Progress and Challenges of Neural Prostheses: Cochlear, Retinal Implants,

Sung June Kim

School of Electrical Engineering and Computer Science
NanoBioelectronics & Systems Research Center,
Seoul National University

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. BME-29, NO. 12, DECEMBER 1982

A Comparison of Techniques for Classification of Multiple Neural Signals

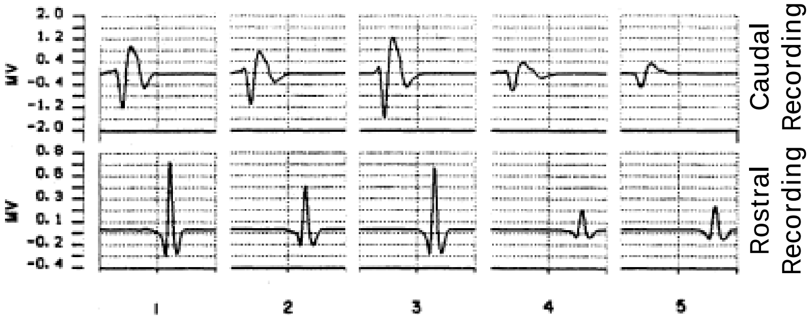
BRUCE C. WHEELER, MEMBER, IEEE, AND WILLIAM J. HEETDERKS, MEMBER, IEEE

Bruce C. Wheeler (S'74–M'80) was born in Schenectady, NY in 1948. He received the S.B. degree from the Massachusetts Institute of Technology, Cambridge, MA, in 1971, and the M.S. and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, NY, in 1977 and 1981, respectively.

Since 1980 he has been a Visiting Assistant Professor of Electrical Engineering and Bioengineering at the University of Illinois at Urbana-Champaign, Urbana. His research interests include signal processing and fabrication and use of electrode arrays for multiple neuron recording.

Dr. Wheeler is a member of Phi Beta Kappa.

Recording of the ventral nerve cord of the cockroach



A. Waveform Parameters
B. Template Matching
C. Optimal Filtering
D. Principal Components I
E. Principal Components II
F. Maximin Filter

TABLE III
CLASSIFICATION OF WAVEFORMS IN FIG. 9

Spike #	1	2	3	4	5	6	7	8	9	10	11	12	13
Correct Unit	1	2	1	2	3	1	2	2	1	4	3	4	3
SNR (dB)	8	4	13	17	2	1	13	−3	2	−7	3	15	14
(1/SNR) (%)	40	63	22	14	79	89	22	140	79	220	71	18	20

Number of Waveforms Correctly Classified

Method	Number of Classifier Features 1	2	3	4	5	>5
Template						12
PC IA	6	9	11	11	12	
PC IB	6	9	10	10	12	
PC II	10	11	12	12	12	
Maximin	8	7	11	12	11	
Opt. Filt.					10	
Max. Amp.	8					
Delay	8					
Amps + Delay					8	

Separation matrices were computed using the different classification features

Template Matching

Unit 2	3	4	5	
33	40	27	30	1
	28	20	20	2
		31	35	3
			12	4

PC-IA: 1 feature

Unit 2	3	4	5	
3.1	10	13	17	1
	13	10	14	2
		23	27	3
			3.8	4

PC-IA: 3 features

Unit 2	3	4	5	
33	40	26	19	1
	27	16	17	2
		30	35	3
			5.6	4

PC-IB: 1 feature

Unit 2	3	4	5	
1.6	4.1	11	13	1
	5.6	9.2	12	2
		15	17	3
			2.6	4

PC-IB: 3 features

Unit 2	3	4	5	
32	37	23	29	1
	21	15	17	2
		29	35	3
			8.3	4

PC-II: 1 feature

Unit 2	3	4	5	
21	39	12	10	1
	17	9.0	12	2
		27	29	3
			2.2	4

PC-II: 3 features

Unit 2	3	4	5	
33	40	27	30	1
	28	19	20	2
		31	35	3
			5.6	4

Maximin: 1 feature

Unit 2	3	4	5	
3.5	6.9	3.4	10	1
	10	6.9	14	2
		3.5	3.5	3
			6.9	4

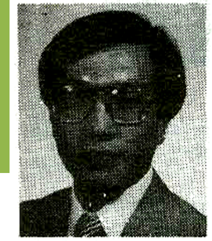
Maximin: 3 features

Unit 2	3	4	5	
21	32	26	27	1
	28	8.5	16	2
		27	34	3
			10	4

IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. BME-32, NO. 7, JULY 1985

Laser-Induced Fabrication of a Transsubstrate Microelectrode Array and Its Neurophysiological Performance

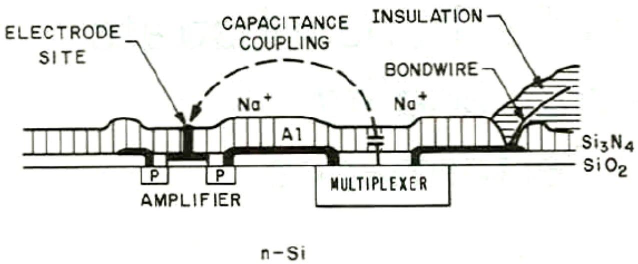
SUNG J. KIM, MEMBER, IEEE, MYUNGHWAN KIM, SENIOR MEMBER, IEEE, AND WILLIAM J. HEETDERKS, MEMBER, IEEE



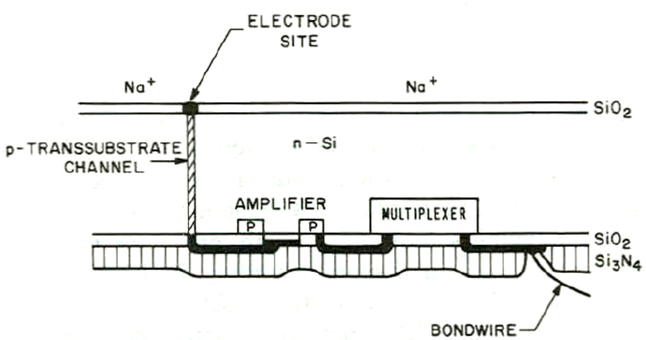
Sung J. Kim (S'80–M'83) was born in Seoul, Korea, on October 24, 1954. He received the B.S. degree in electronics engineering from Seoul National University, Seoul, Korea, in 1978 and the M.S. and Ph.D. degrees in electrical engineering from Cornell University, Ithaca, NY, in 1981 and 1983, respectively.

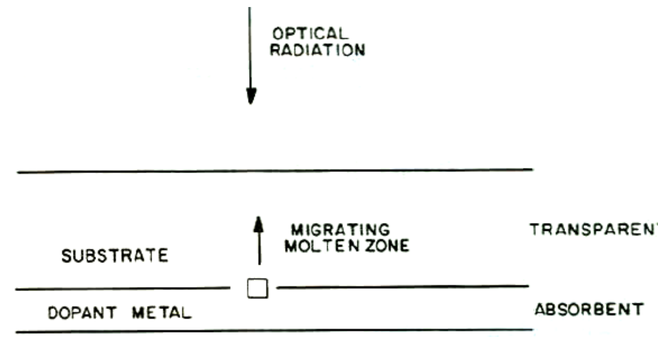
At Cornell, he was engaged in developing electrodes for chornic neural recordings and fabricating microelectrode arrays using semiconductor processing techniques. He is currently a member of the Technical Staff of AT&T Bell Laboratories, Allentown, PA. His professional interests include neurophysiology, and design and processing of VLSI circuits and devices.

Problems with conventional MEA

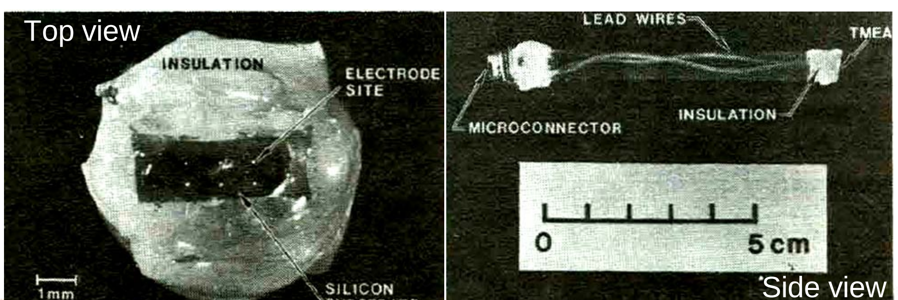


Solution by active transsubstrate MEA (TMEA)

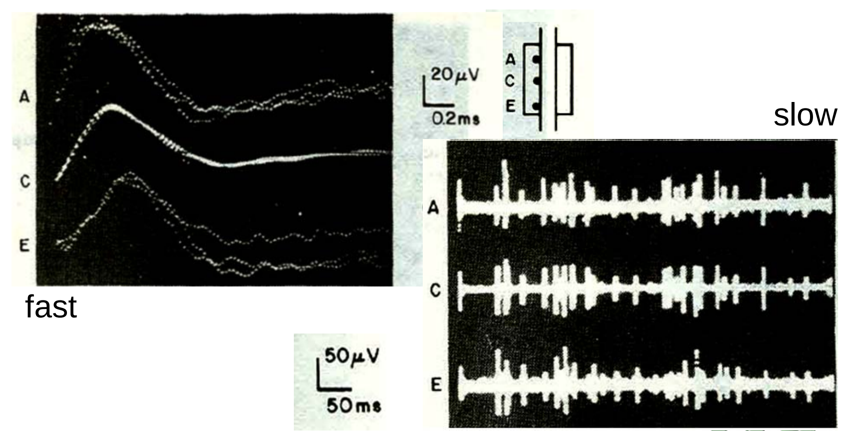




Photoinduced zone migration (PIZM)

