Benefits afforded by precurved electrode arrays: speech and auditory perception for adult cochlear implant recipients

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1

Learning Objectives

- After this course learners will be able to describe expected CI outcomes by a large clinical population without knowledge of electrode location and device wear time and compare this broad range of variability to what we could expect with more knowledge of individualized variables.
- After this course learners will be able to describe differences between classic literature and newer studies providing evidence for greater channel specificity in modern-day CI recipients with precurved electrode arrays localized in scala tympani.
- After this course learners will be able to describe the potential beneficial effects of a well-placed precurved electrode array (such as CI632) on upper stimulation levels, spectral resolution, and speech recognition in quiet and noise.

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2

Disclosures

- Research presented here is funded by the **NIH NIDCD**
- VUMC CI program: industry-sponsored studies from Advanced Bionics (AB), Cochlear, and MED-EL
- Consultant: AB, Cochlear

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3

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Andie DeFreese

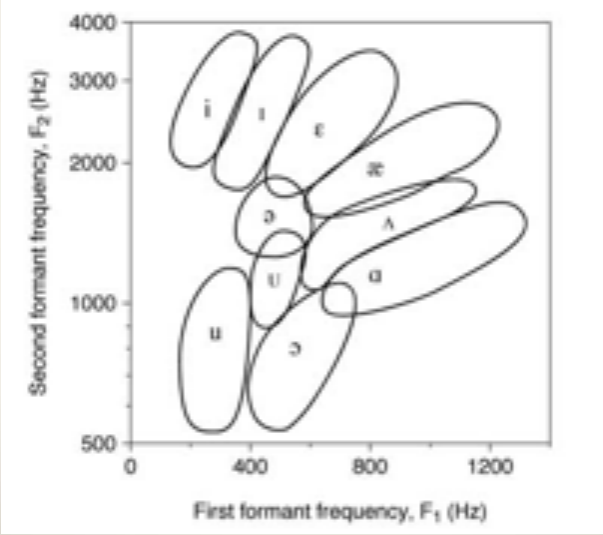
4

hip with

Wilson BS, Dorman MF. (2008). *J Rehab Res Dev*, 45(5): 695-730.

The cochlear implant:

"…the most successful of all neural prostheses developed to date"



Peterson & Barney (1952). *J Acoust Soc Am,* 24: 175–184.s

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Wilson BS, Dorman MF. (2008). *J Rehab Res Dev*, 45(5): 695-730.

The cochlear implant:

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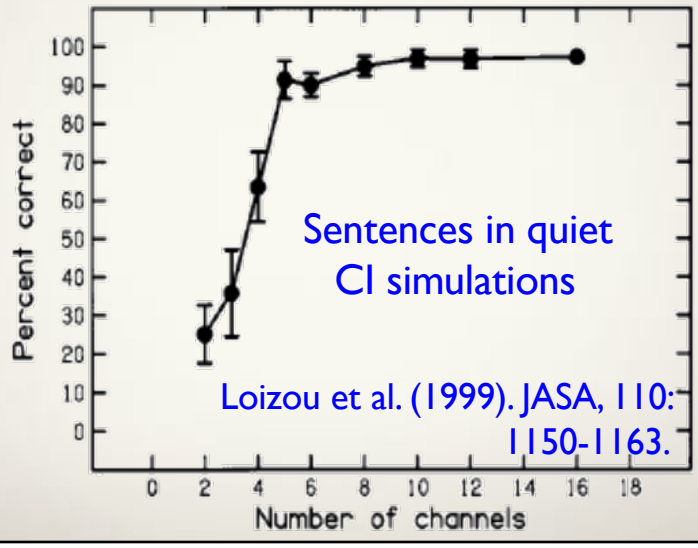

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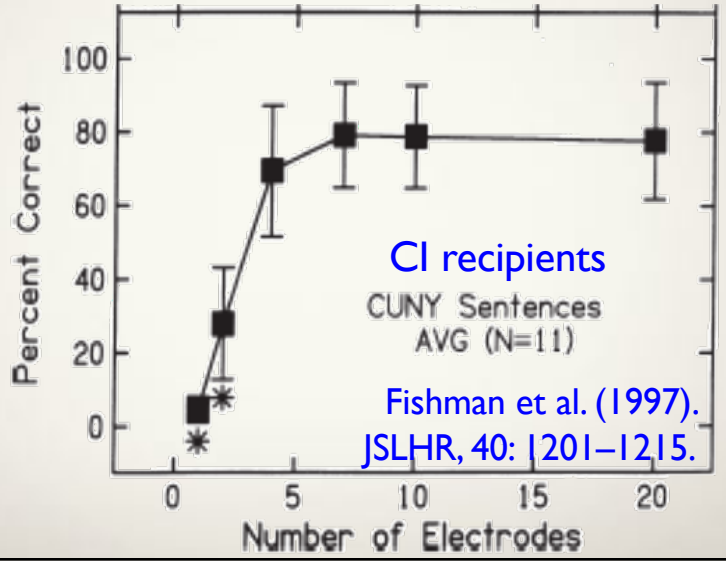
Wilson BS, Dorman MF. (2008). *J Rehab Res Dev*, 45(5): 695-730.

The cochlear implant:

"…the most successful of all neural prostheses developed to date"



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Cochlear implants: one size fits all?

- Device selection & programming → one-size-fits-all?
- Default parameters & electrode arrays used for <u>most recipients</u>
  - stimulation rate
  - Stimulation strategy
  - electrode-frequency allocation
  - max # of active electrodes
- Defaults are used despite differences in cochlear anatomy, electrode insertion depth, scalar/electrode location, electrode array, listening environment, etc.

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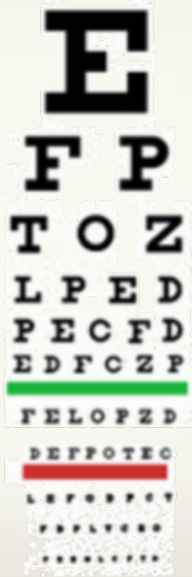
One size fits all?



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One size fits all?

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One size fits all?

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11

One size fits all?

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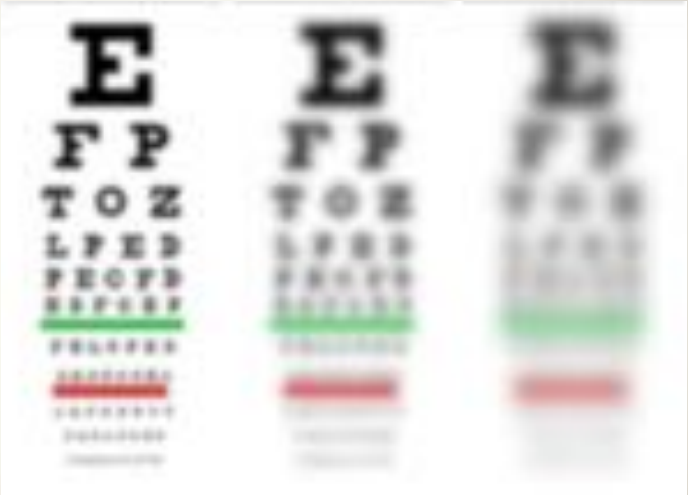
One size fits all?



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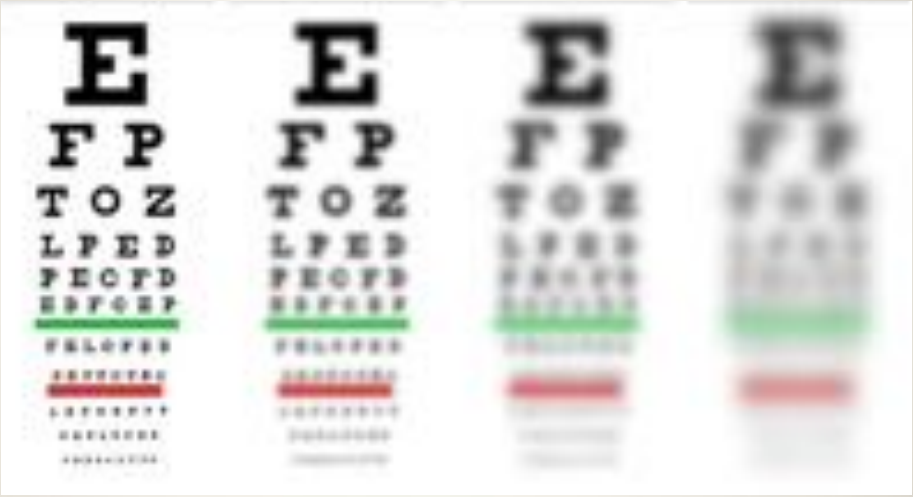
One size fits all?



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One size fits all?

Programming: one size fits all?

- Program threshold (T) and comfort (C/M) levels across the electrode array
  - Similar sets of parameters
    - Stimulation rate, pulse width, frequency allocation, # of active electrodes, # of maxima, etc.

