Cochlear Implants

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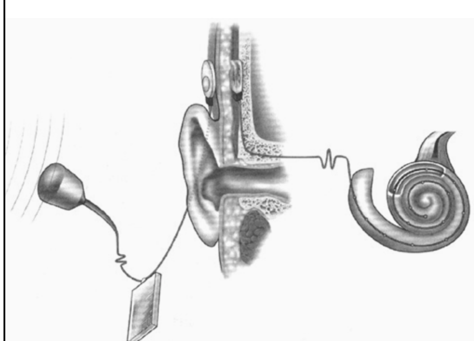
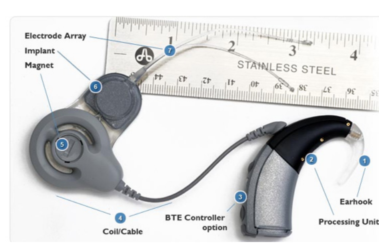
Blake S. Wilson & Michael F. Dorman (2008) Cochlear implants: Current designs and future possibilities. *J Rehab. Res. & Dev.* 45:695–730.

Hubert H. Lim, Minoo Lenarz, & Thomas Lenarz (2009) Auditory midbrain implant: A review. *Trends in Amplif.* 13:149-180. Also *Hearing Res.* (2015) in press.

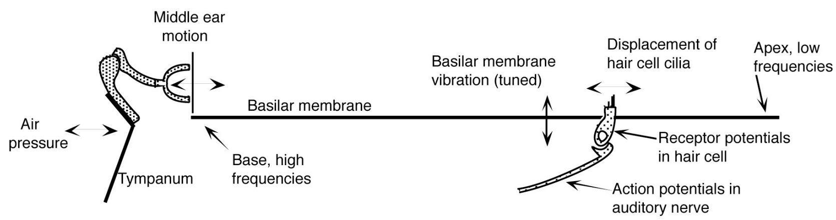
Components of a current cochlear implant system



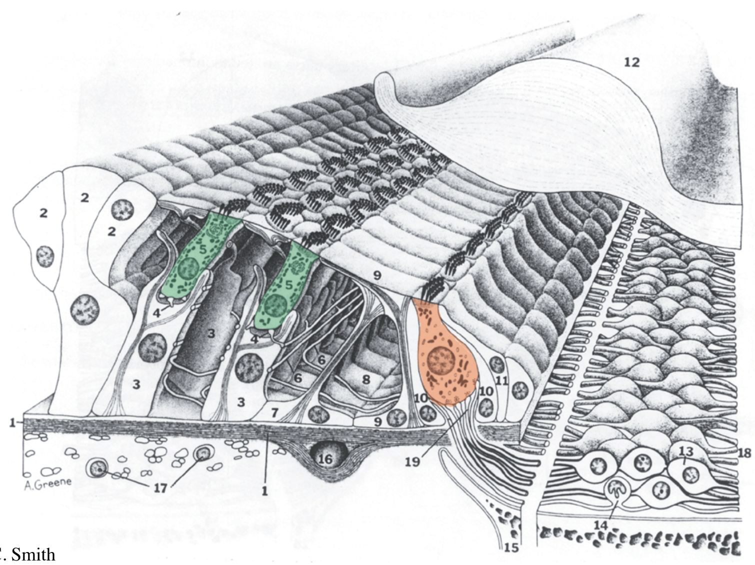


Wilson 2000; Cochlear Corp. website, 2007.

The steps in cochlear transduction:

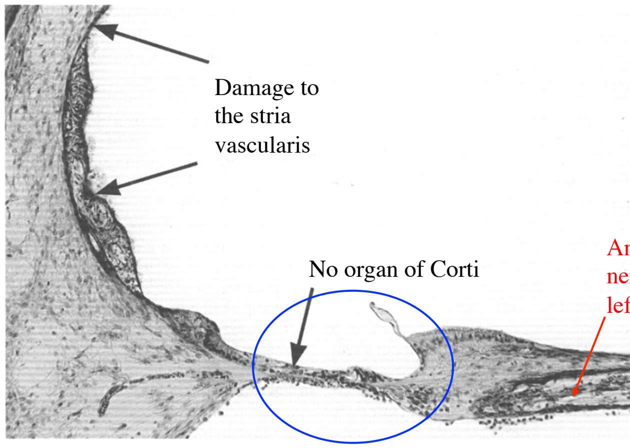


Inner and outer hair cells: outer hair cells amplify BM displacement; inner hair cells are the transducers for ANFs