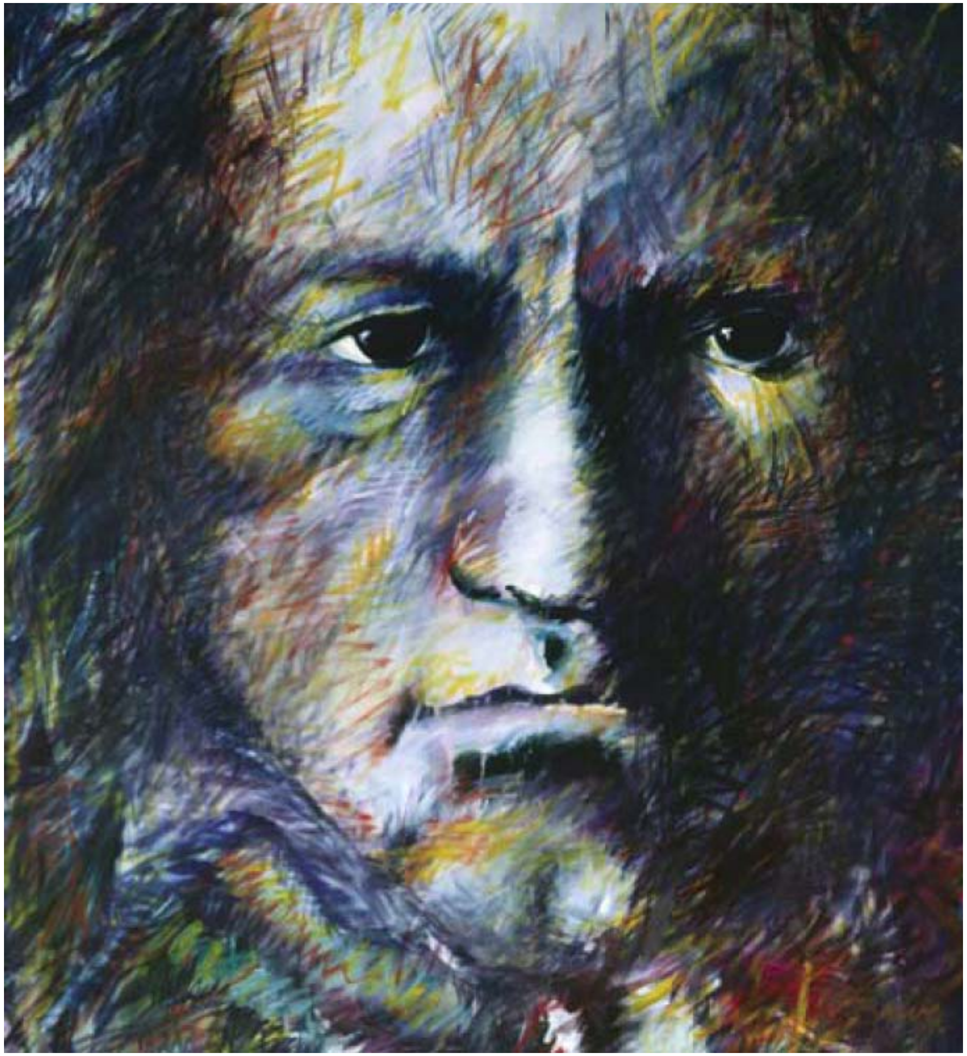


<Completed TMEA assembly>



<Simultaneous recordings>

Who am I?

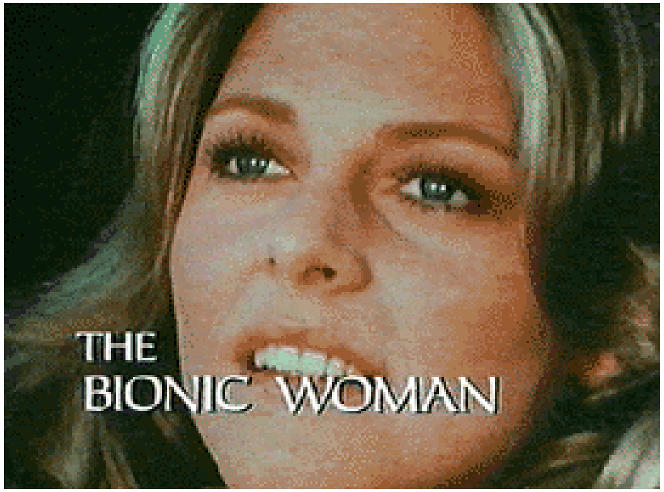


Neural Prosthesis

- A device that connects directly with the nervous system to replace or supplement sensory or motor function.

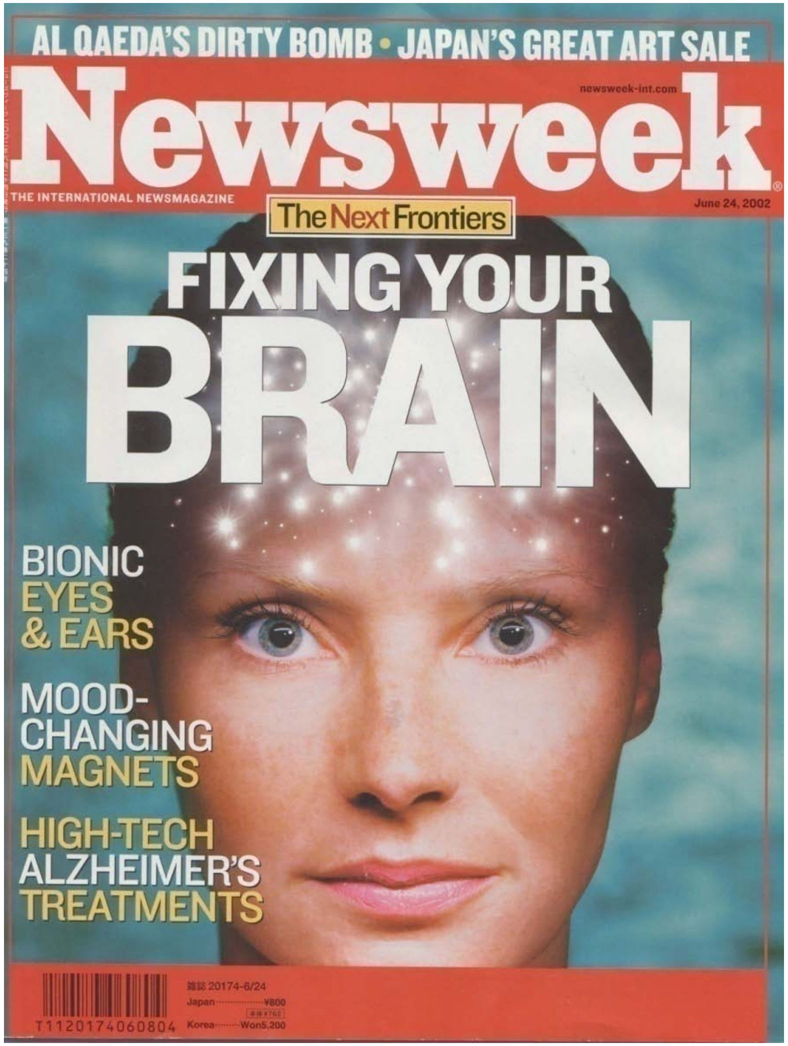
- A device that improves the quality of life of a neurologically impaired individual so much that he/she is willing to put up with the surgery, gadgetry, etc.

It used to be Science Fiction.



Now it is a Science.

And it is Newsworthy.



2002.6.24. NEWSWEEK

How to Recharge The Second Sense

New cochlear-implant technology can enhance hearing in 80 percent of patients who are deaf

BY BRAD STONE

SEVENTY-THREE-YEAR-OLD CORA Jean Kleppe couldn't hear the gong of the grandfather clock in her living room, nor the bark of her little white dog, Whitney. When she went to the movies, the former schoolteacher from San Mateo, Calif., had to imagine the dialogue. And on a recent trip to Italy, her best friend, Melba Mallon, ended up repeating everything the mumbling tour guide said so Kleppe could understand it. Like her mother, Kleppe started going deaf in her 40s, and for the next three decades the deterioration of her hearing outpaced a series of increasingly powerful hearing aids. Last winter her audiologist suggested that she abandon these external devices altogether, and try something radically different: a prosthetic audio implant. Kleppe immediately signed up. "It's the chance of a lifetime," she says. The grandfather clock, the dog's bark "are sounds I can't wait to hear."

Cochlear implants actually consist of three linked components: a microphone placed behind the ear, which picks up sounds; a speech processor, often worn on the patient's belt, which converts the sounds into electrical signals, and a surgically implanted receptor, which stimulates the groups of neurons in the cochlea, a seashell-shaped bone that sends nerve impulses to the brain. Cochlear implants first hit the market in 1985, but they were controversial through the mid-'90s, partly because they improved hearing in only 30 to 40 percent of patients. Today, advances in the technology have silenced most critics. Doctors say they can now significantly enhance hearing in 80 percent of patients, and even children born deaf are candidates for the procedure. But they should be treated within their first five years, before the brain loses its ability to process sound (children and adults who have been deaf for longer periods of time often fall into the other 20 percent). "It's reaching a point where we can restore hearing to levels that approach the hearing of normal people—where we can actually cure deafness," says Albert Maltan, a senior vice president of Advanced Bionics, which makes the Bionic Ear, the implant used by both Kleppe and talk-show host Rush Limbaugh, who had the surgery in December.

The idea of electrically stimulating the auditory system is nothing new. In the 18th century, Italian physicist Count Volta hooked two metal rods to his most famous invention, the battery, and inserted them into his healthy ears, generating a sound like the boiling of thick soup. By the 1970s, scientists had figured out that electrical pulses needed to be targeted to localized groups of hair cells, which convey different sets of tonal and pitch information to the brain. While the first generation of cochlear implants used a single, clumsy electrode to convey the entire spectrum of sound, today's devices have up to 24 electrodes, each stimulating a different patch of neurons.

The results still aren't perfect. People with the implant often say voices sound metallic, like a radio broadcast. And few are able to enjoy the tonal richness of music. Many also still lip-read to complement their new hearing, particularly in loud environments—though they are able to use the telephone, where there's little background noise. The surgery costs up to $50,000, and most insurance policies will cover it.

For patients like Cora Jean Kleppe, it's worth every penny. Last month Kleppe and her friend Melba drove to the University of California, San Francisco, Hospital, four weeks after her surgery, to have Kleppe's implant programmed and activated. Kleppe was shown how to clip the microphone behind her ear and how to change the batteries in the speech processor. Then, right there in the hospital, her doctor remotely activated the implant. "It's going to sound strange," the doctor warned. Kleppe started to talk and then interrupted herself: "Does my voice sound like that?" Thirty minutes later she's walking around the hospital lobby, looking at Melba with wonder every time her friend speaks. "We can talk," she says. "We can gossip forever now." ■

WE CAN REBUILD HER: Kleppe, sporting the microphone of her new Bionic Ear

How It Works

1 EARPIECE A microphone near the ear captures an 80-decibel range of sound, 100 percent more than previous models.

2 PROCESSOR A built-in microcomputer filters and analyzes the sound from the microphone, converting it into digital signals.

3 IMPLANT The signals are sent to a headpiece above the ear, which transmits them via radio waves to a receiver under the skin. They are then sent through a wire to electrodes in the cochlea.

4 COCHLEA Based on the signals transmitted by the headpiece, electrodes stimulate nerves, which carry sound to the brain.