ASSUMPTIONS:

- electrodes are in the right place & similar insertion across ears
- electrode-to-neural interface is uniform across the array

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One size fits all?

Programming: one size fits all?

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ASSUMPTIONS:

- ~~electrodes are in the right place & similar insertion across ears~~
- ~~electrode-to-neural interface is uniform across the array~~

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Objective: "Precision medicine" model for audiology & CI programming

- Using pre- and post-operative CT scans
  - determine position of implanted electrode arrays *relative to stimulation targets*
  - Create patient-specific, customized CI maps
  - Verification of device placement
    - Also useful for surgical training & refinement

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Background

***In vivo* electrode position identification:**

CT imaging approaches (Verbist et al., 2005. *Am J Neuroradiol.* 26: 424-429; Aschendorff et al. 2007. *Ear Hear.* 28: 75S-79S)

- High quality images of electrodes
- Not visible: Basilar membrane, Reissner's membrane, spiral ganglion

- Identification of electrode location and electrode-to-neural interface is impossible with standard CT

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Background

In vivo electrode position identification

- Register pre-op CT to post-op CT in which electrodes are visible
- Permits computation of scalar location & electrode-to-modiolus distance
  - **Automatic**—based on statistical shape modeling
  - Accounts for **non-rigid variations** in cochlear anatomy
  - Degree of error ~ 0.10 to 0.15 mm

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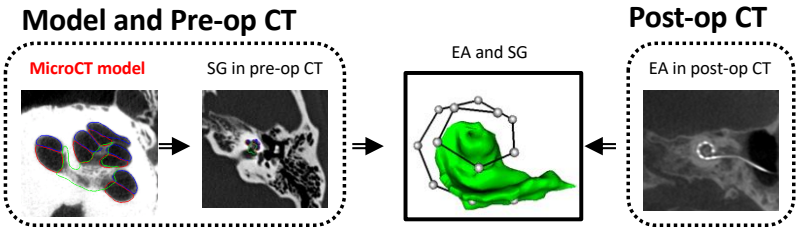
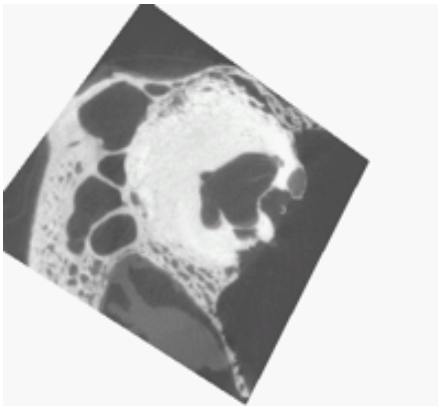


cadaver microCT

Lateral to medial

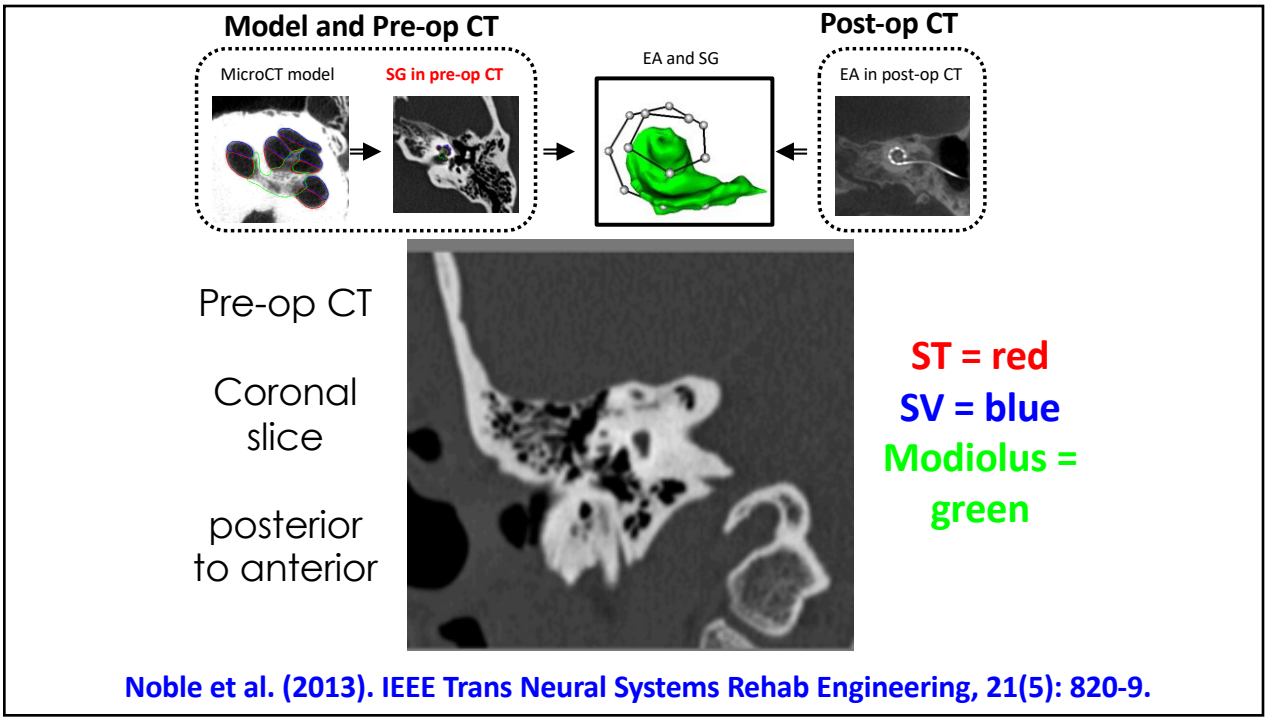


ST = red
SV = blue
Modiolus = green
Manual delineation in specimens

Noble et al. (2013). IEEE Trans Neural Systems Rehab Engineering, 21(5): 820-9.

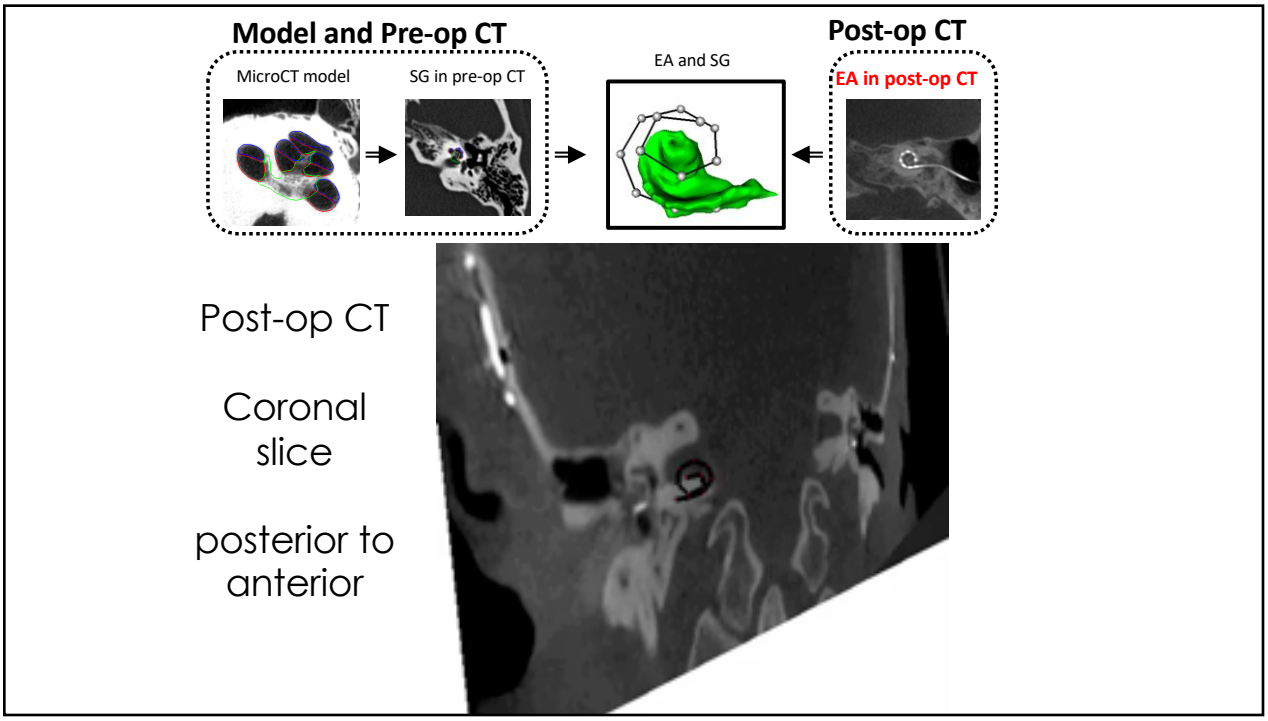
20

hip with



Noble et al. (2013). IEEE Trans Neural Systems Rehab Engineering, 21(5): 820-9.