C. Smith

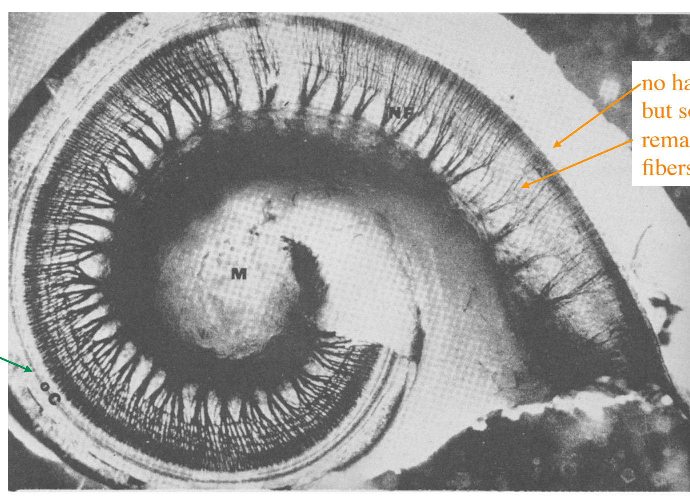
Here, we are concerned with cochleae whose hair cells have been destroyed by some pathological process, in this case Meniere's disease. The underlying pathology can be in the hair cells themselves or in other cells in the cochlea (the *stria* in this case), but the effect on hearing depends on the direct or indirect damage to the hair cells.



Ng et al. 2000

Fortunately, the auditory nerve fibers often survive the loss of hair cells. Typically 10-70% of fibers survive (depending on how long since the hair cells were lost)! The idea of a cochlear implant is to electrically stimulate these remaining fibers.

The basal turn of the cochlea of a 93 year old man with considerable hair-cell loss

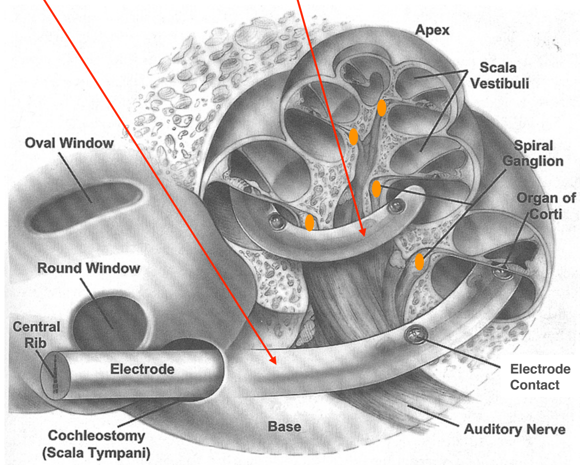


Bredberg, 1968

The main practical technical challenge is the coiling of the cochlea.

It is necessary to design a bundle of electrodes that can be inserted through the round window into scala tympani pushed as far up the cochlear coil as possible.

Two problems: how to avoid damaging the remaining cochlea, especially the nerve; and how to stimulate fibers in the apex, where the electrode won't reach.



Orange ellipses are the locations of spiral ganglion cell bodies (auditory nerve fiber cell bodies).

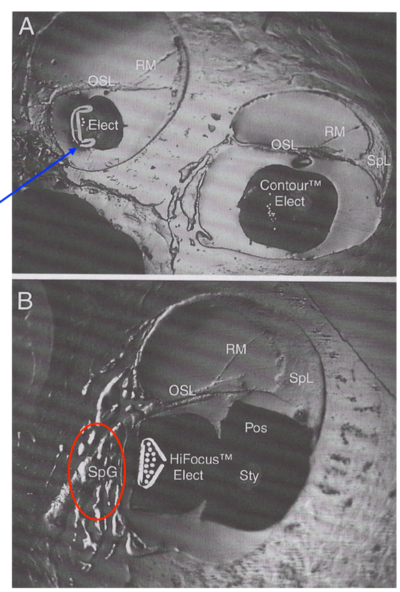
Loeb, 1985

Examples of sections of the scala tympani of human temporal bones (post mortem), showing electrodes in typical positions. In this case, a positioner (*Pos*) was used to place the electrode near the spiral ganglion (*SpG*).