Headpiece · Receiver placed under skin · Wire to cochlea · Microphone · Processor · Middle ear · Cochlea · Hearing nerve · Eardrum · Outer ear · Ear canal · Electrodes · Nerve

SOURCE: ADVANCED BIONICS

NEWSWEEK JUNE 24, 2002

PHOTOGRAPH BY JOHN CLARK FOR NEWSWEEK

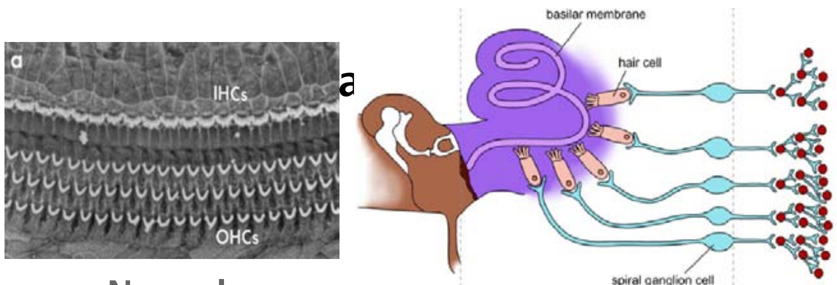
Successful Areas of Neural Prosthesis

- **Hearing: Cochlear Implant**
- **Parkinson's Disease: DBS (Deep Brain Stimulation)**
- **Vision: Retina Implant**
- **Others to come**

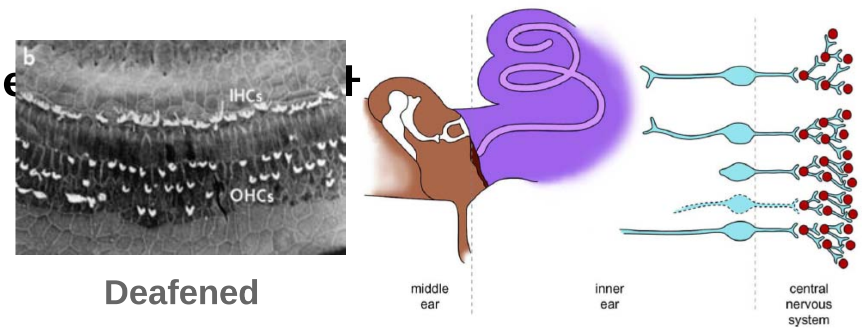
Artificial Hearing
인공청각

Sound Sensing Mechanism

Cochlear Implant for Sensori-neural Hearing Loss



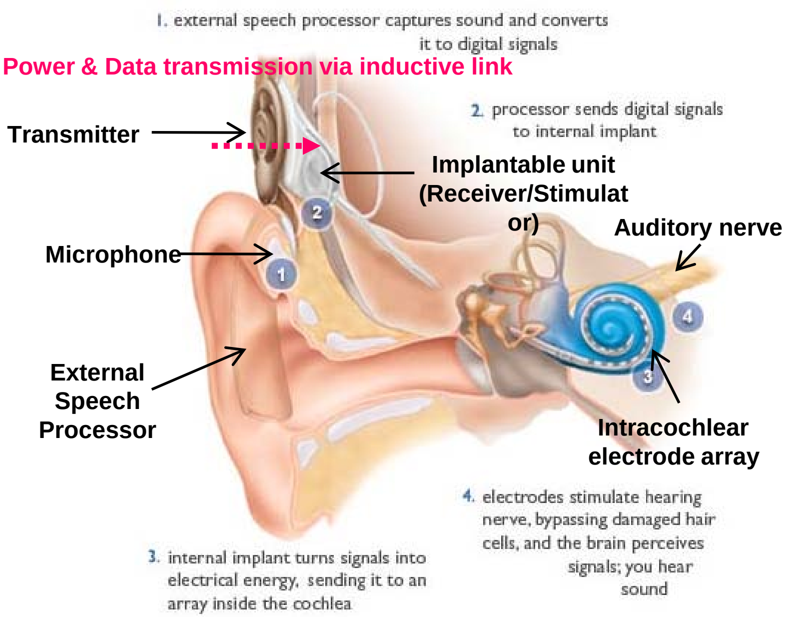
Normal



Deafened

B. Wilson & M. Dorman (IEEE Sensors Journal, 2008)

- **Artificial Hearing by Cochlear Implant**



External Speech

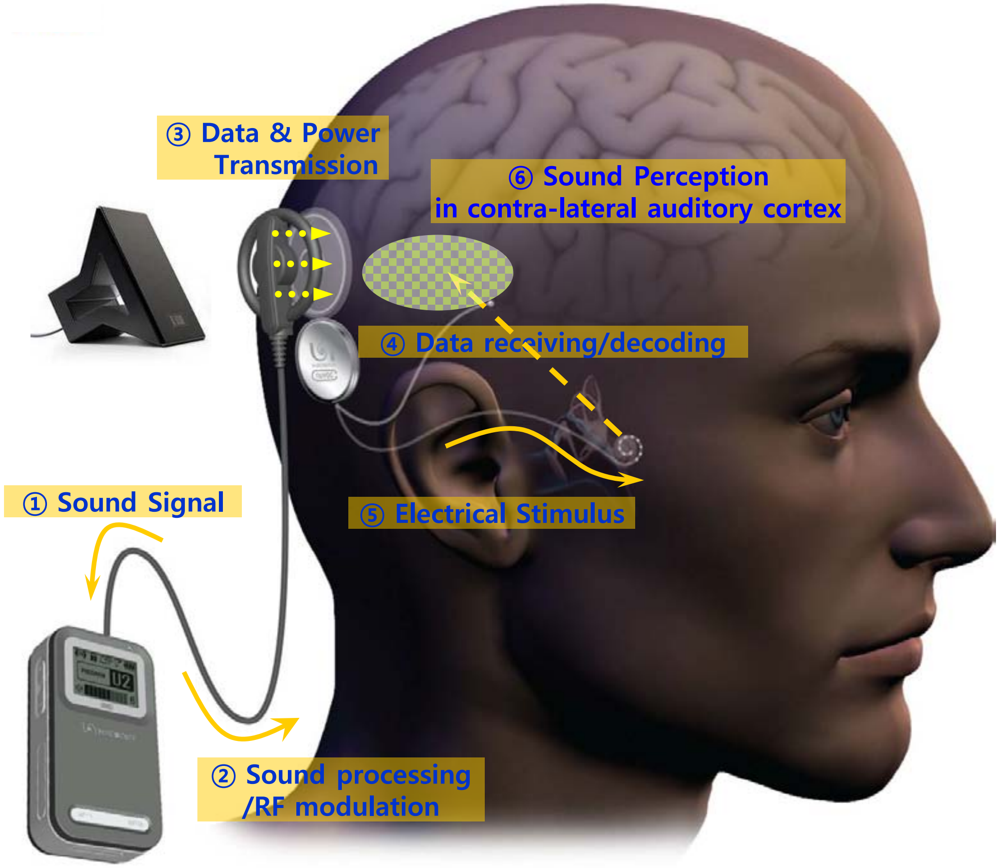
Implantable Unit

www.cochlear.com

Cochlear Implant

◆ A Neuroprosthetic device that can provide a sense of sound to people who are deaf or profoundly hearing-impaired by stimulating auditory neurons electrically.

◆ The most successfully-commercialized (since 1982) sensory prosthetic system (CI market: ~570 mUSD@2006).

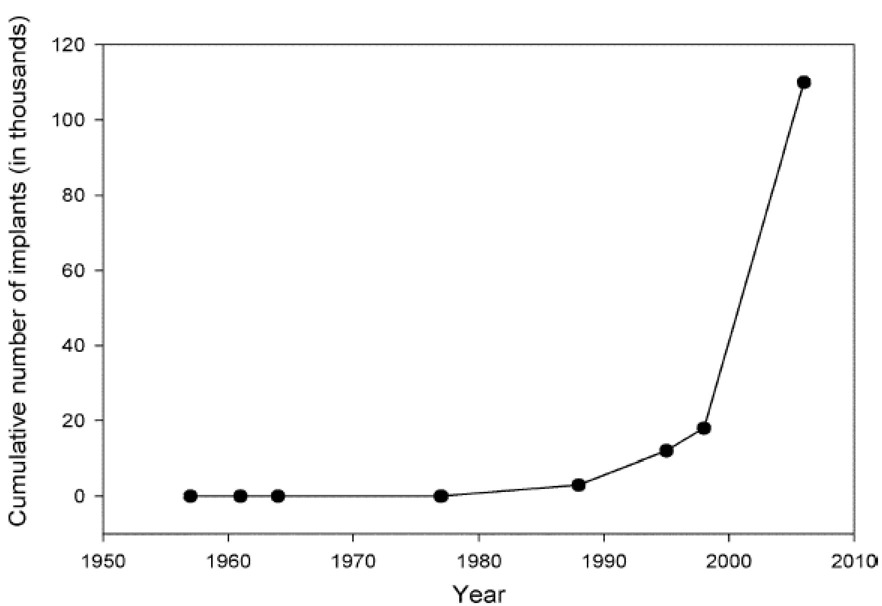


The basic premise was: There is no way to replace even crudely the exquisite structure and function of the cochlea

Surprising Performance of Present-Day CIs

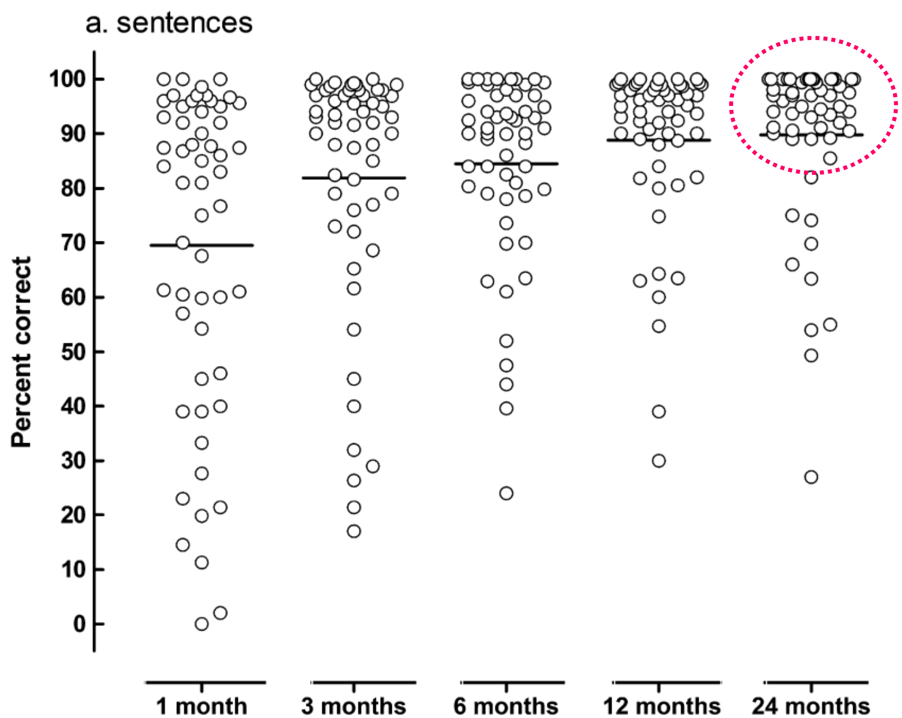
- **The CI is the most successful neural prosthesis to date**
- **Cumulative CI users: approximately 120,000 persons**
- **Open- set speech recognition scores (in quiet): about 90 %**