21



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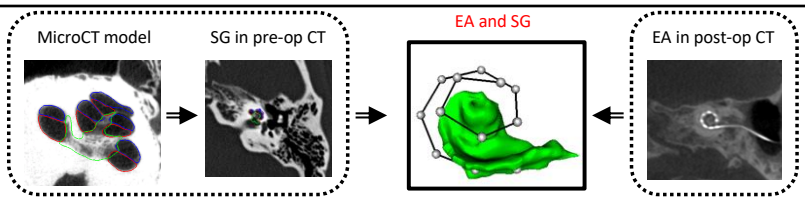
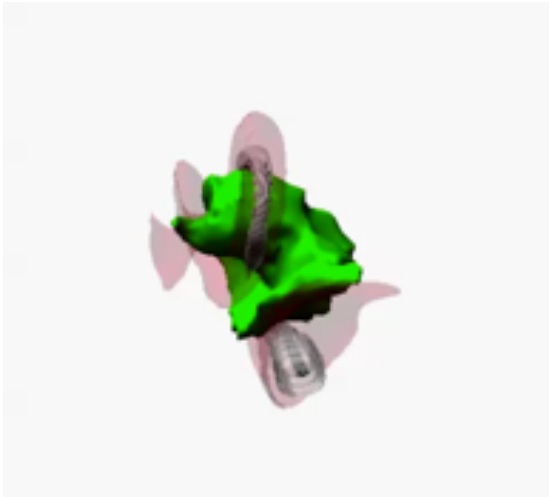


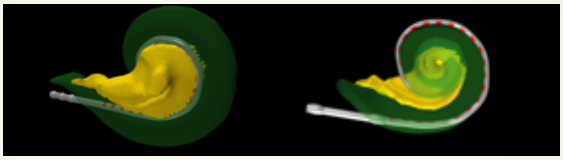


ST = red
SV = blue

23

Why does electrode position matter?

- Electrode-to-modiolus distance correlated with charge for upper stim levels (e.g., Litvak et al., 2007; Kang et al., 2015; Davis et al., 2016)



Modiolus: yellow
Green: scala tympani

- Higher charge → greater channel interaction (e.g., Chatterjee & Shannon, 1998; Chatterjee et al., 2006)
- Greater channel interaction → poorer spectral resolution

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3D reconstruction
Non-rigid statistical shape model

CI532
AVG electrode-to-modiolus distance: **0.13 mm**

CI532
AVG electrode-to-modiolus distance: **0.60 mm**

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Modiolus: Yellow

25

Chakravorti et al. (2019). Otol Neurotol, 40:617-624.

Further Evidence of the Relationship Between Cochlear Implant Electrode Positioning and Hearing Outcomes

*Srijata Chakravorti, *†‡Jack H. Noble, †René H. Gifford, *Benoit M. Dawant, ‡Brendan P. O'Connell, *Jianing Wang, and ‡Robert F. Labadie

*Department of Electrical Engineering and Computer Science, Vanderbilt University; †Vanderbilt Bill Wilkerson Center, Department of Hearing and Speech Sciences; and ‡Department of Otolaryngology–Head and Neck Surgery, Vanderbilt University Medical Center, Nashville, Tennessee

Background: Postoperative imaging studies by numerous groups have revealed that final cochlear implant (CI) electrode position impacts audiological outcomes with scalar location consistently shown to be a significant factor. Modiolar proximity has been less extensively studied, and findings regarding the effect of insertion depth have been inconsistent.
Methods: Using previously developed automated algorithms, we determined CI electrode position in an Institutional Review Board-approved database of 220 CI ears. Generalized linear models (GLM) were used to analyze the relationship between audiological outcomes and factors including age, duration of CI use, device type, and electrode position.
Results: For precurved arrays, GLM revealed that scalar position, modiolar proximity, base insertion depth, and sex onset of deafness were significant for Bamford-Kawal-Bench Sentences in Noise (BKB-SIN) ($R = 0.51$, $p < 0.001$, $n = 85$) scores. Other factors were not significant in the final model after controlling for these variables. For straight arrays, we found the insertion depth, postlingual deafness, and length of CI use to be highly significant ($R = 0.47$, $p < 0.001$) factors for CNC words (91 arrays), while for BKB-SIN scores the most significant ($R = 0.47$, $p < 0.001$) factors were insertion depth, younger age, and postlingual deafness (89 arrays).
Conclusion: Our results confirm the significance of electrode positioning in audiological outcomes. The most significant positional predictors of outcome for precurved arrays were full scala tympani (ST) insertion and the modiolar distance, while for the lateral wall arrays the depth of insertion was the most significant factor. **Key Words:** Cochlear implant—Electrode position—Insertion depth—Modiolar distance—Outcomes—

26

hip with

Chakravorti et al. (2019). Otol Neurotol, 40:617-624.

Multiple regression: CT-based localization

- Dataset: 220 CI implanted ears from an IRB-approved database of CI users who had post-operative CT
- Test scores used: CNC words, BKB-SIN
- CI position determined by segmenting cochlear anatomy and automatically localizing the electrodes on postoperative CTs

Manufacturer	Straight Arrays	Precurved Arrays
Advanced Bionics (AB)	Hifocus 1J (29)	Mid-Scala (21)
Cochlear (CO)	422/522 (20), 24RE(ST) (11)	Contour Advance (89)
MED-EL (ME)	Flex24 (3), Flex28 (22), Medium (1), Standard (24)	

27

	Precurved Arrays		Straight Arrays	
	CNC words (N = 92)	BKB-SIN (N = 85)	CNC Words (N = 91)	BKB-SIN (N = 89)
Audiological Scores	52.4 ± 25.0 % [0 - 92]	13.5 ± 6.0 dB [2.5 - 23.5]	43.8 ± 25.5 % [0 - 100]	14.8 ± 5.6 dB [1.5 - 23.5]
Full ST insertion	**N = 47 (51%)**	**N = 42 (49%)**	**N =77 (85%)**	**N =72 (81%)**
Mean modiolar distance	0.48 ± 0.15 mm [0.16 - 0.92]	0.47 ± 0.15 mm [0.16 - 0.82]	1.16 ± 0.16 mm [0.44 - 1.63]	1.16 ± 0.16 mm [0.44 - 1.63]
Base insertion depth	2.32 ± 1.16 mm [-3.01 - 6.30]	2.26 ± 1.06 mm [-3.01 - 4.25]	1.42 ± 2.41 mm [-9.57 - 4.60]	1.36 ± 2.43 mm [-9.57 - 4.60]
Tip insertion depth	376 ± 68 ° [115 - 679]	371 ± 62 ° [115 - 584]	454 ± 128 ° [217 - 717]	454 ± 130 ° [217 - 717]
Age at implantation	57.1 ± 16.9 years [12.2 - 89.2]	57.9 ± 16.9 years [12.2 - 89.2]	56.1 ± 18.0 years [7.0 - 85.9]	56.0 ± 18.0 years [7.0 - 85.9]
Gender	40 ♀ 52♂	35 ♀ 50♂	38 ♀ 53♂	38 ♀ 51♂
Prelingually deafened	N= 13 (14%)	N = 13 (15%)	N = 18 (20%)	N = 18 (20%)
Length of CI use	2.8 ± 2.4 years [0.5 -12.9]	2.8 ± 2.4 years [0.5 - 12.9]	2.9 ± 3.6 years [0.2 - 16.6]	2.9 ± 3.6 years [0.2 - 16.6]

28

Chakravorti et al. (2019). Otol Neurotol, 40:617-624.

- **Variables found to be significant:**
  - **Precurved:**
    - mean electrode-to-modiolus distance (mm)
    - age at implantation
    - full ST insertion
    - prelingual onset of deafness
  - **Straight**
    - base insertion depth
    - prelingual onset of deafness

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29

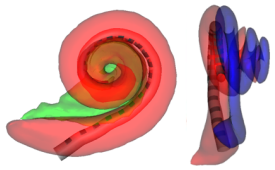
Case study:

- Male, CI at 35 y/o
- Postlingual
- 5 years CI experience

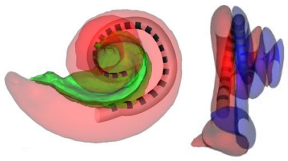
Using **Precurved** array

	ST insertion	Electrode-to-modiolus distance (mm)	CNC score
Good	1 (full ST)	0.18	82%
Average	0.5 (mostly ST)	0.48	56%
Poor	0	0.78	30%

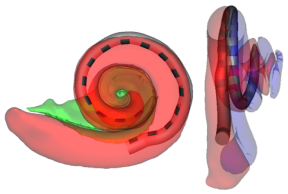
Good positioning:



Population average positioning:



Poor positioning:



30

Case study:

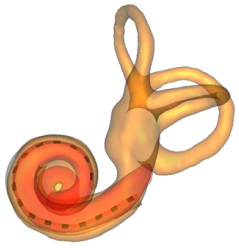
- Male, CI at 35 y/o
- Postlingual
- 5 years CI experience