Multiple electrode wires can be seen, along with an electrode contact.

(Positioners have turned out to do damage to the bone of the cochlea and to not improve stimulation much, so they are no longer used.)

Given that such electrode implants can be done; how should the acoustic stimulus be encoded in this device?

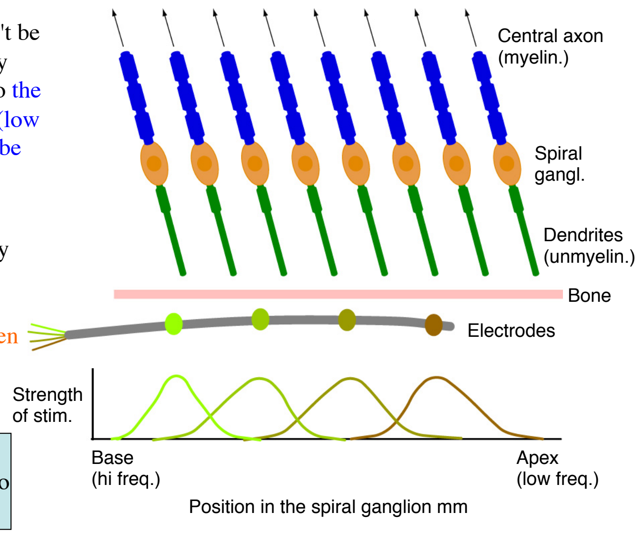


Leake and Rebscher, 2004

Coding issues in implants reduce to how the stimulus is applied to the fibers and how independently different fibers can be activated.

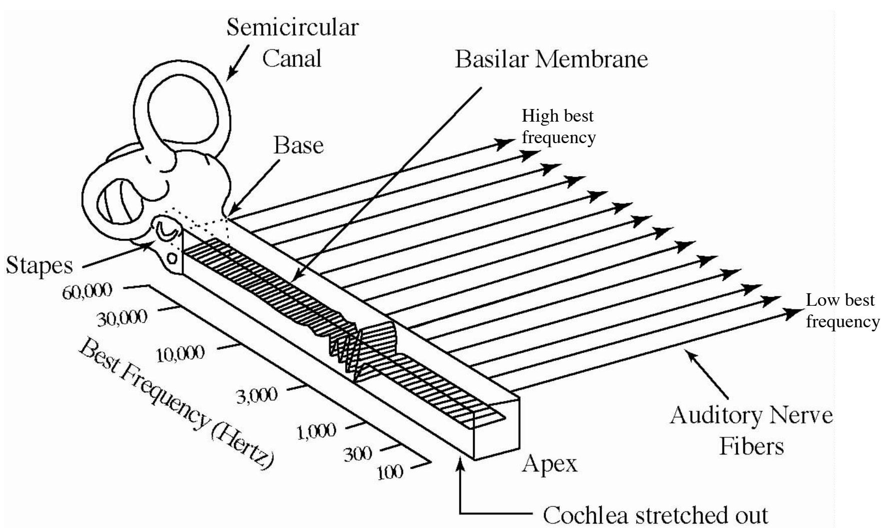
This schematic sketch shows the problems:

1. The electrodes can't be inserted all the way into the cochlea, so the most apical fibers (low frequencies) can't be stimulated.
2. The electrodes are embedded in a very conductive fluid chamber causing interactions between electrodes.

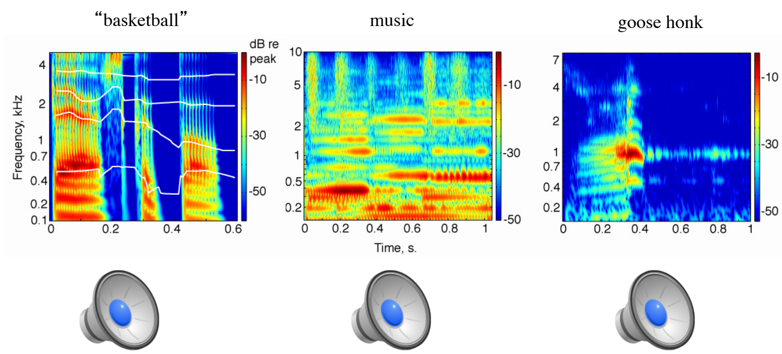


#2 limits the number of independent electrodes to about 8.

