. CONCERTO and SONATA has a titanium housing, while PULSAR is made of impact resistant ceramic and is the world's smallest CI. The external component is an audio processor, which is worn on the ear. It consists of a control unit, a battery pack, and a coil that transmits information through the skin to the receiver in the implant.

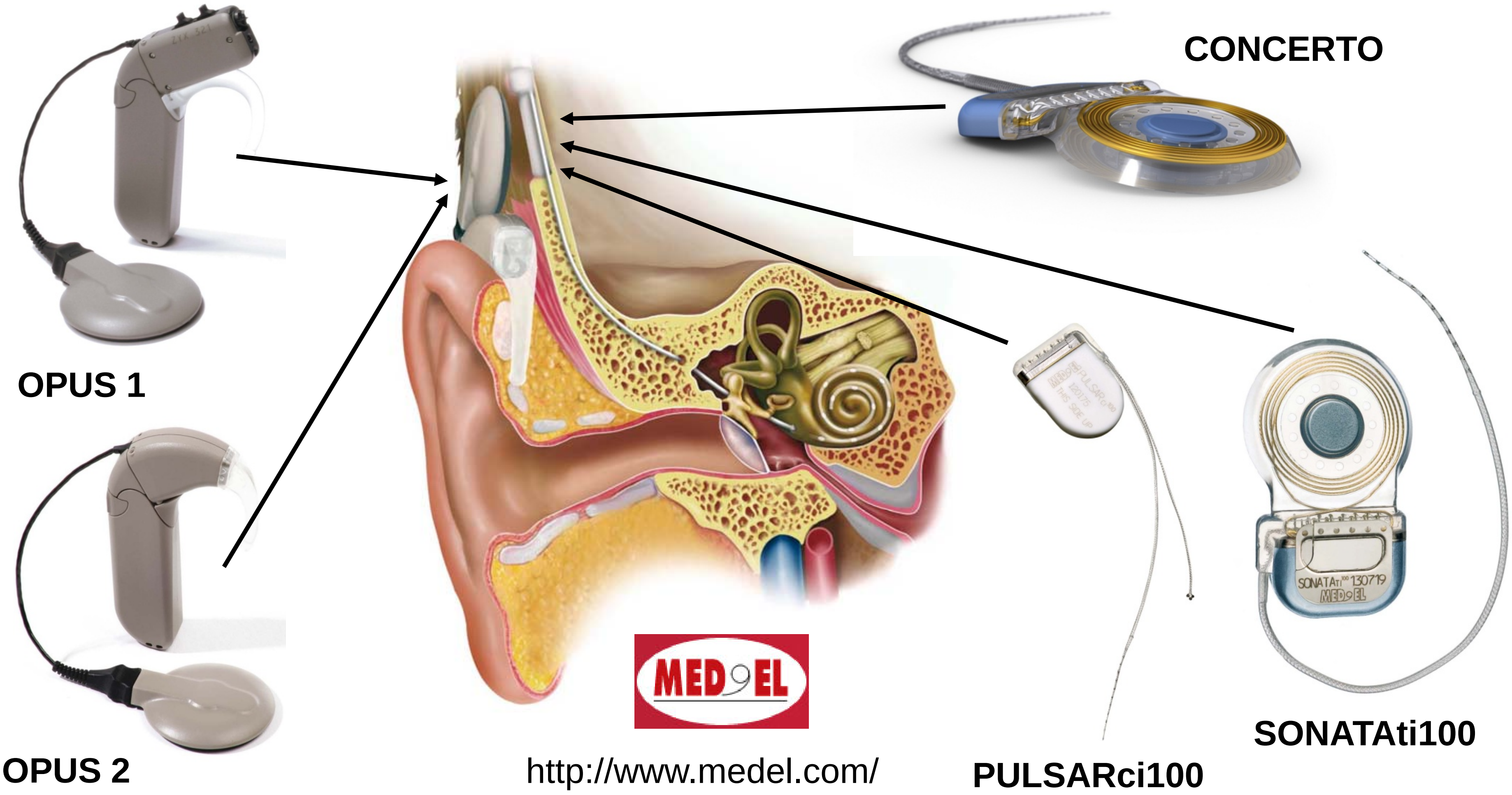


Figure 19. Parts of the Med-El Maestro Cochlear Implant Sytem

MED-EL MAESTRO: FEATURES AND BENEFITS

- **Automatic Sound Management** detects changing listening situations on-the-go, adapting automatically, so the user do not has to.
- **FineHearing** technology introduces a new dimension to musical perception. It processes also the fine details of sound, and provides additional pitch information, especially in the low frequencies, that is essential for the appreciation of music.
- **Complete Cochlear Coverage**: the electrode array is inserted through the entire length of the cochlea. This has the advantage to stimulate also in the apex of the cochlea, where the low frequencies are represented.
- The **FineTuner** remote control allows users to make changes to volume or sensitivity while keeping the processor on the ear. (Only for OPUS 2)
- Built-in **telecoil**, wireless access to **FM, Bluetooth** and **Assistive Listening Devices**.
- Battery life of up to a week.