Using **Straight** array

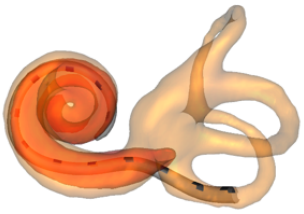
	Base Insertion Depth (mm)	CNC score
Good	6.24	68%
Average	1.42	52%
Poor	-3.4	36%

Good positioning:

Population average positioning:



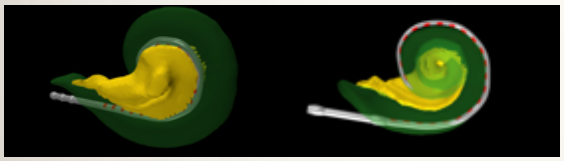
Poor positioning:

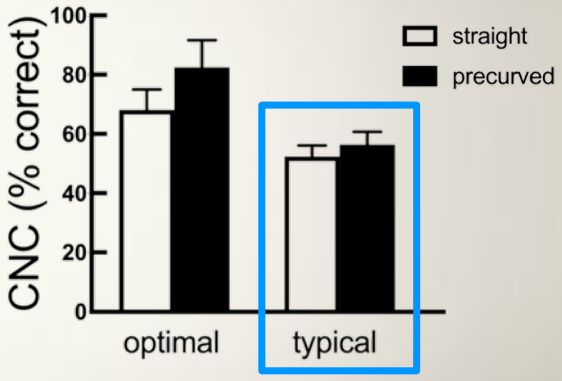


31

Chakravorti et al. (2019). Otol Neurotol, 40:617-624.

- **Electrode position matters!**
- **Precurved > straight**
  - ...when precurved electrode array is optimally positioned





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32

Summary

- Electrode position matters!
- Precurved > straight
  - When precurved is well positioned…
- Use of imaging and image processing can improve → hearing outcomes, patient counseling, future electrode design, CI programming, surgical outcomes
  - 13.4% of patients have extracochlear electrodes not specified in operative report (Holder et al. 2018. Otol Neurotol, 39:e325–e331)
- Future work: augment database with more patient data and other demographic factors such as duration of deafness, etiology, cognition, stimulation strategy, data logging, etc.

33

Holder et al. (2019). *Otol Neurotol*, 40: 1160-66.s

Matched Cohort Comparison Indicates Superiority of Precurved Electrode Arrays

*Jourdan T. Holder, †Robert J. Yawn, †Ashley M. Nassiri, *Robert T. Dwyer, †Alejandro Rivas, †Robert F. Labadie, and *René H. Gifford

*Department of Hearing and Speech Sciences; and †Department of Otolaryngology–Head and Neck Surgery, Vanderbilt University Medical Center, Nashville, Tennessee

Objective: Characterize differences in adult cochlear implant outcomes and programming parameters for a straight (CI422/522) and a precurved (CI532) electrode array.
Setting: Cochlear implant (CI) program at a tertiary otologic center.
Patients: Fifty-eight adults were included in the study; 29 were implanted with CI422 or CI522 and 29 were implanted with CI532. Each CI532 recipient was matched to a CI422/522 recipient in terms of age and preoperative hearing thresholds for comparison purposes.
Main Outcome Measures: Consonant-Nucleus-Consonant (CNC) words, AzBio sentences, residual audiometric thresholds, and Speech Spatial Qualities (SSQ) questionnaire collected 6 months postoperatively were used to characterize outcomes. Pulse duration, maxima, impedances, and overall charge measurements were used to characterize programming parameters.
Results: Postoperative unaided low frequency pure-tone average (LFPTA) was significantly better for the CI532 group. CNC scores were significantly better for the CI532 group. Impedances and pulse duration were significantly lower for the CI532 group, but there was no difference in overall charge between the groups.
Conclusion: The CI532 group showed either similar or statistically superior results on all measures when compared with the CI422/522 suggesting that the CI532 electrode may be an advantageous substitute for the CI522. **Key Words:** Audiology—Cochlear implant—Electrode array—Electrode type—Outcomes.

Otol Neurotol **40**:1160–1166, 2019.

34

hip with

Holder et al. (2019). *Otol Neurotol*, 40: 1160-66.

- n = 58
- 29 CI422/CI522, 29 CI532
- Matched cohort comparison -- 6 months post activation
  - Age
  - Preoperative audiometric thresholds
    - No significant difference between groups for preop CNC word rec or postop daily CI use

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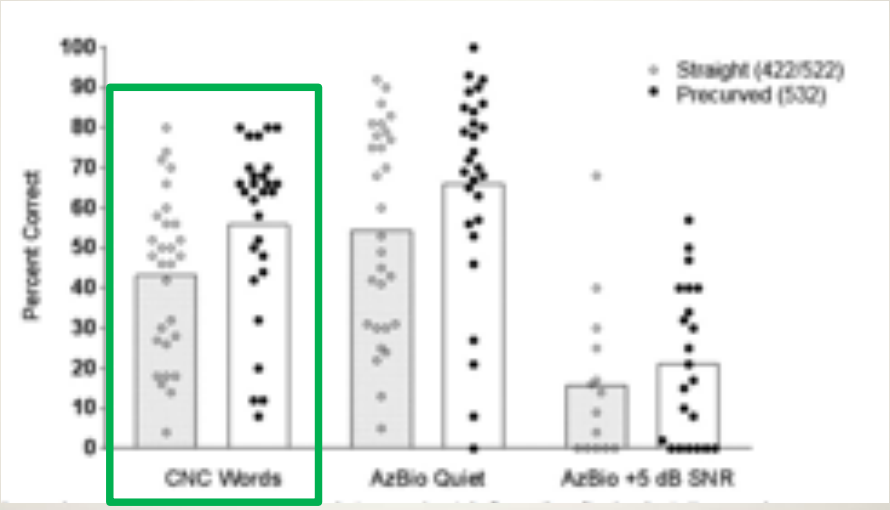
Holder et al. (2019). *Otol Neurotol*, 40: 1160-66.



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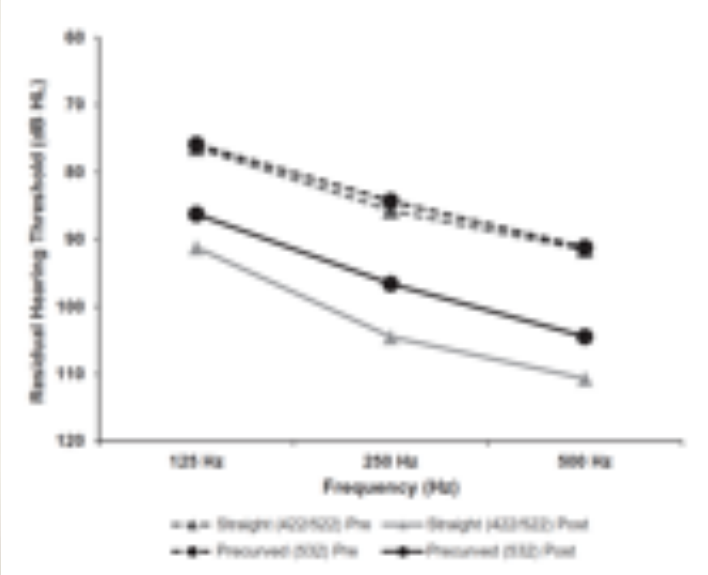
p = 0.016

36

Holder et al. (2019). *Otol Neurotol*, 40: 1160-66.



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37

Summary

- Electrode type matters!
- As compared to straight electrodes (422/522), precurved electrode arrays (532/632) →
  - Significantly higher CNC word rec
    - Higher AzBio sentence recognition in quiet & noise (+5 dB SNR)
  - Significantly better hearing preservation
  - Significantly lower electrode impedances
    - Lower charge at C level