The most successful approaches to cochlear implant designs have attempted to reproduce the normal patterns of activity in the cochlea in response to sound. This means the *tonotopic organization* of the basilar membrane and auditory nerve.



Sounds are complex patterns in time and frequency. These are illustrated by the spectrum plots below. Both the distribution of energy across frequency and the fluctuations in energy with time are important to sound perception.

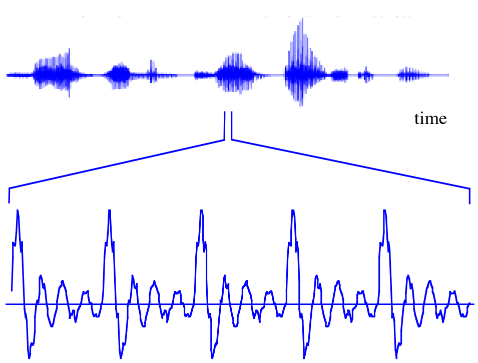


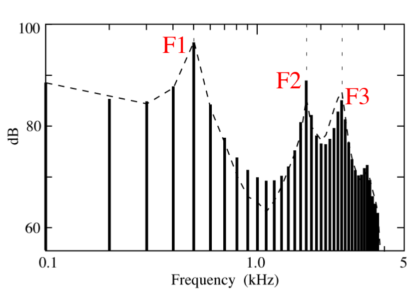
X-axis - time

Y-axis - frequency, using a scale similar to the cochlea

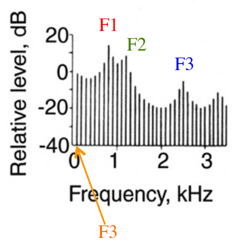
Z-axis - signal intensity in dB = $20 \log_{10} P$

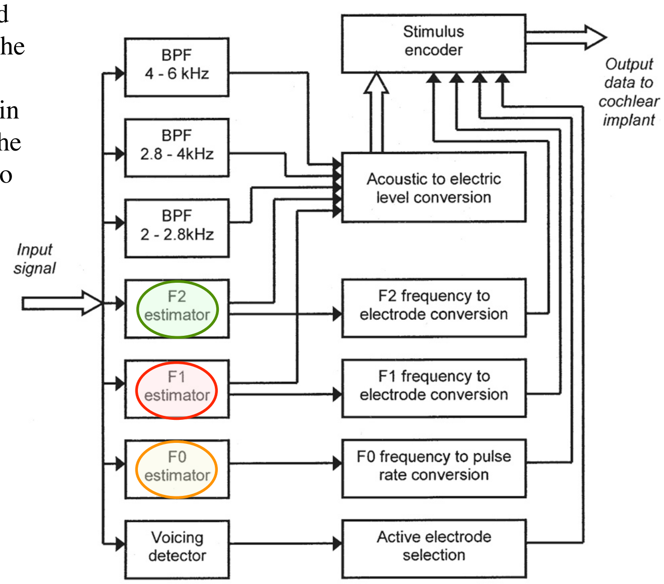
The frequency content of speech changes constantly in time. In the example below, the sentence “Five women played basketball” is shown in the time domain (left). A portion of the time waveform of one vowel (pl<u>ay</u>ed) is expanded at bottom left. At right is the frequency content of the signal during that vowel (magnitude of the Fourier transform). The formant frequencies are marked.





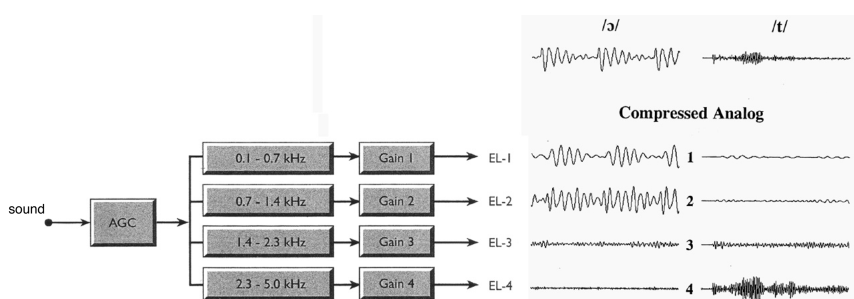
A cool idea that turned out bad: coding both the general frequency content of the sound (in the first 3 channels), the frequencies of first two formants F1 and F2, and the voice periodicity (F0).