Cumulative number of implants across years



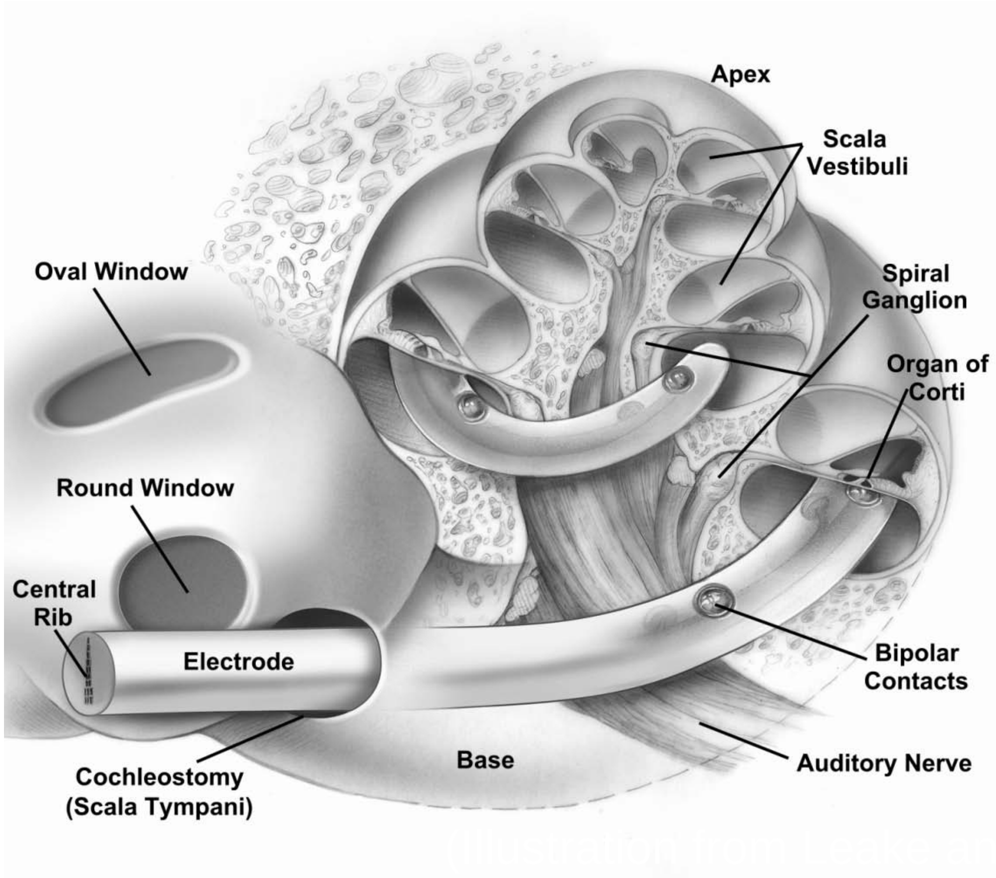
B. Wilson & M. Dorman (IEEE Sensors Journal, 2008)

Percent correct scores for 55 CI users

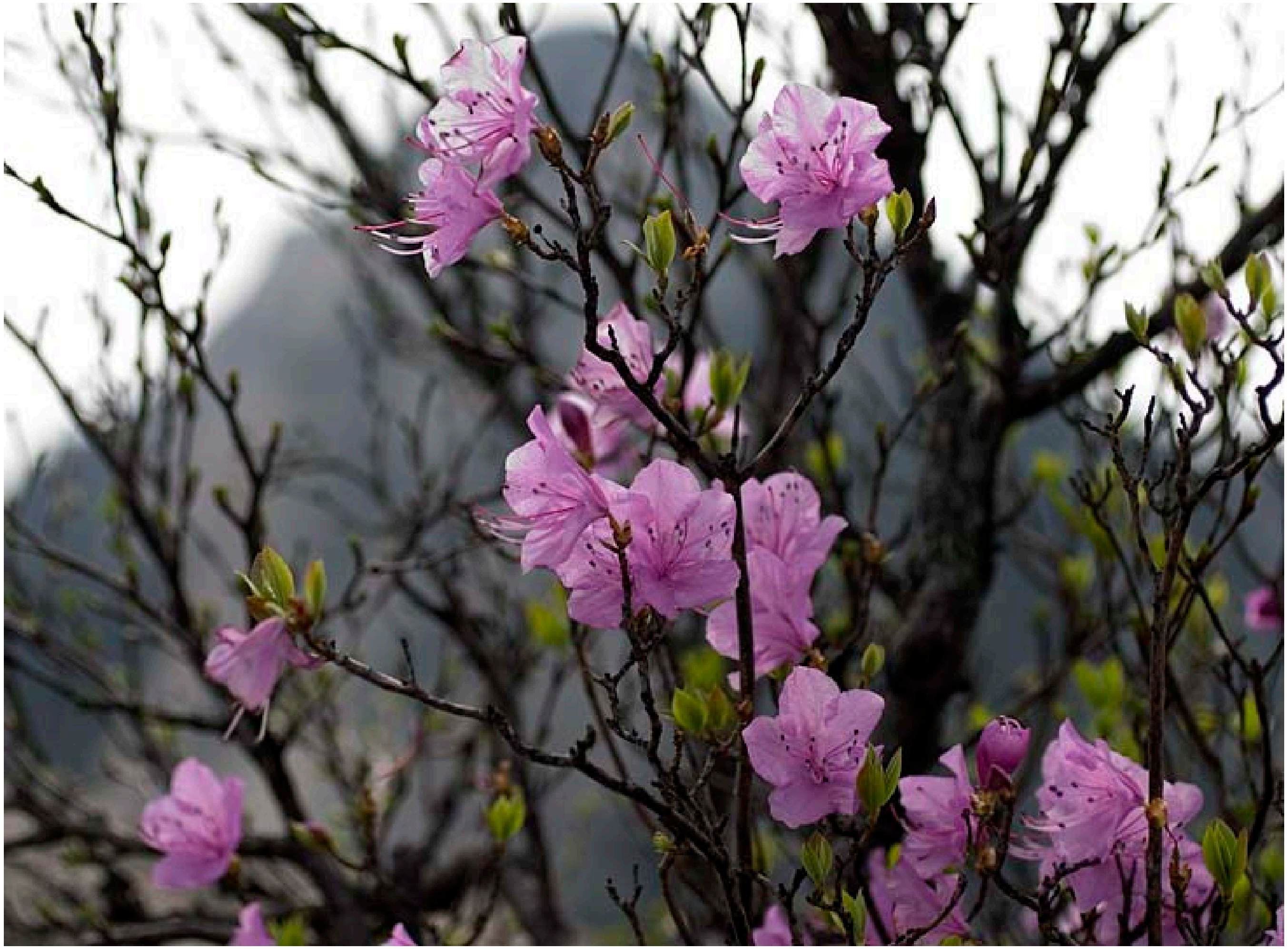


B. Wilson & M. Dorman (Hearing Research, 2008)

Number of channels= number of electrode sites



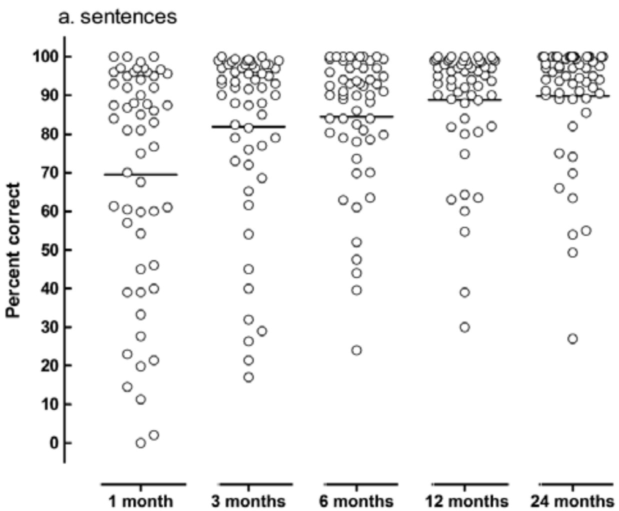
인공와우를 통한 음성인식 과정 시뮬레이션

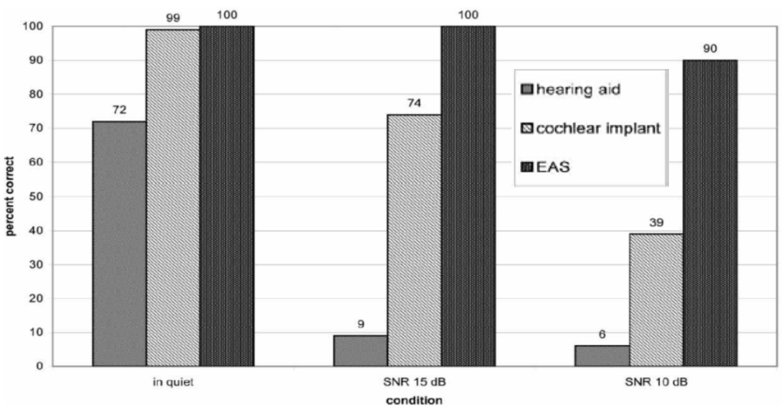


1　2　4　6　8　16　24　32　64　N

Limitations of Present-Day CIs

- **Wide range of outcomes**
- **Speech reception in noise**
- **Sound localization**
- **Reception of signals more complex than speech, e.g., symphonic music**
- **High effort in listening for the great majority of patients**
- **High Cost**

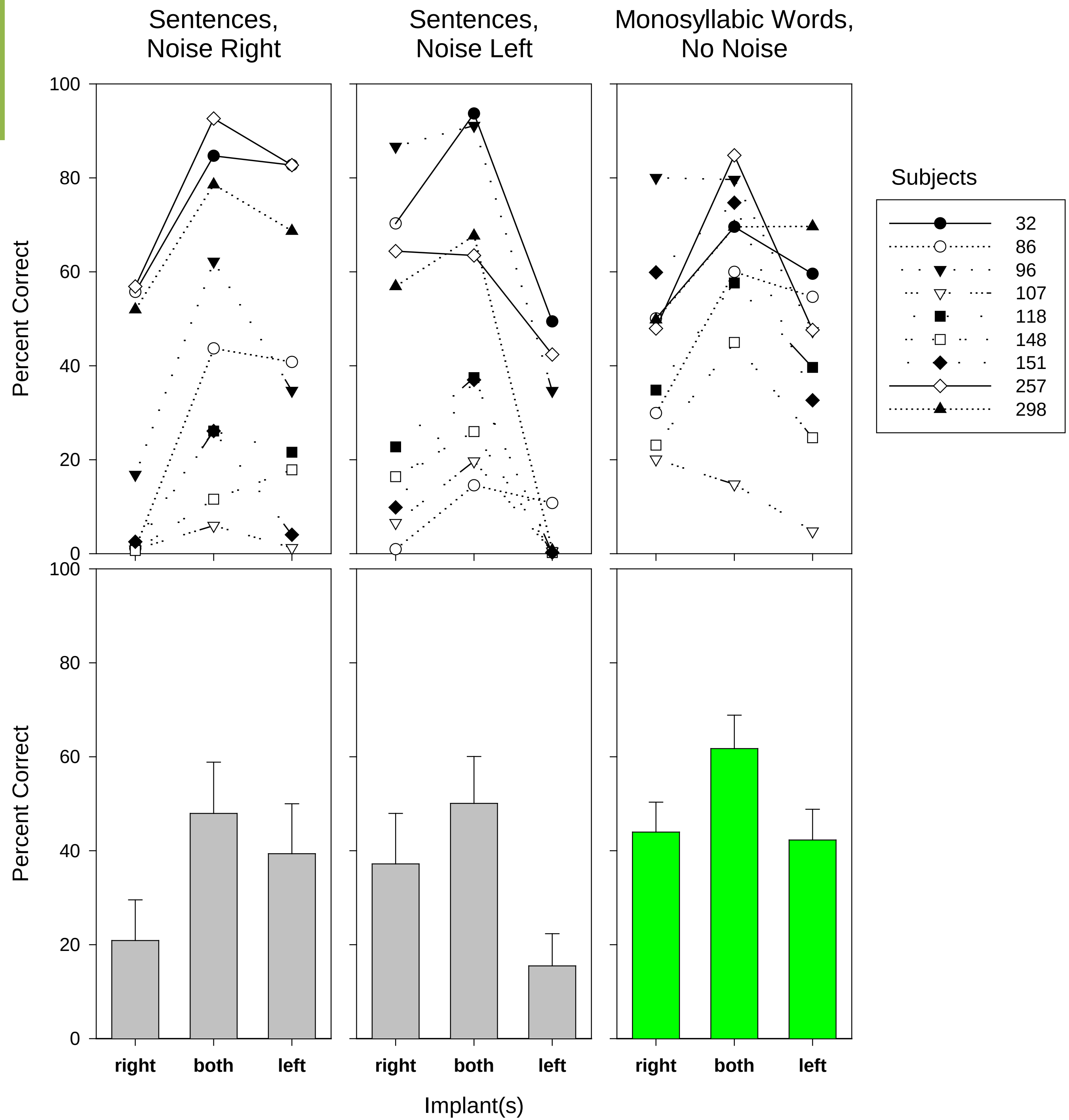




Two recent advances

- **Bilateral electrical stimulation**
- **Combined electric and acoustic stimulation (EAS) for patients with residual, low-frequency hearing**