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38

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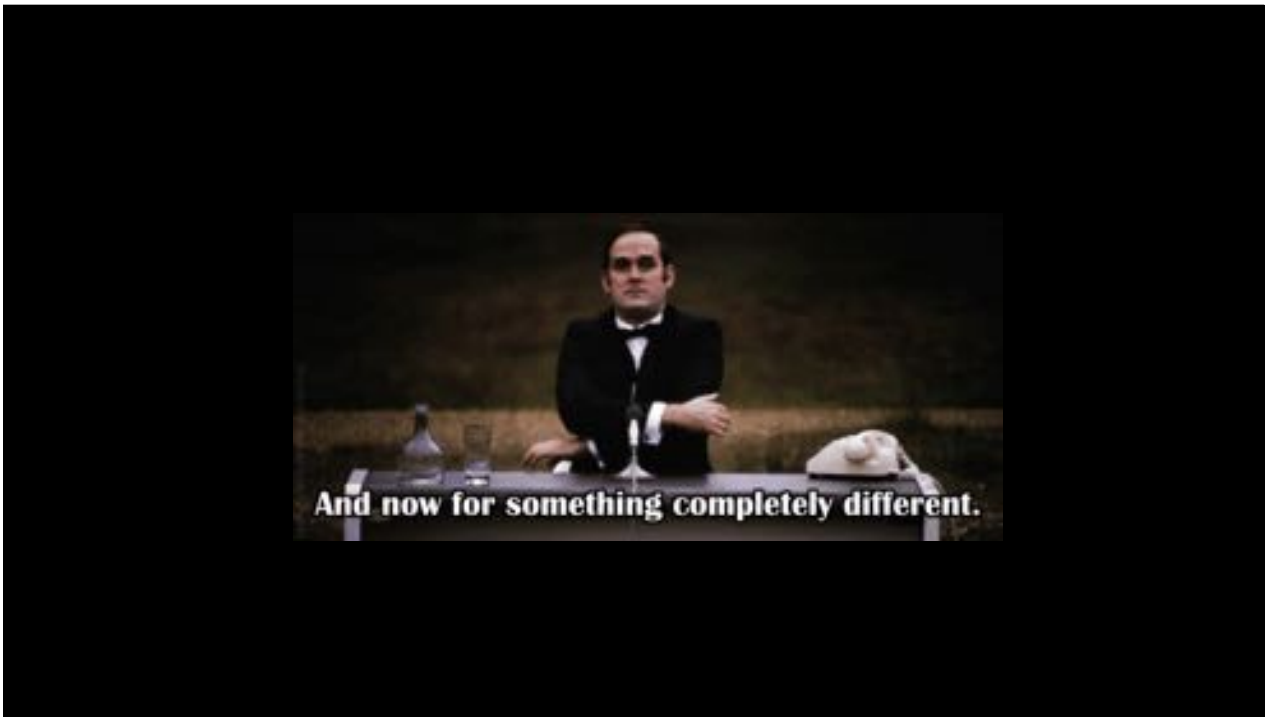
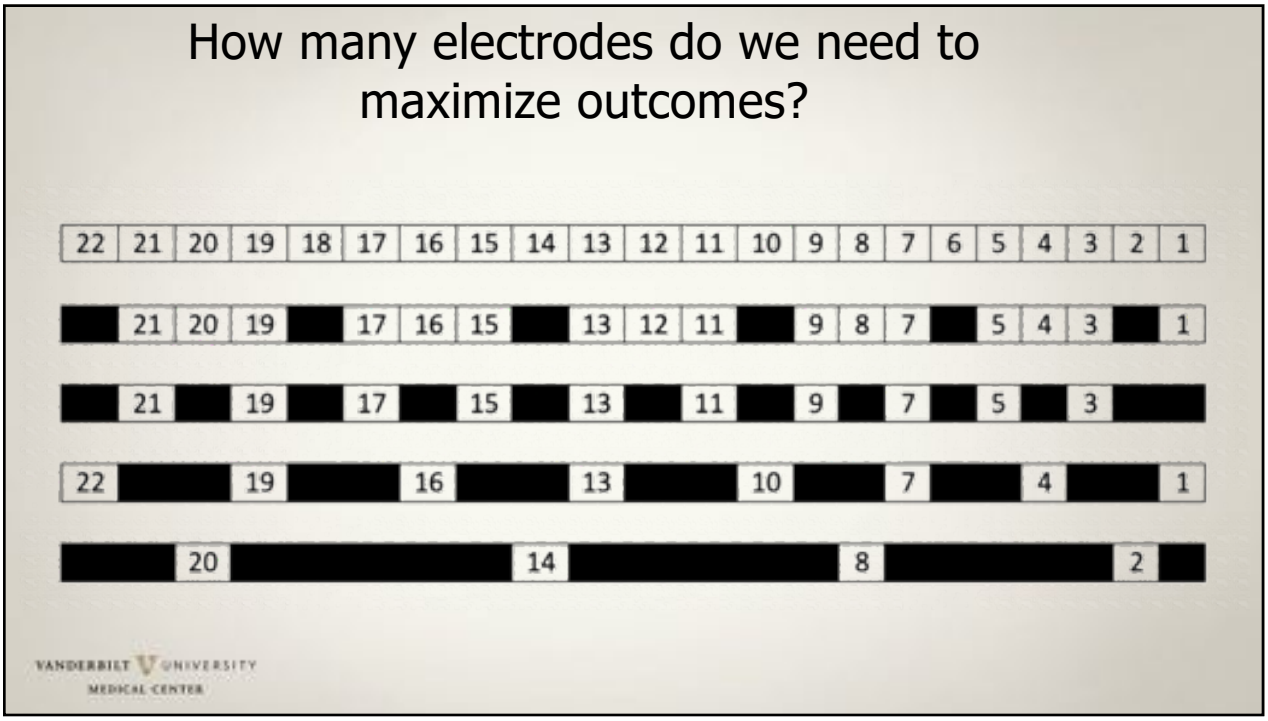

And now for something completely different.

39


How many electrodes do we need to maximize outcomes?
22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
21 20 19 17 16 15 13 12 11 9 8 7 5 4 3 1
21 19 17 15 13 11 9 7 5 3
22 19 16 13 10 7 4 1
20 14 8 2
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40

Information from past studies with CI recipients:

Above 4-8 channels, there were no additional gains for:

- Consonants
- Vowelss
- Monosyllables
- Sentences in quiet
- Sentences in noise

Fishman et al., 1997; Dorman et al., 1997; Friesen et al., 2001; Shannon et al., 2011

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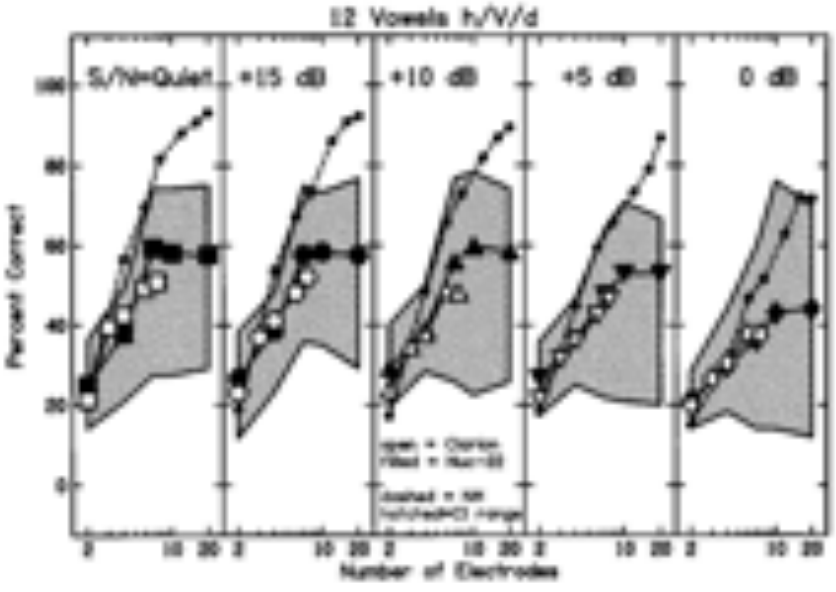
41

Friesen et al. (2001). *J Acoust Soc Am*, 110: 1150-63.



42

Berg et al. (2019). *J Acoust Soc Am*, 145: 1556-1564

Speech recognition as a function of the number of channels in perimodiolar electrode recipients

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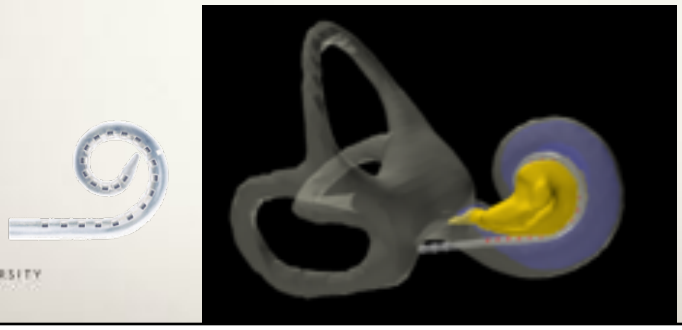
This study investigated the number of channels needed for maximum speech understanding and sound quality in 30 adult cochlear implant (CI) recipients with perimodiolar electrode arrays verified via imaging to be completely within scala tympani (ST). Performance was assessed using a continuous interleaved sampling (CIS) strategy with 4, 8, 10, and 16 channels and n-of-m with 16

43

Berg et al. (2019). *J Acoust Soc Am*, 145: 1556-1564

- N = 11 precurved electrode recipients
- 7 CI24RE(CA), 4 CI532
- Mean age = 67 years (24 to 87 years)
- Imaging and 3D reconstruction to determine scalar location
  - All completely in scala tympani (ST)