McDermott, 2004

A better approach to CI encoding was the *compressed analog* (CA) strategy, which uses a bank of bandpass filters to separate the sound by frequency. Electrodes are then stimulated directly by the electrical signals at the outputs of the filters. Presumably this should reproduce something like the temporal patterns of of the stimuli within each frequency band.



Electrode interaction is a severe limitation on the performance of the CA processor.

electrical stimuli to the electrodes

B. Wilson, 2000

The current state of the art in implants is some version of the CIS (*continuous interleaved sampling*) design. It consists of

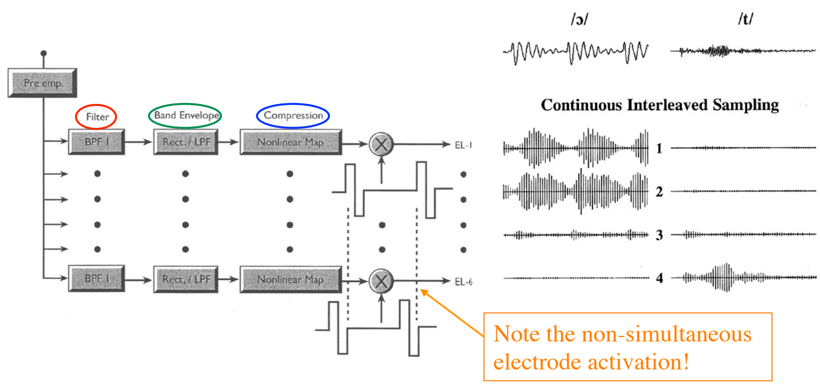
A bank of bandpass filters that do a tonotopic analysis of the speech.

Rectification to extract the *envelope* of the signals from the filters.

The envelope sets the amplitudes of bipolar electrical pulses on the electrodes.

Compression is done in mapping the envelope to the pulse amplitudes.

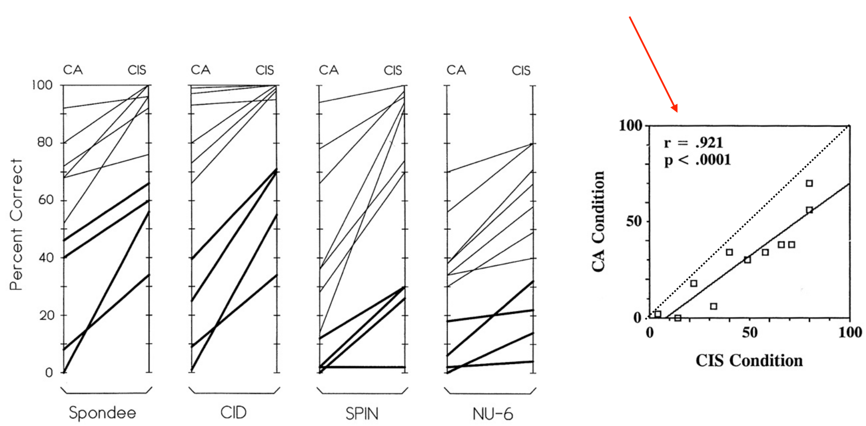
Stimulation is done at a very high rate (>400 Hz, can be over 1 kHz), but non-simultaneously on the different electrodes to reduce electrode interaction.



B. Wilson, 2000

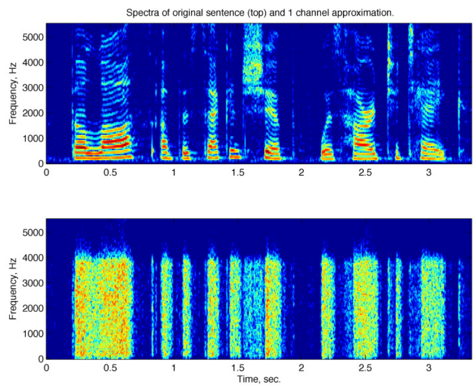
How well do cochlear implants work? The data below are from 11 pretty-good implant users, comparing CA and CIS protocols. The tests are various measures of word recognition that vary in difficulty. The CIS does better, demonstrating the importance of avoiding electrode interactions.