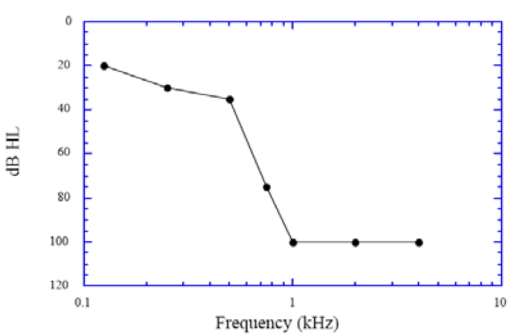
Results with bilateral implants using independent processors, Müller *et al*., 2002



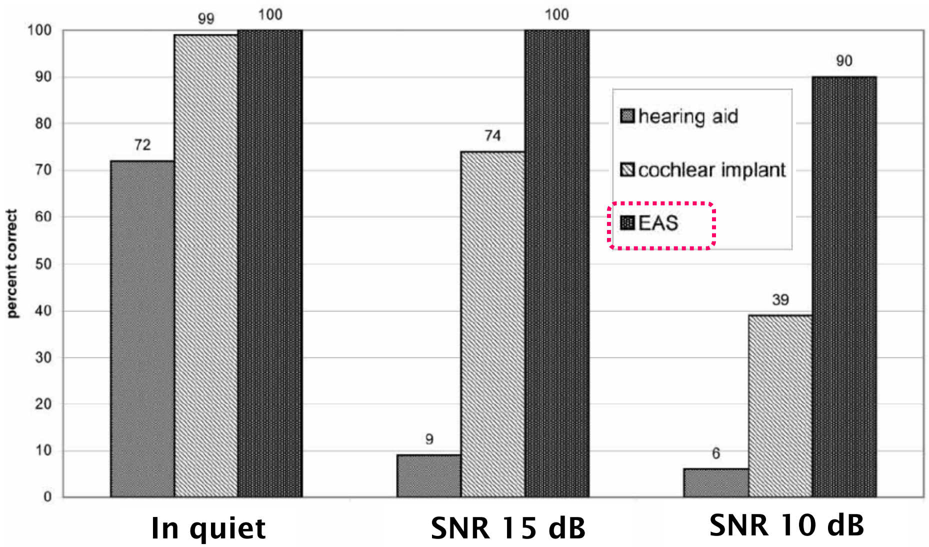
Combined Electric-Acoustic Stimulation (EAS)

- Combined EAS: Hearing Aid (HA) + Cochlear Implant (CI) on same ear
- Many implant candidates → Good low- frequency hearing but poor high frequency hearing
- Low- frequency → Acoustic Hearing using a HA
  High- frequency → Electrical Hearing using a CI
- Good speech perception in noisy environments
- Latest EAS technique
  - Surgery: the round window approach (conventional method → cochleostomy)
  - Electrode: flex, long & thin electrode (full insertion)

Ski-slope type SNHL



Hybrid CI Device
(HA+CI)

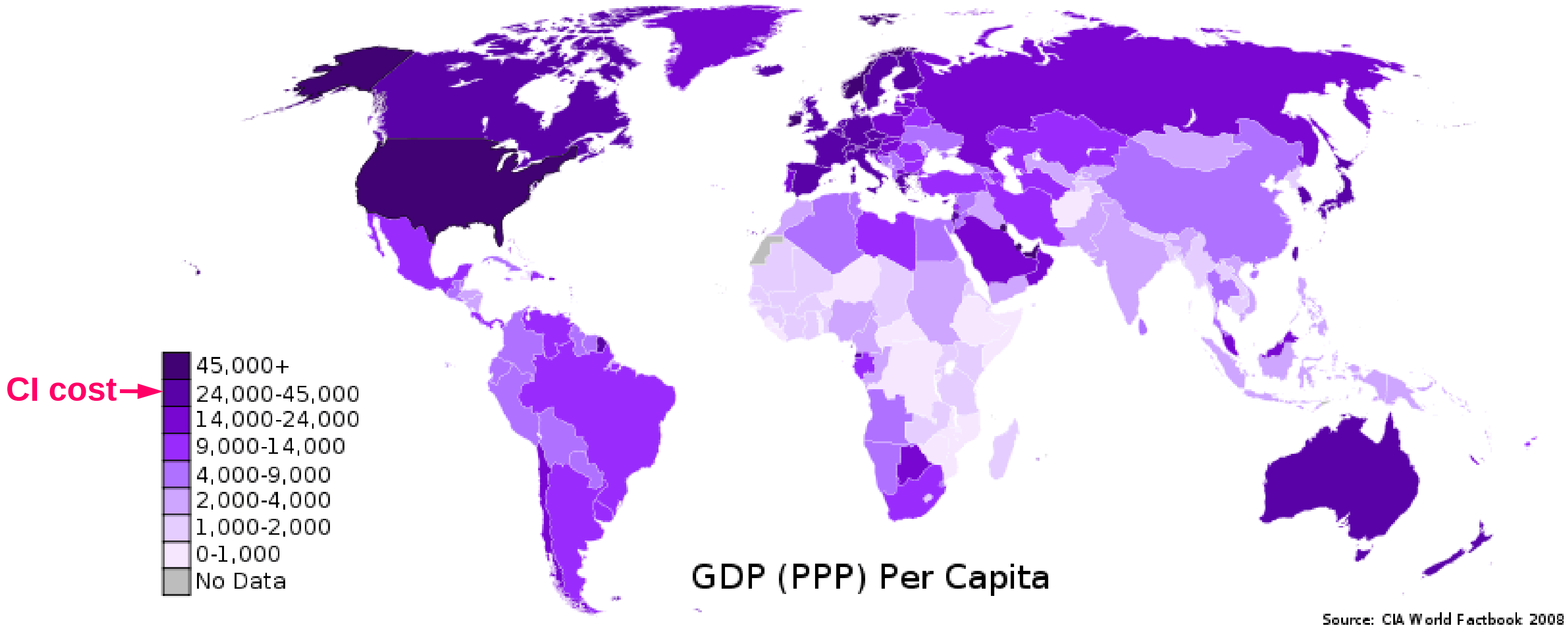


W. Gstoettner et al. (Acta Oto-Laryngologica, 2004)

Cost Problem: Surprising Performance , but–.

- **CI cost (device only): around 25,000 USD**

- **About 278 million people had moderate to profound hearing impairment. 80% of them live in low- and middle- income countries. (2005, WHO)**
  - **Where cochlear implant is not or rarely affordable**



Towards low cost but highly efficient CI

- **Our effort:**

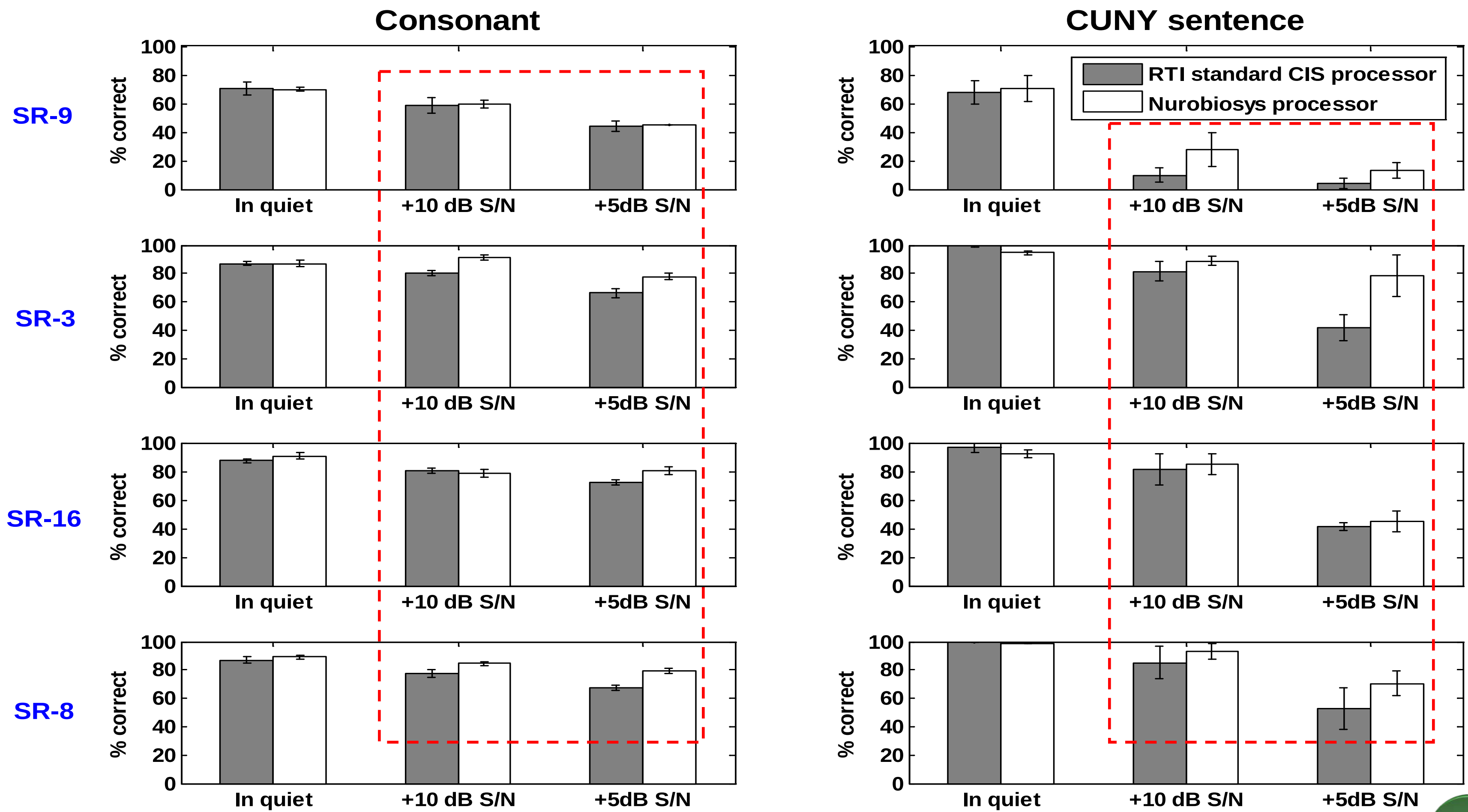
- SNU-NUROBIOSYS Cochlear Implant System
  - Academic-Industrial collaboration
  - Great helps from international experts

- **All technical options were carefully selected to make SIMPLE and LOW-COST cochlear implant with maintaining effectiveness of the system**