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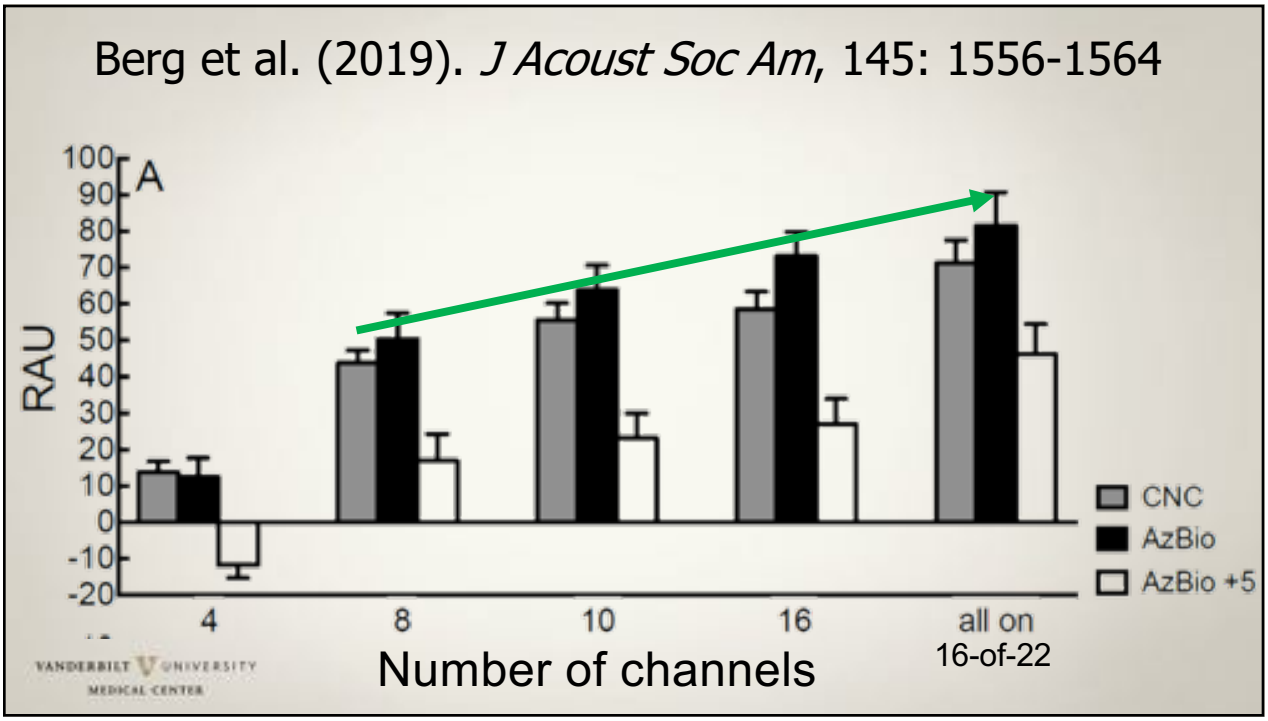
44


Berg et al. (2019). *J Acoust Soc Am*, 145: 1556-1564
A
RAU
100
90
80
70
60
50
40
30
20
10
0
-10
-20
4
8
10
16
all on
16-of-22
Number of channels
CNC
AzBio
AzBio +5
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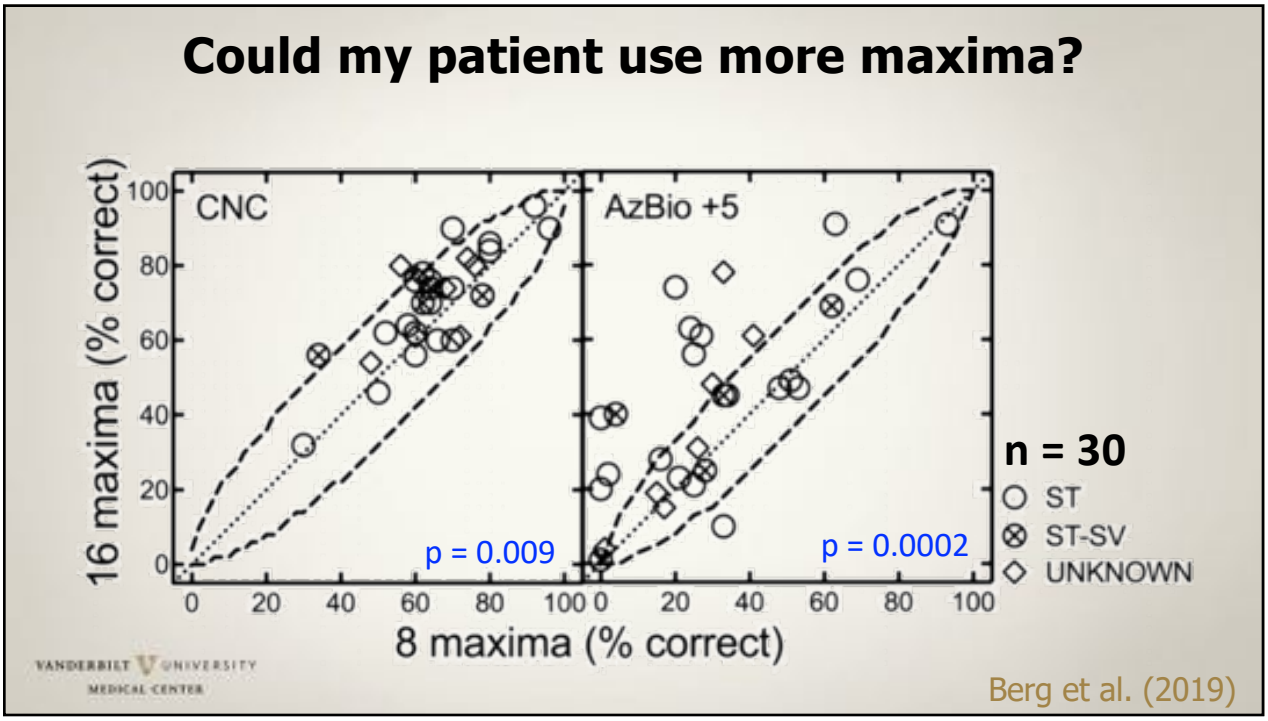
45


Could my patient use more maxima?
CNC
AzBio +5
16 maxima (% correct)
8 maxima (% correct)
p = 0.009
p = 0.0002
n = 30
ST
ST-SV
UNKNOWN
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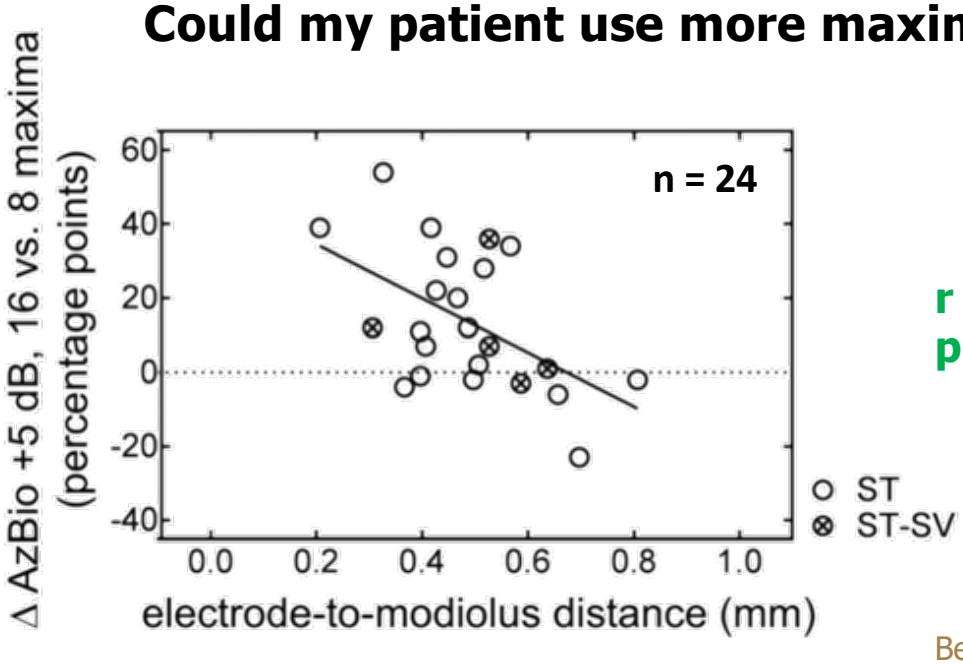
Berg et al. (2019)

46

Could my patient use more maxima?



r = -0.52
p = 0.010

Berg et al. (2019)