Note the variability among subjects, typical of cochlear implant users.



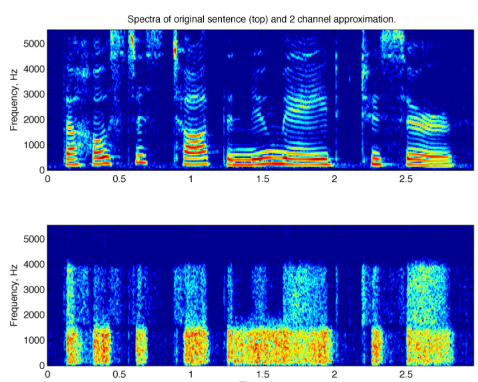
Wilson et al. 1993, 1995

What does a cochlear implant sound like to the user? Below is a simulation of a 1-channel implant.

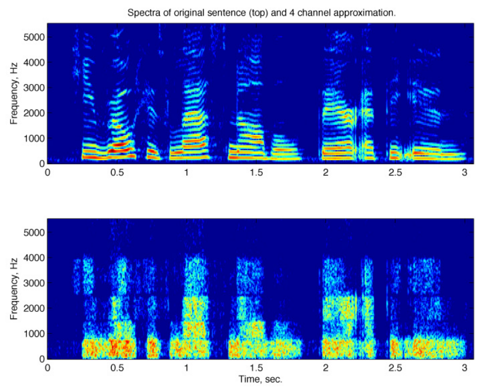


The .wav files of these sentences are on-line on Web-CT.

2 - channels



4 - channels



Additional demos that illustrate the differences between cochlear encoding of speech versus music are available at http://research.meei.harvard.edu/chimera/index.html.

Some facts to ponder:

1. The implants can't be inserted all the way into the cochlea. This means that low frequencies can't be connected to the lowest-frequency auditory nerve fibers. Apparently the brain can overcome this problem.
2. Cochlear implants typically have fewer than 8 functional channels (although they may have as many as 22 electrodes). The normal human cochlea has 3,000 inner hair cells and 30,000 auditory-nerve fibers. There are 14-19 independent channels (critical bands) in the speech frequency range. Why do implants work with so few channels?
3. A big difficulty in implant design is electrode interaction, i.e. different electrodes stimulate overlapping populations of fibers. This limits how many independent electrodes there can be. Strangely bipolar electrode arrangements don't improve performance.
4. The implant doesn't activate fibers "naturally". Fibers usually discharge randomly and don't fire at rates above ~200 Hz. Would it make implants better if they activated fibers more normally?
5. Plasticity in the central auditory system is essential. This means counteracting degeneration of central circuits. It can take 1-2 years to “learn” to use a cochlear implant.
6. Implants only work for speech if the subject has adequate language. Thus persons who lost their hearing after learning language do much better than those who were deafened very early or were born deaf.
7. In many situations (e.g. background noise), we are helped by being able to compare the stimuli at two ears. Current CIs don't do that. Would it help if they did?

Some frontiers:

Music currently sounds horrible through an implant (e.g. Shannon's music demos at http://www.hei.org/research/shannon/simulations/. Music plus the difficulty of hearing speech in noise are the biggest problem CI users have.

Binaural hearing is essential to sound localization and noise reduction (demasking) in environmental situations. So far few subjects have been implanted binaurally, but the technical problems of designing a CI for binaural use are difficult (especially for ITDs, but also for ILDs given compression).

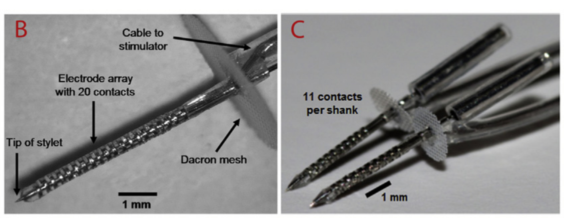
Is electrical stimulation the best way? Recent work is exploring using pulses of infrared light to directly stimulate the nerve (with heat). This approach might solve the problem of electrode interaction. Another idea is to engineer light-activated ion channels into remaining auditory-nerve fibers to allow light activation.