COCHLEAR NUCLEUS 5 SYSTEM

The Nucleus 5 system (Figure 20.) consists of the Cochlear Nucleus CP810 Sound Processor with titanium foundation (it is the industry's smallest sound processor and the world's most water-resistant sound processor, and supports ACE, CIS and SPEAK sound coding strategies), the Cochlear Nucleus CI512 Cochlear Implant (industry's thinnest titanium cochlear implant), and the Cochlear Nucleus CR110 Remote Assistant (to adjust the sound processor wirelessly). The electrode array has a curved design, with 22 electrodes and with access to 161 intermediate pitches. The stimulation rate is up to 30000 pulses per second and one channel is stimulated at one time. The Nucleus 5 system provides the industry leading hearing performance with the highest speech recognition scores in a multi-center clinical study. It is MRI compatible and compatible with FM systems, can connect to any music and gaming sound source with a headphone jack. It has a battery life around two days.

http://www.cochlear.com/

Figure 20. The Cochlear Nucleus 5 System

COCHLEAR NUCLEUS 5 SYSTEM: FEATURES

- **AutoPhone** for automatic phone detection through auto telecoil. The telecoil automatically activates when a phone is held next to the sound processor.
- The **SmartSound technology's Set It and Go** program automatically adapts to the environment around the user, it intelligently adjusts to fit the unique environments automatically. Set It and Go refines and clarifies sound in different environments for a richer, clearer listening experience. SmartSound technology has also power programs like MUSIC, FOCUS and NOISE.
- **Dual microphone zoom technology** was designed to enhance hearing performance in noisy environments and is a very effective way to improve speech performance in noise.

ADVANCED BIONICS HARMONY HIRESOLUTION BIONIC EAR SYSTEM

The cochlear implant of Advanced Bionics consists of the Harmony BTE (Behind the Ear) Sound Processor and the HiRes 90K Implant with HiFocus electrodes for neural targeting. The HiRes 90K Implant can manage 90K data updates per second, up to 83000 stimulation pulses per second and up 120 bands of spectral information. It has an internal memory, a bidirectional telemetry, and a removable magnet for MRI scans. It supports (together with the sound processor) several sound coding strategies: HiRes-S with Fidelity 120, HiRes-P with Fidelity 120, HiRes-S, HiRes-P, CIS and MPS programming modes. The Harmony sound processor has an electronically integrated telecoil and a battery life around one day. Another two solutions of sound processors are available: the Platinum Series Sound Processor (PSP) is a discreet body-worn processor with the same processing programs as the ear-level processors and the Auria BTE Sound Processor is a lightweight solution for high-resolution sound.

AB HARMONY SYSTEM - FEATURES

- **HiResolution Sound**: It has five times more resolution than any other cochlear implant system.
- **HiRes Fidelity 120:** Offers 120 spectral bands for unsurpassed spectral (pitch) resolution to hear all the colorful details of sound.
- **AutoSound Processing:** Automatically adapts to the users surroundings or continually makes adjustments to keep up with changing sound environments.
- **ClearVoice** is a strategy, built on HiRes Fidelity 120 technology, and is designed to automatically analyze and adapt to each listening situation encountered throughout the day, separating the distracting noises from speech.
- **T-Mic™ Microphone:** the only microphone placed naturally at the opening of the ear for highly focused hearing while providing wireless connectivity to cell phones, MP3 players, and more.
- **Wide IDR** (input dynamic range) enables to hear more sound with less distortion so that it is easier to hear music and make out lyrics and individual instruments.