47

3D reconstruction
Non-rigid statistical shape model

CI532
AVG electrode-to-modiolus distance: **0.13 mm**

CI522
AVG electrode-to-modiolus distance: **1.18 mm**

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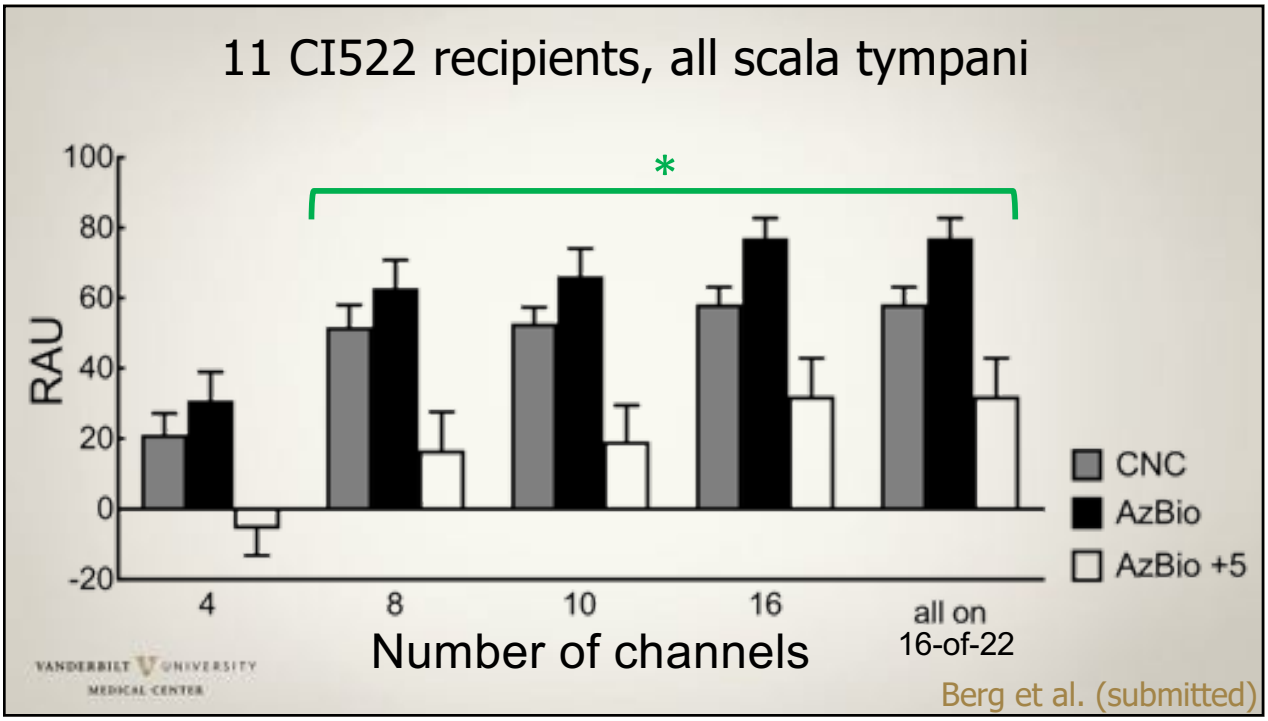
SV: blue, **Modiolus: Yellow**

48


11 CI522 recipients, all scala tympani
*
100
80
60
40
20
0
-20
RAU
4
8
10
16
all on
16-of-22
Number of channels
CNC
AzBio
AzBio +5
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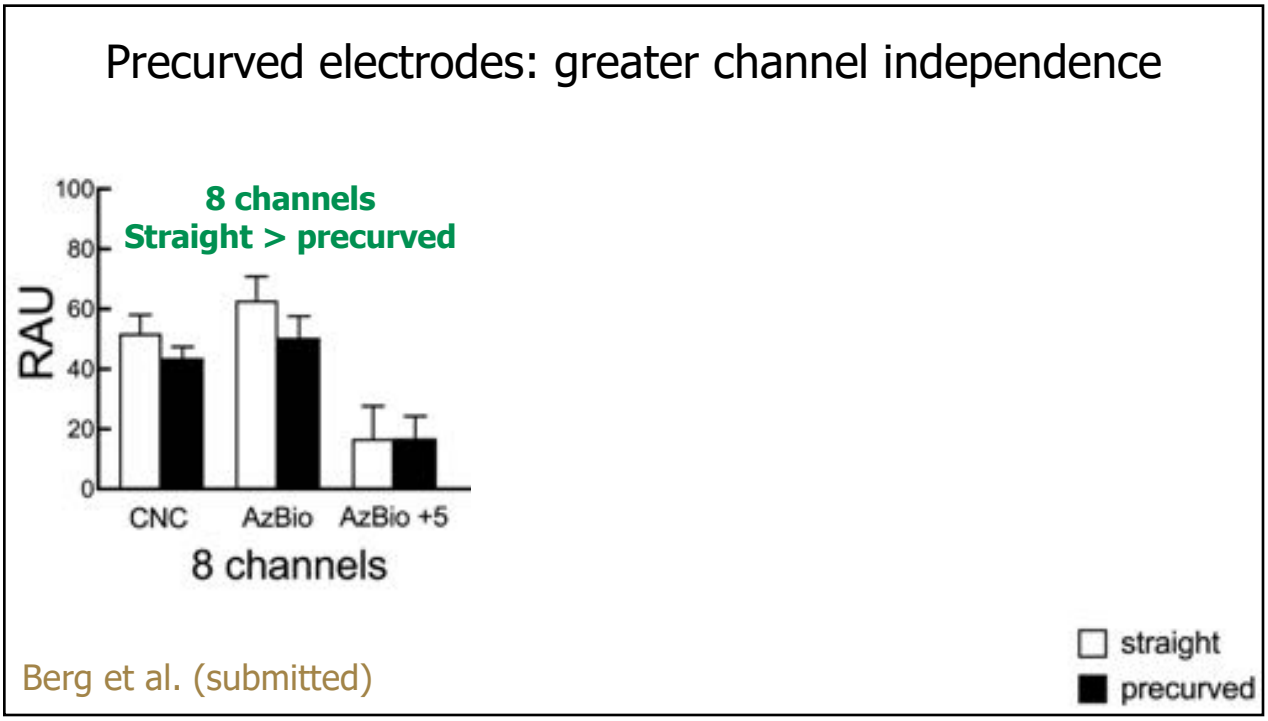
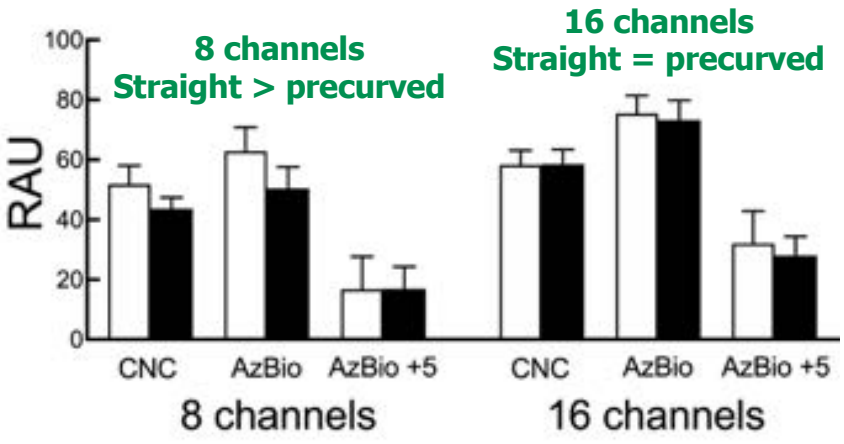
Berg et al. (submitted)

49


Precurved electrodes: greater channel independence
8 channels
Straight > precurved
100
80
60
40
20
0
RAU
CNC
AzBio
AzBio +5
8 channels
straight
precurved
Berg et al. (submitted)

50

Precurved electrodes: greater channel independence

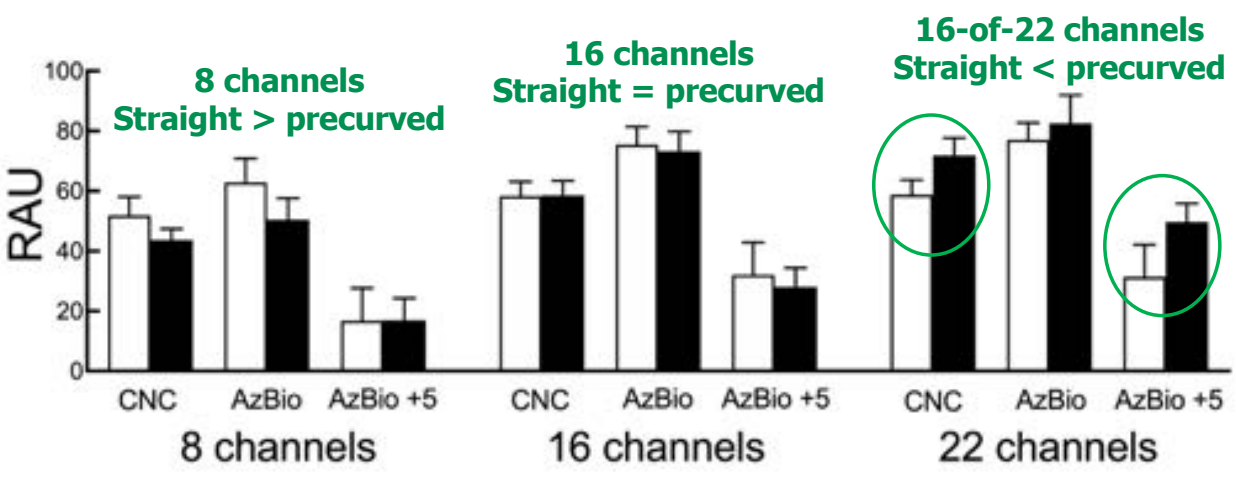


Berg et al. (submitted)

straight
precurved

51

Precurved electrodes: greater channel independence



Berg et al. (submitted)

straight
precurved

52

Summary

- Current CI users w/ precurved electrodes are different from those studied in the classic literature
  - Still no gains beyond 8 electrodes for straight arrays
- Rethink assumptions about number of active electrodes, role of electrode placement, maxima (for n-of-m), default parameters?
- **Clinical tip:** assess speech recognition in noise acutely in clinic with 16 maxima vs. 8 maxima
  - Higher default maxima for 532/632