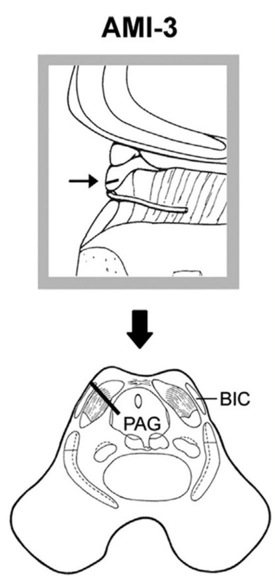
Some CI candidates have residual low-frequency (<250 Hz) hearing. A short implant can be put in the basal cochlea to provide high-frequency information without damaging the acoustic hearing at low frequencies. Such mixed-mode implants often work quite well.

Some CI candidates have cochleas that can't be implanted or no surviving auditory nerve. For such candidates, implantation in the brainstem is necessary.

Electrodes can be implanted into the cochlear nucleus or, as here, in the inferior colliculus. The electrodes are penetrating with 22 contacts on rings around their circumference (below). An example of a successful placement into the inferior colliculus is shown at right.

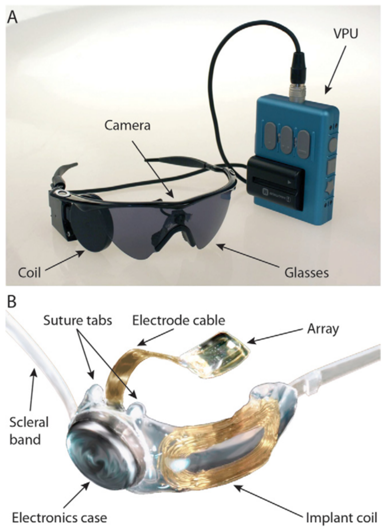
So far, results are not as good for central as for a cochlear implantation, presumably because of the complexity of stimulus coding in central nuclei.

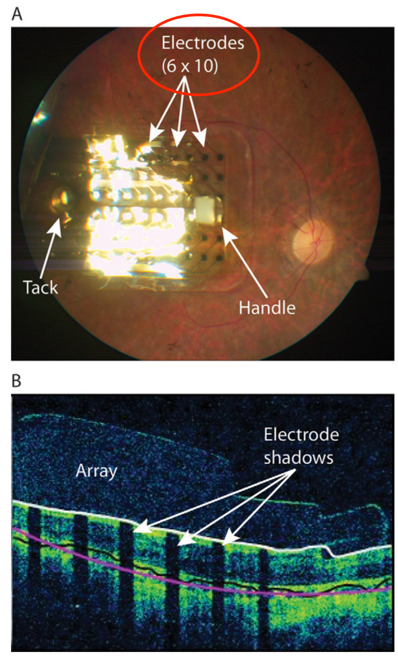




Lim and Lenarz, 2015

Retinal implant ("Second Sight") currently tested on ~30 patients.

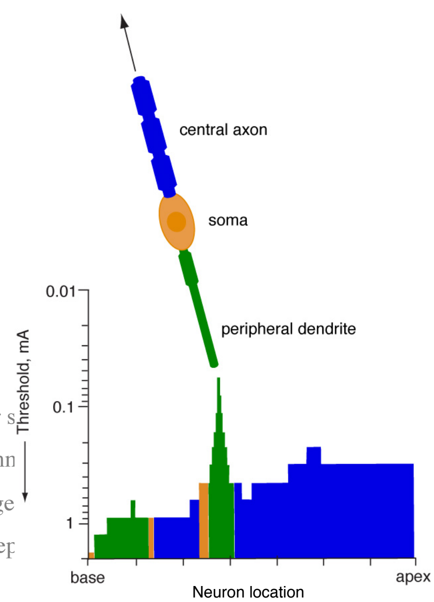




Design issues:

1. What is the site of initiation of the action potential? Computations of current spread from an electrode show that the fiber may be excited at several sites, because of the complex geometry of the cochlea. The lowest threshold site is on the peripheral dendrite. Note that higher threshold stimulation extends most of the length of the cochlea.