NEURELEC DIGISONIC SP SYSTEM

The main parts of the Digisonic SP system is the SAPHYR (SAPHYR SP and SAPHYR CX) with two omnidirectional microphones, an auxiliary Ultra-Low Noise socket (connection point to different audio sources and FM systems), a high-precision electronic card and an integrated telecoil. The Double DSP technology assures compatibility with the older generations of implants, while offering four times more sound processing. The sound processor offers 4 programs and a long battery life of several days. Another sound processors from Neurolec are the Digisonic BW and Digisonic BTE. The internal part of the system is the Digisonic SP implant (fixed with screws to the skull during the surgery), which consists of a small ceramic and titanium box and an electrode array with 20 electrodes (inserted 25 mm deep into the cochlea). It supports monopolar or common ground stimulation through biphasic pulses. The stimulation frequency is 24000 pulses per second. The implant is compatible with MRI tests at 1.5 Tesla. Two other type of implants are the Digisonic DX10 and the Digisonic CONVEX.

ELECTRIC ACOUSTIC STIMULATION (EAS)

There is a certain patient group that has some degree of residual hearing in the low frequencies and a severe hearing loss in the high frequencies (partial deafness). They suffer from inadequate speech comprehension, even in the best aided condition. On their audiogram there is no or just a moderate hearing loss visible below 1.5 kHz, but above 1.5 kHz there is a severe to profound sensorineural hearing impairment present. For the treatment of this type of hearing loss Electric Acoustic Stimulation is a good solution. EAS is the use of a traditional hearing aid and a cochlear implant together in the same ear. The hearing aid acoustically amplifies low frequencies (< 1 kHz), while the cochlear implant electrically stimulates the middle and high frequencies (1-8 kHz). The inner ear processes acoustic and electric stimuli simultaneously. The insertion depth of the cochlear implant electrode is between 18-22 mm, to preserve the low-frequency hearing. Med-El offers an EAS Hearing Implant System, with an internal component (SONATA or PULSAR, and FLEX Electrode Array) and an external audio processor (DUET). (Figure 21.)