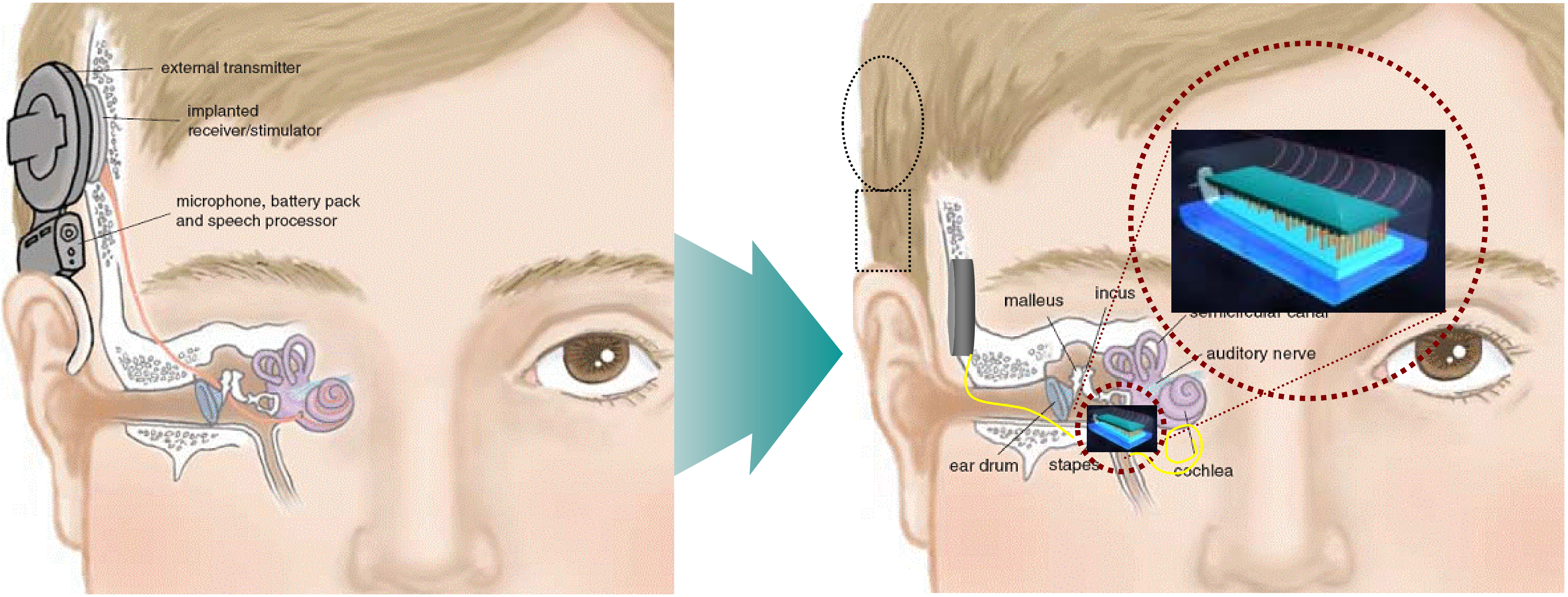
- **Approved on 2009 by Korea FDA**

Pre-clinical Test Results

◆ **SNU-NUROBIOSYS CI system showed a similar level of performance as compared with RTI standard CIS processor, and especially the system showed better performances in noise.**



New Pioneer design project
For a Totally Implantable Cochlear Implant



Conventional Cochlear Implant | **New Concept Cochlear Implant**

- Zero Power Artificial Basilar Membrane instead of Microphone and Speech Processor
- ➔ Totally Implantable
- Reduced Power consumption (30mW) (1/8 lower than conventional systems (235mW))
- Without Align Magnet ➔ MR-Compatible

Pioneer Research Program - National Research Foundation of Korea (2009 -)

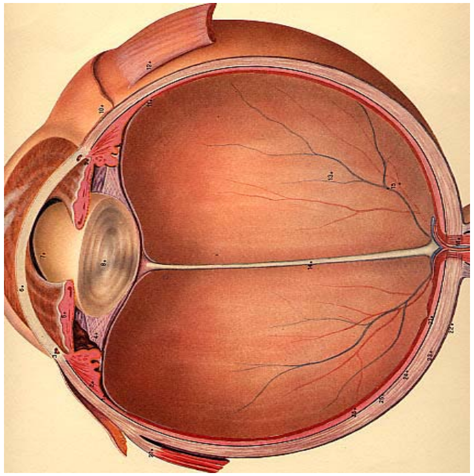
인공시각
“Let There Be Light”
Genesis 1:3

눈은 어떻게 보는가 (EBS 원더풀사이언스 2010년5월13일)

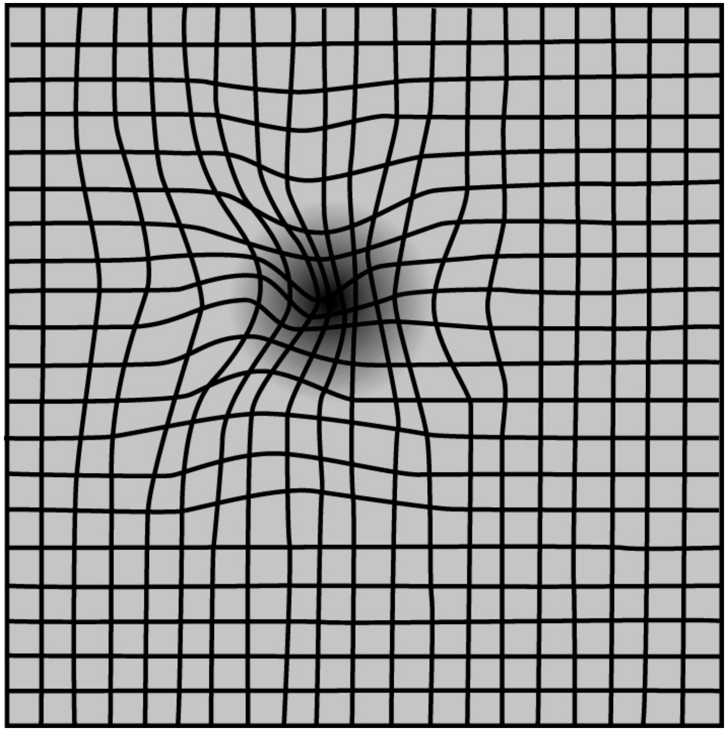
Care for Blindness

- **Visual impairment :**
  - **Legally considered percentage of lost body function: 24%(Uniocular) and 100%(binocular)**

- **30% of blindness in the adult**
  - **Retinitis Pigmentosa (RP)** 망막색소변성; 1/4000(Normal)
  - **Age- related Macular Degeneration (AMD)** 나이관련황반변성; 1/20(>aged 65)



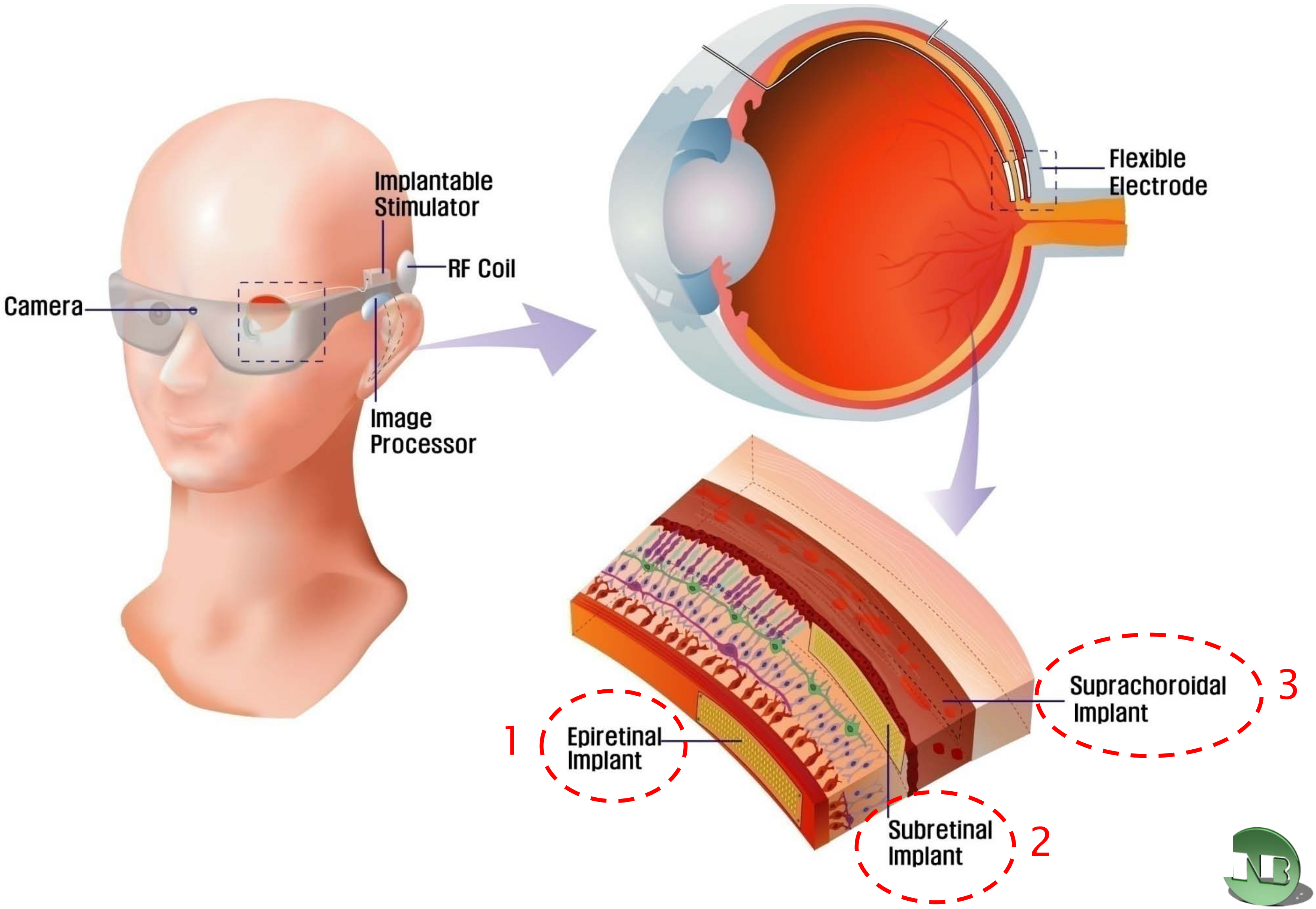
The world that patients with macular degeneration see



Artificial Vision Inspired by:

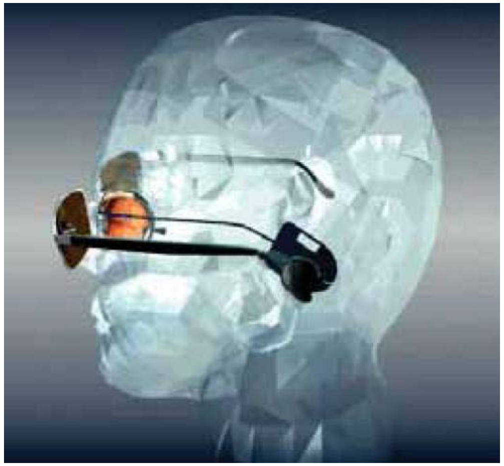
- Inspiration and Perspiration
  - advances in semiconductor technology; VLSI
  - successful result in artificial cochlear implant
  - relatively well- preserved inner retinal neurons in RP & AMD
- from late 1980's
  - Retinal stimulation
    - MEEI- MIT (Boston Retinal Implant)
    - Wilmer- NCSU - > USC (Doheny)
    - SUB- RET (Germany)
    - EPI- RET (Germany)
    - SNU (Korea)
    - Osaka (Japan)
  - Optic nerve stimulator
    - Louvain (Belgium)