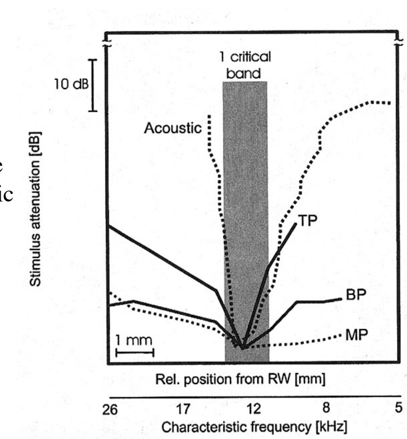
2. Monopolar versus bipolar versus tripolar s
3. Monophasic versus biphasic versus asymn
4. Mapping of thresholds and dynamic range
5. Rate and place pitch - two different percep



after Frijns et al. 2001

Design issues:

1. What is the site of initiation of the action potential?
2. Monopolar versus bipolar versus tripolar stimulation? Bipolar electrode coupling gives a more confined electric field in the cochlea and increases the extent to which electrodes activate different populations of neurons. Tripolar is even better. Strangely, BP and TP stimulation don't improve implant speech performance.

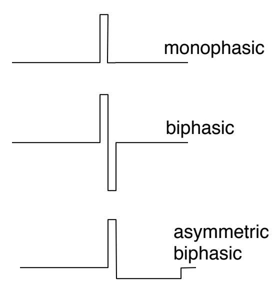


3. Monophasic versus biphasic versus asymmetric monophasic.
4. Mapping of thresholds and dynamic ranges.
5. Rate and place pitch - two different perceptual aspects of the stimulus.

Snyder et al. 1990

Design issues:

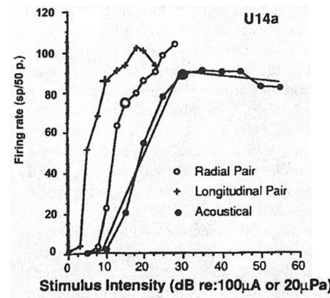
1. What is the site of initiation of the action potential?
2. Monopolar versus bipolar versus tripolar stimulation?
3. Monophasic versus biphasic versus asymmetric monophasic. The net charge passed by the electrode must be zero, so that monophasic stimulation is not possible, even though it gives lower thresholds. Asymmetric biphasic pulses have also been tried.



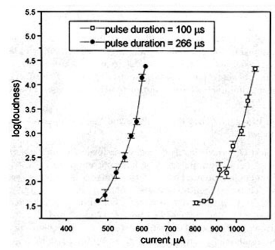
4. Mapping of thresholds and dynamic ranges.
5. Rate and place pitch - two different perceptual aspects of the stimulus.

Design issues:

1. What is the site of initiation of the action potential?
2. Monopolar versus bipolar versus tripolar stimulation?
3. Monophasic versus biphasic versus asymmetric monophasic.
4. Mapping of thresholds and dynamic ranges. At right are dynamic ranges for cortical neurons (top) and loudness in a CI patient (bottom). Note the compression of dynamic range, requiring gain control circuitry.



Raggio and Schreiner 1994



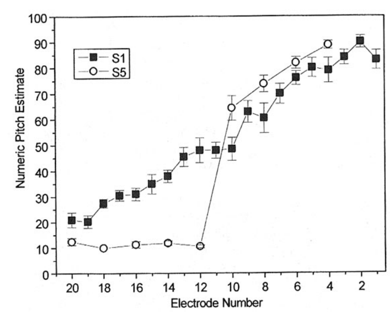
McKay, 2004

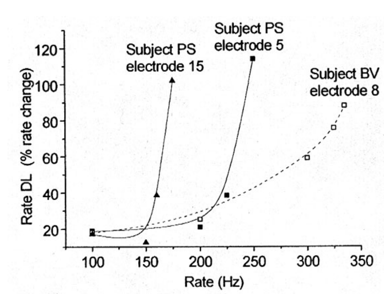
5. Rate and place pitch - two different perceptual aspects of the stimulus.

Design issues:

1. What is the site of initiation of the action potential?
2. Monopolar versus bipolar versus tripolar stimulation?
3. Monophasic versus biphasic versus asymmetric monophasic.
4. Mapping of thresholds and dynamic ranges.
5. Rate and place pitch. The plots at right shows how CI users perceive the pitch (sense of high versus low) of pulse trains according to electrode stimulated (top) and the stimulus pulse rate (bottom). Pulse rate is perceived over a relatively narrow range, compared to normal listeners.

   Rate and place pitches seem to be independent aspects of the percept.





Cohen et al. 1996 and McKay 2004