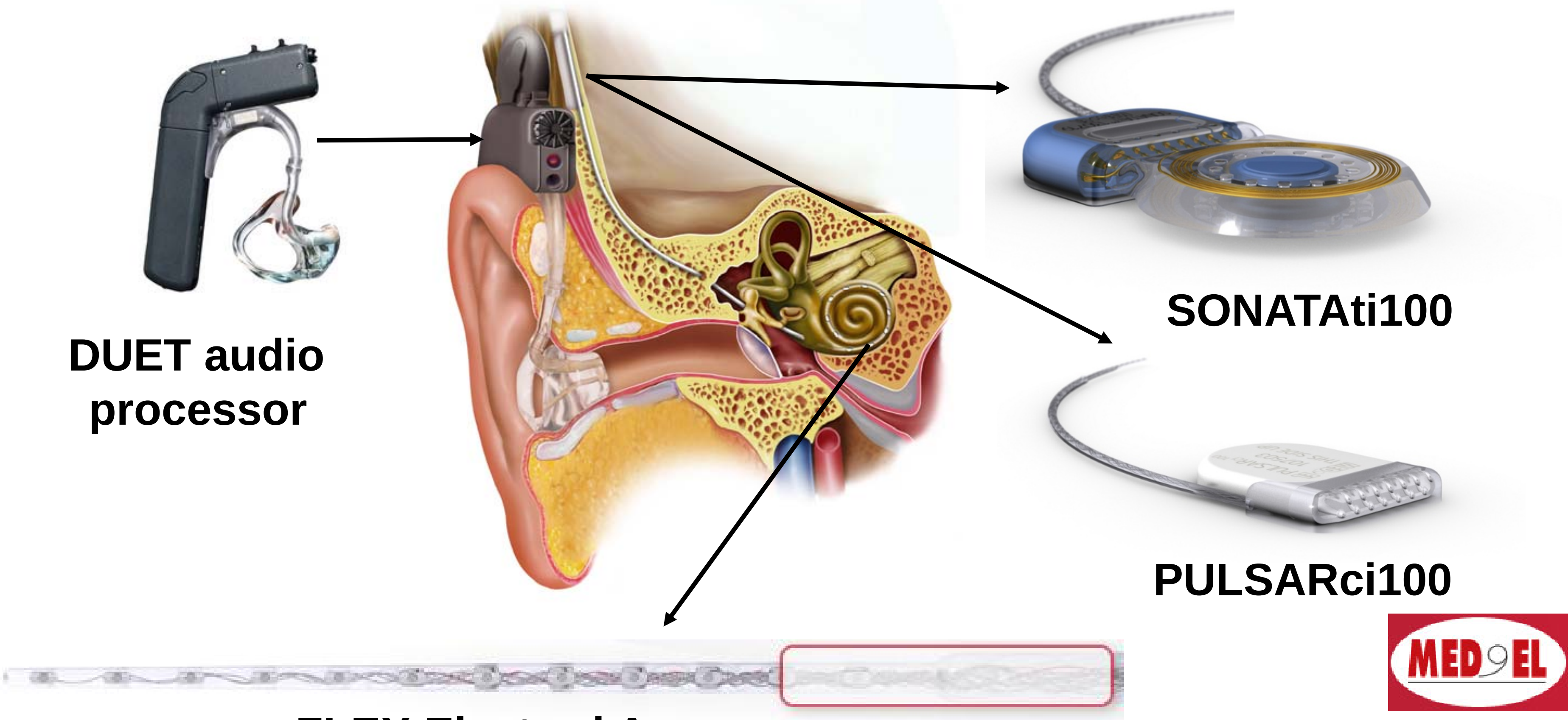


Figure 21. Parts of the Med-El EAS Hearing Implant System

AUDITORY BRAINSTEM IMPLANT (ABI)

Auditory brainstem implants are required when tumors (usually caused by neurofibromatosis type 2 or NF2) involving also the acoustic nerve, have to be surgically removed. The damage of the cochlear nerves results in deafness, and in this case other implantable hearing aids, like cochlear implants or MEIHDs can not be used. ABI bypasses the cochlea and cochlear nerve, and are implanted into the lateral recess of the fourth ventricle adjacent to the cochlear nucleus. It provides the patient with auditory perception by electrically stimulating (bipolar or monopolar) the ventral cochlear nucleus (the cochlear nucleus complex has two parts: the ventral and the dorsal cochlear nucleus) with surface or penetrating electrodes. The ground electrode is placed in the temporalis muscle. The surgery and the implantation of the system is a difficult task, because the cochlear nucleus is hard to approach and the surface electrode array is not easy to fix, but the recently developed multichannel penetrating electrodes make the insertion safer (and also increase the precision of electric stimulation, but they are still in clinical phase).

AUDITORY BRAINSTEM IMPLANT (ABI)

After the insertion, the electrodes with nonauditory responses has to be collected (this are disregarded further on). The remaining electrodes (with auditory responses) are pitch scaled and finally the implant is programmed. ABI provides enough auditory information to facilitate lip-reading abilities and a few are able to achieve open-set (no lip-reading cues) speech understanding.

The companies mentioned in the cochlear implant section have also developed brainstem implants. The Nucleus 24 ABI is solution produced by Cochlear Corporation: their device incorporates an array of 21 platinum disc electrodes (surface electrodes), a microphone headset, a transmitter coil, and a digital speech processor (SPrint) that offers 4 user-selectable programs, as well as programmable volume and sensitivity controls. The processor uses the SPEAK speech coding strategy. Med-El has a 12 electrode array implant with a speech processor based on the C40+ cochlear implant, while Advanced Bionics developed a 16 electrode array implant based on the Clarion-1.2 CI. The solution of Neurolec for people with NF2 is the Digisonic SP ABI.

AUDITORY MIDBRAIN IMPLANT (AMI)

It is the newest method to restore hearing and it is still in experimental stage (clinical trials in 2007). The initial candidates are people with NF2 (like in case of ABI). The AMI is implanted at the same surgical setting when the acoustic neuromas of NF2 patients are removed. The implantation is performed with the help of a 3D intraoperative system with CT and MRI images based on bone-anchored registration method. Electrodes are placed in the inferior colliculus (IC), which lies downstream from the cochlear nucleus along the central auditory pathway and shares with this structure a tonotopic organization. The target is the central nucleus of the inferior colliculus (ICC) but other regions like the lateral lemniscus and the dorsal cortex of the IC were also implanted. The AMI has the advantage of bypassing the cochlear nucleus at the pons, which may be damaged by tumor growth. A disadvantage is a potentially more complicated surgical approach. The IC consists of a well-defined laminated organization and because these laminae correspond to different frequency layers it also has a well-defined tonotopic organization.

AUDITORY MIDBRAIN IMPLANT (AMI) - PARTS

A penetrating electrode array has been developed in collaboration with Cochlear Corporation, which consists of a single pin with 20 platinum ring electrodes linearly spaced at intervals of 200 micrometers. The contact sites have a width of 100 μm. The single-shank multi-site array is designed according the dimensions of the human IC with the goal of stimulating the different layers of the ICC. The ring electrode has a diameter of 0.4 mm and is 0.1 mm wide. It is positioned along the tonotopic gradient of the ICC. The electrode sites connected to a parylene-coated 25 um thick platinum-iridium wire. The Dacron mesh anchors the electrode array onto the surface of the neural tissue and also prevents overinsertation into the IC. The other components of the AMI are similar to a cochlear implant: an external unit with a processor and a behind-the-ear (BTE) microphone and an implanted receiver-stimulator internal unit. The AMI uses lower stimulation current values compared to cochlear implants.