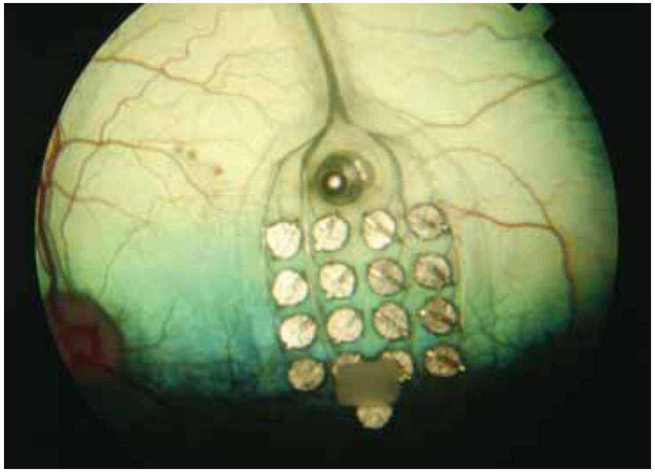
Current Approaches in Retinal Prostheses



인공시각 동작원리 (EBS 원더풀사이언스 2010년5월13일)

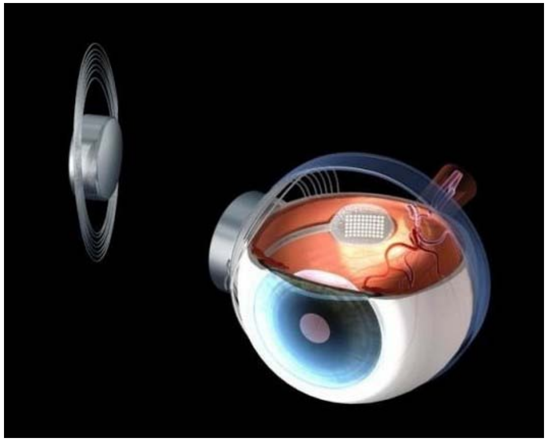
Epi-retinal Stimulators - USC (Doheny) / Second Sight

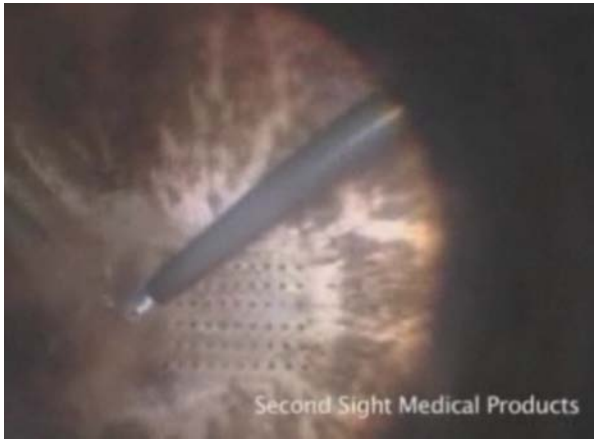




Argus™ I (Model 1)

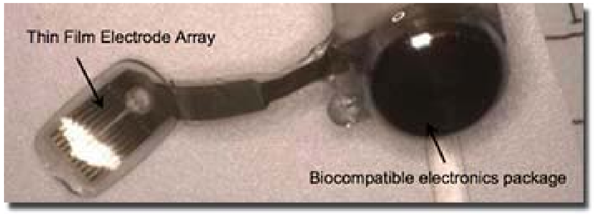
- 16-Pt electrodes on Silicone
- Ceramic Package
- Implanted in 6 patients (2002 ~ 2004)
- The patients could detect phosphene.





Argus™ II (Model 2)

- 60-Pt discs on parylene-C
- Metal/Ceramic Package
- Implanted in 32 patients (~ 2010)



이식환자들영상

원리-1.외부기 (모형)

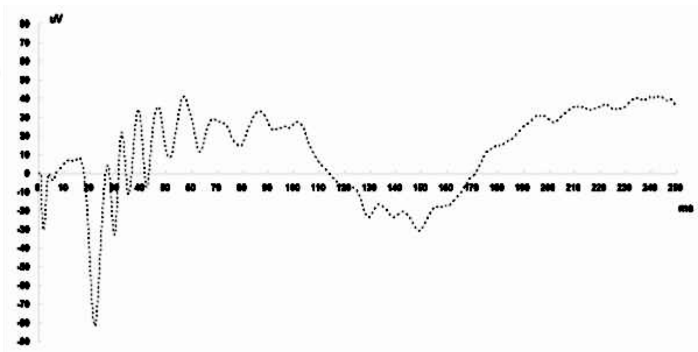
내부기(이식장치)

인공시각-어떻게 보는가? 전극수와 관련해서

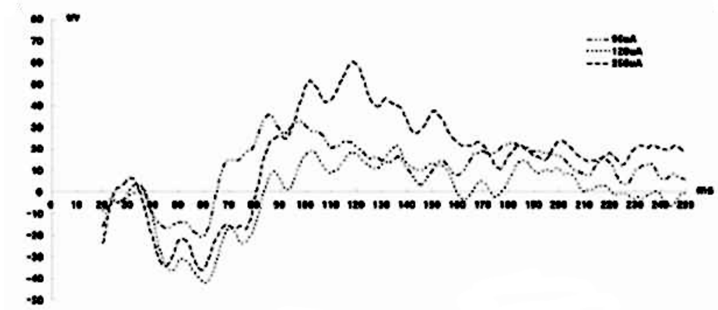
SNU artificial retina

- Nano-bio system research center (for 9 years, 3 main subjects)
  - supported by KOSEF(KOREA SCIENCE AND ENGINEERING FOUNDATION)
  - development of electrode for retina stimulation as a subject in Neural chip/MEMS
- Nano artificial vision research center (for 6 years)
  - supported by Minister for Health, Welfare and Family Affairs
  - development of SNU artificial retina system and application to a human body
- Collaborators
  - ophthalmology
  - physiology
  - Electrical Engineering & Computer Science
  - biomedical engineering

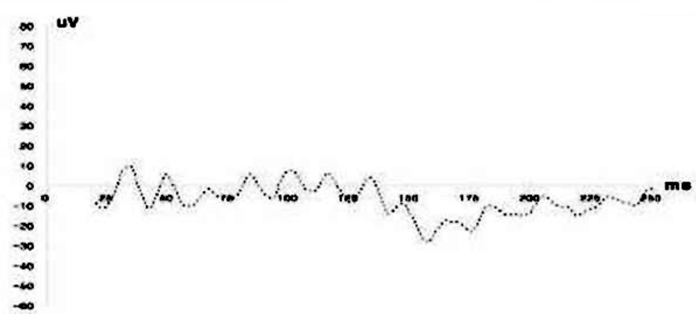
Electrophysiological recording after insertion of retinal stimulator



Visual evoked Cortical potential (VECP)

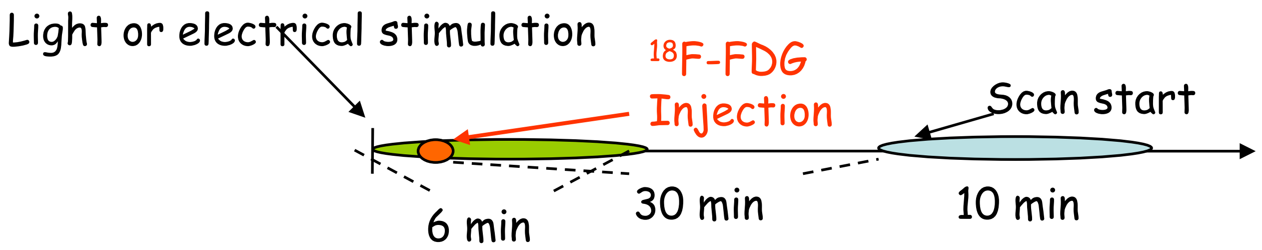


Electrically evoked cortical potential
(EECP)

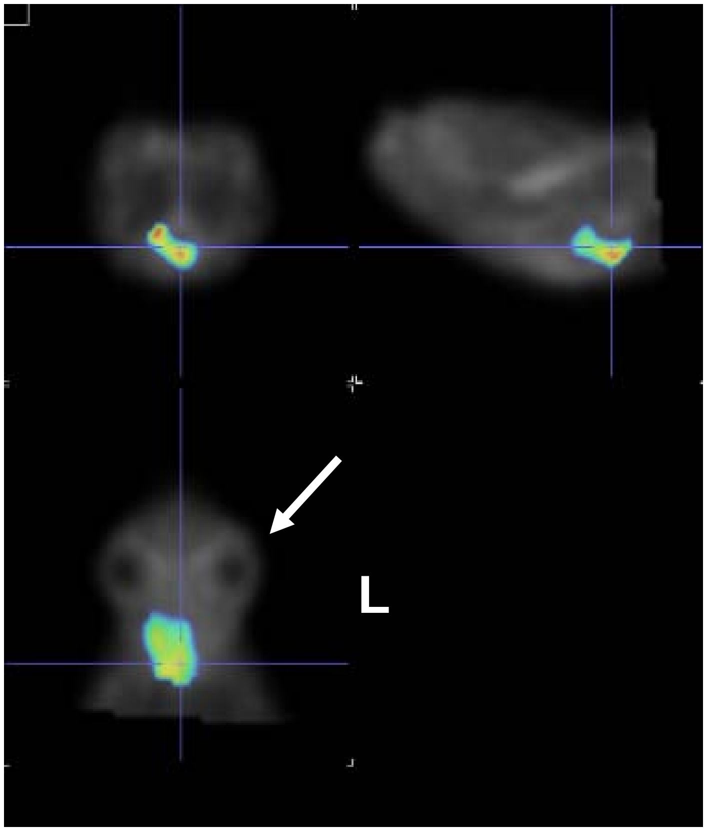


After optic nerve cutting

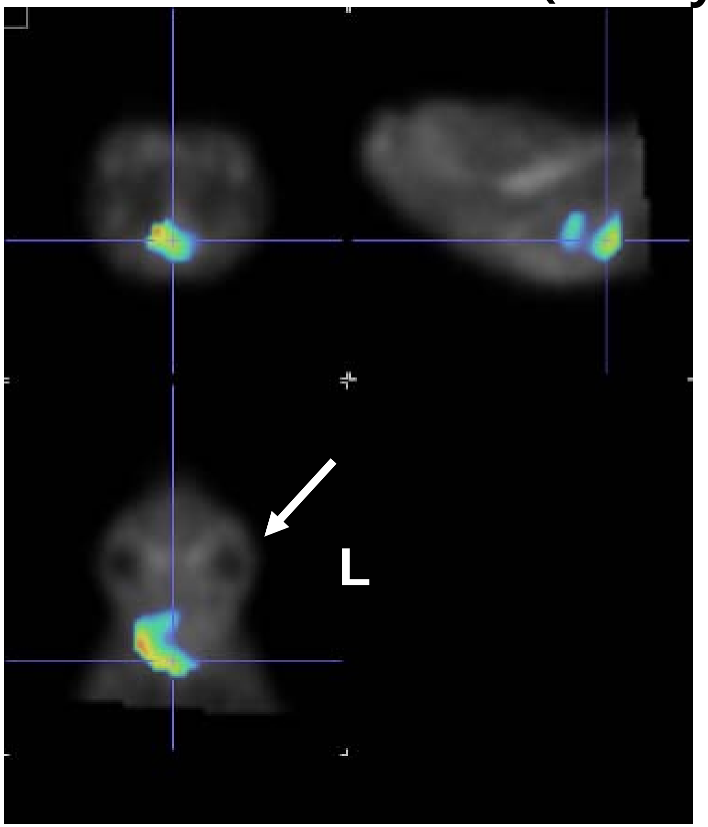
Range of increase in glyco-metabolism of visual cortex (PET image)