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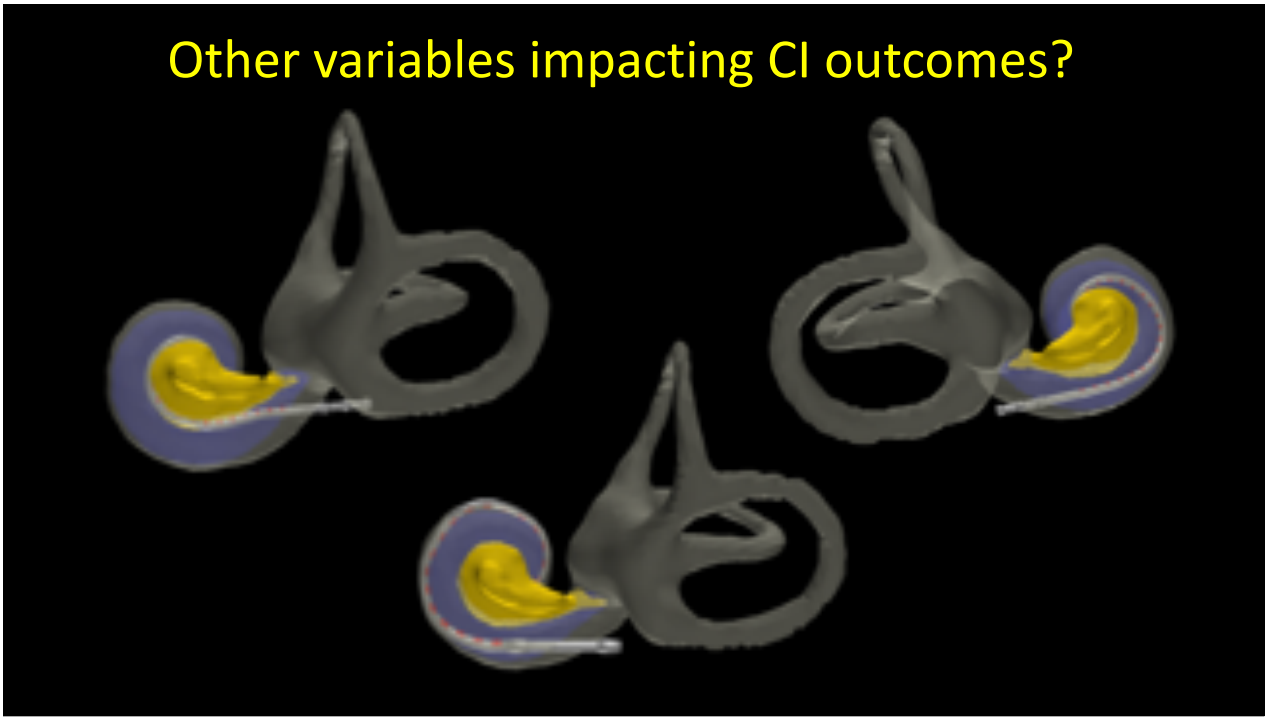
53

Other variables impacting CI outcomes?



54

Impact of CI processor wear time

Busch et al. (2017). JSLHR, 60: 1362-1377.

- 1501 patients' data logs, 0-96 yrs
- Daily CI use ~2.3 to > 15 hours/day (mean = 10.5)

Easwar et al. (2018). JAAA, 29: 835-846.

- 65 children with CI, 1-18 yrs
- Significant relationship between daily CI wear time & speech rec

Guerzoni & Cuda (2018). Int J Pediatr Otorhinolaryngol, 101:81–6.

- 10 children with CI, 20-36 months
- Significant correlation between daily CI wear time & vocabulary (MBCDI) after 1 year of CI use

55

Impact of CI processor wear time

Schvartz-Leyzac et al. (2017). Otol Neurotol, 40:e686–93.

- 177 patients' data logs, 18-93 yrs
- Mean daily CI use = 12.1 hrs
- Daily CI use was significantly correlated with CNC word rec ($r = 0.43$, $p < 0.001$) and AzBio sentence rec in quiet ($r = 0.39$, $p < 0.001$)
- Correlations were strongest for recipients aged 41 to 93 yrs
  - Youngest age groups did not show a reliable relationship between daily CI use and speech rec
  - But only 23 participants in the sample < 41 yrs

56

Holder et al. (2019). Otol Neurotol, 2019 Nov 1.

Duration of Processor Use Per Day Is Significantly Correlated With Speech Recognition Abilities in Adults With Cochlear Implants

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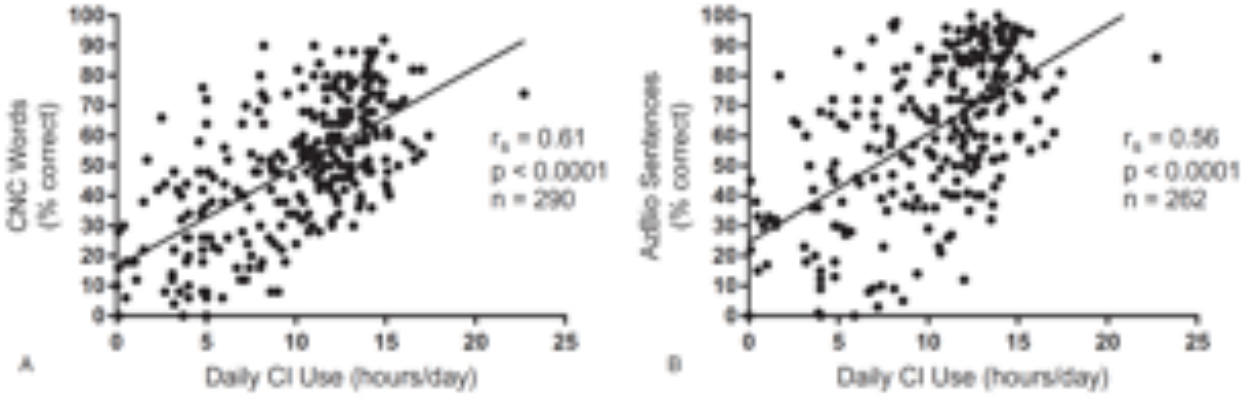
Objective: Quantify the relationship between average hours of processor use per day and measures of speech recognition in post-lingually deafened adults with cochlear implants.
Setting: Cochlear implant (CI) program at a tertiary medical center.
Patients: Three hundred adult (mean age = 64, 130 women) CI users were included.
Main Outcome Measures: Correlation analyses were completed for CI-aided speech recognition (Consonant-Nucleus-Consonant [CNC] monosyllables and AzBio sentences) at approximately 12 months post-implantation and average hours of processor use per day, which was extracted from the CI programming software.
were 49.9 and 61.7% for CNC and AzBio sentence recognition, respectively. We found a strong, significant correlation between hours of processor use per day and consonant-nucleus-consonant (CNC) word recognition ($r_s = 0.61$, $p < 0.0001$) and AzBio sentence recognition ($r_s = 0.56$, $p < 0.0001$).
Conclusions: Results suggest that highest speech recognition outcomes are correlated with greater than 10 hours of CI use per day. Further research is needed to assess the causal link between daily CI use and speech recognition abilities. **Key Words:** Audiology—Cochlear implant—Datalogging—Outcomes—Speech perception.

57

Holder et al. (2019). Otol Neurotol, 2019 Nov 1.

- 300 patients' data logs, 18-96 yrs
- Mean daily CI use = 10.2 hrs (0.1-22.7)



58

Summary and conclusions

- Current CI electrode arrays & surgical techniques are significantly improved
- Current CI recipients are drastically different from those implanted in the past (shorter durations of deafness, better neural survival, better device placement, less intracochlear trauma)
- Variables impacting outcomes: onset of deafness, age at CI (precurved), electrode array placement, electrode-to-modiolus distance (precurved), # channels (precurved), # maxima (precurved), CI use

59

60

61

62