AUDITORY MIDBRAIN IMPLANT (AMI) – RESULTS

Three patients were implanted with AMI. SPEAK and ACE strategies were used for stimulation, with a pulse rate of 250 pps, a pulse width of 100 μs and monopolar configuration. All three patients have obtained hearing benefits from the AMI on a daily basis. There were improvements in lip-reading capabilities and environmental awareness. They could detect temporal changes in the stimulus and differences in pitch percepts depending on the stimulated site (in ICC lower pitch percepts more superficially and higher pitch percepts in deeper regions). One patient obtained 50% correct for vowels, 20% for consonants and 40% for numbers with AMI alone.

WEBPAGES OF COMPANIES RELATED TO IMPLANTABLE HEARING AIDS

- www.cochlear.com
- www.medel.com
- www.advancedbionics.com
- www.neurelec.com
- www.oticonmedical.com
- www.envoymedical.com
- www.otologics.com
- www.ototronix.com

LINKS RELATED TO HEARING AIDS

Cochlear implants and EAS:

http://hear-it.org/page.dsp?page=352

http://emedicine.medscape.com/article/857164-overview

http://en.wikipedia.org/wiki/Cochlear_implant

http://en.wikipedia.org/wiki/Electric_Acoustic_Stimulation

ABI:

http://en.wikipedia.org/wiki/Auditory_brainstem_implant

http://www.youtube.com/watch?v=x6tkE97QrY8

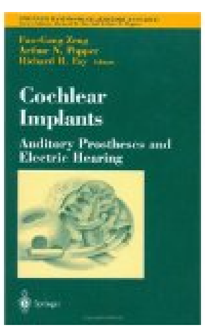
http://www.asha.org/Publications/leader/2011/110315/Auditory-Brainstem-Implants.htm

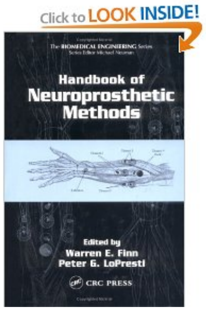
AMI:

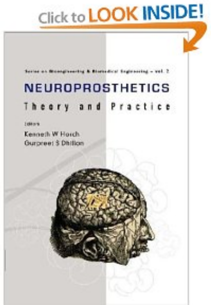
http://www.ncbi.nlm.nih.gov/pubmed?term=auditory%20midbrain%20implant

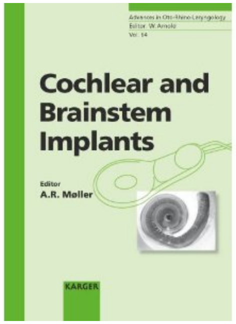
RECOMMENDED LITERATURE

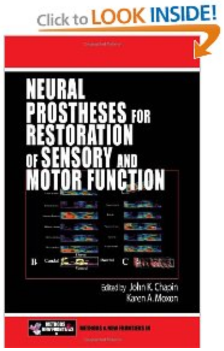
- **Cochlear implants: Auditory Prostheses and Electric Hearing**; Fang-Gang Zeng, Arthur N. Popper, Richard R. Fay; 2004; Springer
- **Handbook of Neuroprosthetic Methods**; Warren E. Finn, Peter G. LoPresti; 2003, CRC Press
- **Neuroprosthetics: Theory and Practice**; Kenneth W. Horch, Gurpreet S. Dhillon; 2004; World Scientific Publishing
- **Cochlear And Brainstem Implants (Advances in Oto-Rhino-Laryngology)**; A.R. Møller; 2006; Karger
- **Neural Prostheses for Restoration of Sensory and Motor Function**; John K. Chapin, Karen A. Moxon; 2000; CRC Press
- More than 500 books related to cochlear implants on www.amazon.com











REVIEW QUESTIONS

- In which way can a cochlear implant (CI) provide hearing sensations?
- What is the working mechanism of CIs?
- What are the main parts and coding strategies of cochlear implants?
- Choose one of mentioned speech coding strategies and describe it!
- What is the difference between sequential and simultaneous stimulation?
- What is the difference between monopolar and bipolar stimulation?
- What is three-stage model of auditory performance?
- How is the speech performance affected by the electrode insertion depth or the number of electrode sites?
- Choose one of mentioned up-to-date CIs and describe it!
- To whom is the EAS system recommended? And the ABI? And the AMI?