Light Stimulation (left eye)

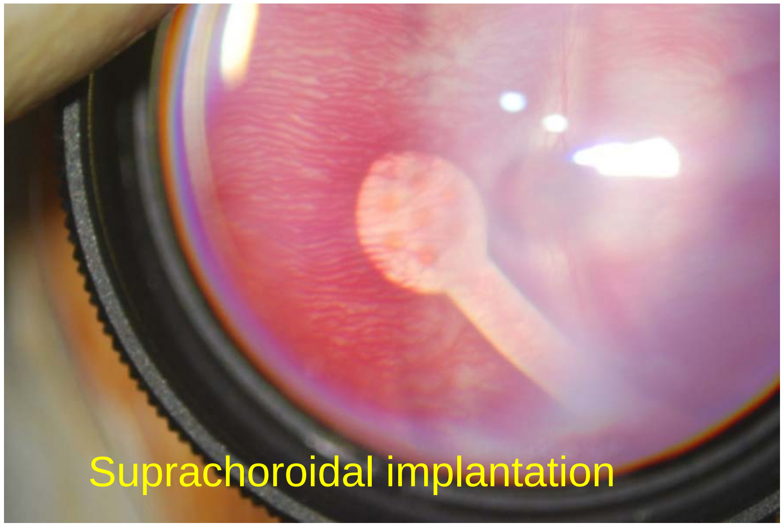


Electrical stimulation (left eye)

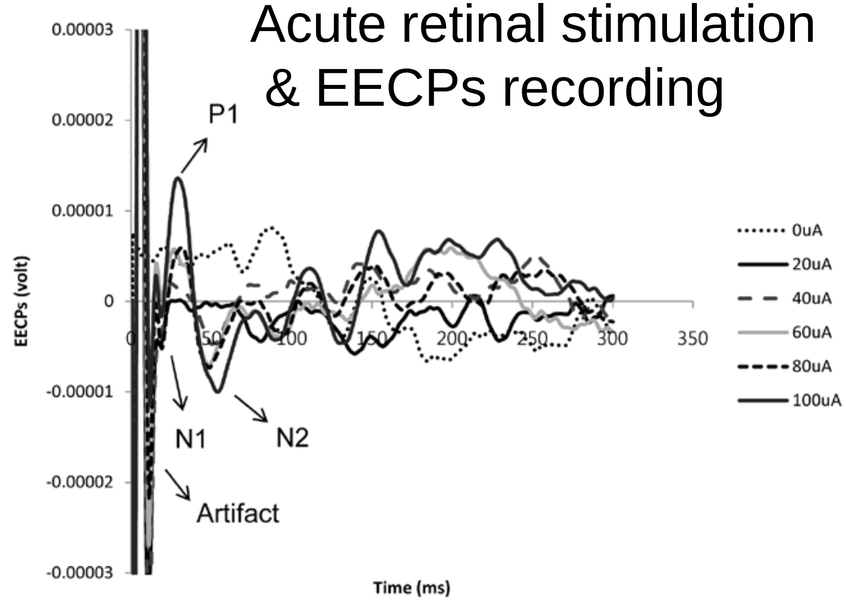


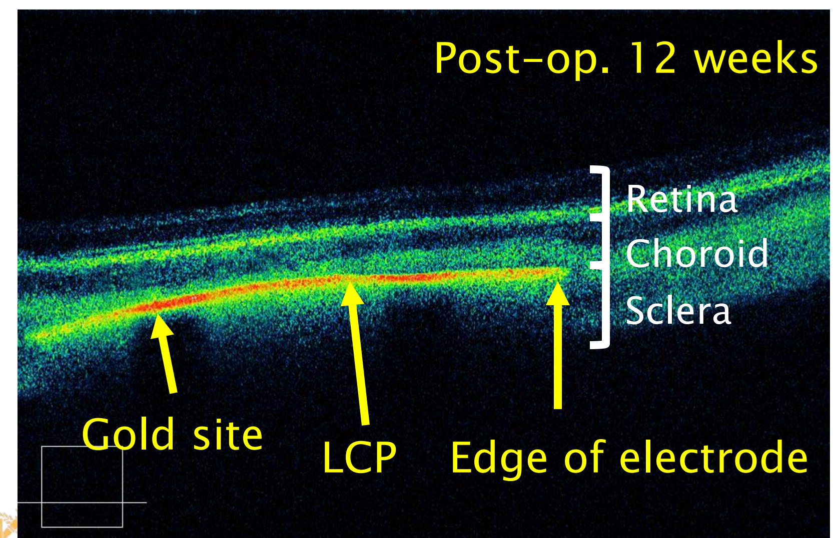
In vivo animal experiments

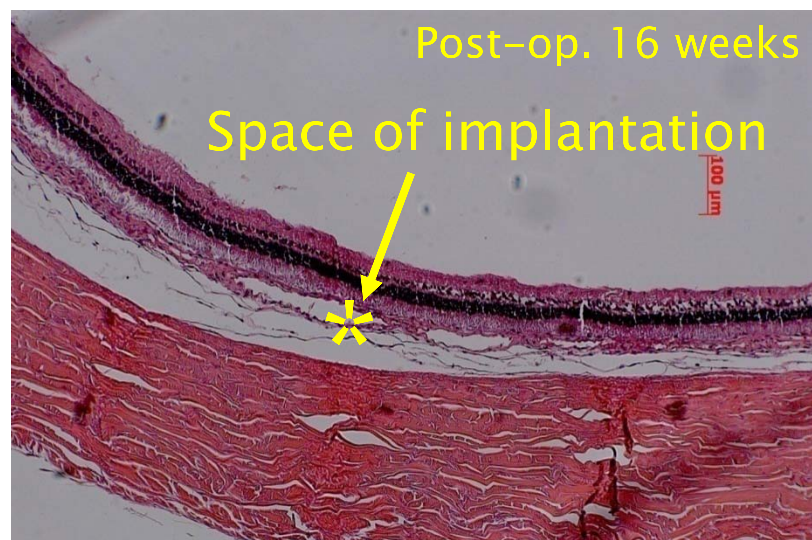
Implantation of LCP electrodes



Acute retinal stimulation & EECPs recording



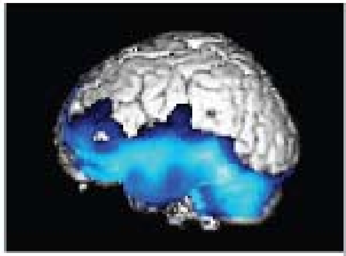
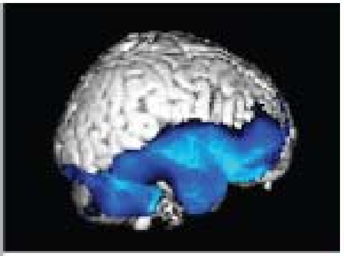
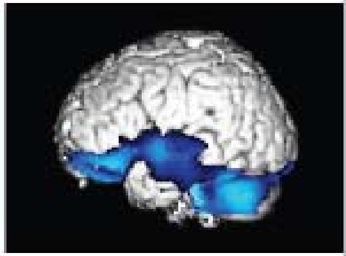
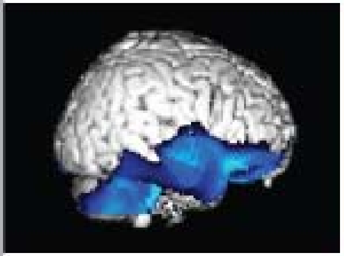
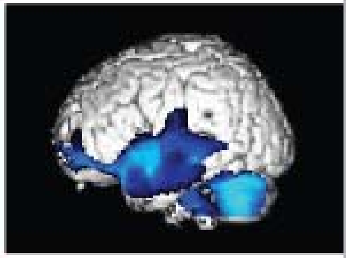
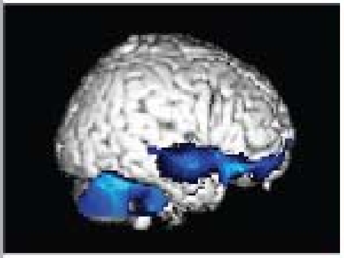
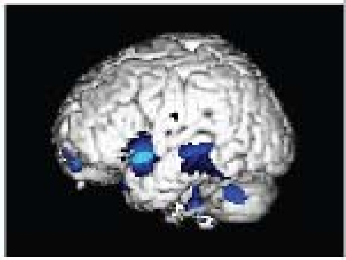
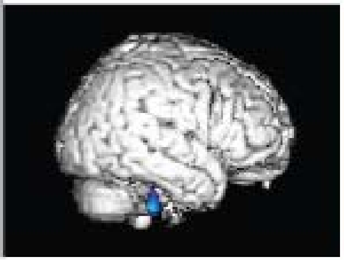




맺으며---인공청각및 시각 Possibilities for the future

- Further development and refinement of bilateral electrical stimulation and of combined EAS (CI)
- Closer mimicking of Natural processing
- Representation of “fine structure” information with implants
- Availability of low cost – but still highly effective – implant systems for widespread application in India, China and other developing countries
- Controlled delivery of neuro- protective or neurotrophic drugs to the implanted cochlea
- A “cognitive neuroscience” or “top down” approach to implant design

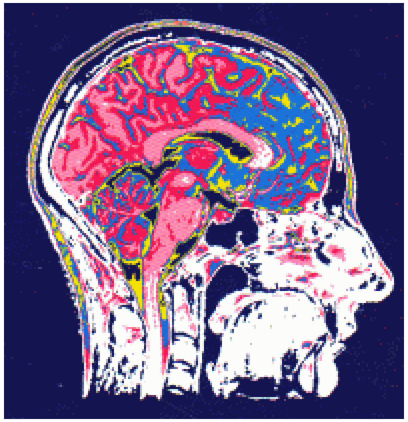
Lee et al., "Cross modal plasticity and cochlear implants," *Nature* 409: 149, 2001.

duration of deafness (years)	left	right	sentence score (% correct)	duration of training (years)
6.5			90	3.8
6.5			67	1.1
11.2			7	1.4
20.3			0	1.9

A “top down” or “cognitive neuroscience” approach to implant design

Traditional approach: Replicate insofar as possible the normal patterns of activity at the auditory nerve.

Alternative approach: Ask what the (usually compromised) brain needs as an input in order to perform optimally.



Lee *et al*. (2001) Cross-modal plasticity and cochlear implants. *Nature*.
Nadol *et al*. (2001) Histopathology of cochlear implants in humans. *Ann Otol Rhinol Laryngol*.
Sharma *et al.* (2002) Rapid development of cortical auditory evoked potentials after early cochlear implantation. *NeuroReport.*